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

1990 – 2004

APRIL 15, 2006

U.S. Environmental Protection Agency

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Washington, DC 20460

U.S.A.

[Inside Front Cover]

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All data tables of this document are available for the full time series 1990 through 2004, 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/globalwarming>.

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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.

[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

Central to any study of climate change is the development of an emissions inventory that identifies and quantifies a country's primary anthropogenic[1] sources and sinks of greenhouse gases. This inventory adheres to both 1) a comprehensive and detailed methodology 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 2004. 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). 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.

[BEGIN BOX]

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

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

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

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

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 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 2003) 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.

[END BOX]

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 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 2004, concentrations of these greenhouse gases have increased globally by 35, 143, and 18 percent, respectively (IPCC 2001, Hofmann 2004).

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 2001).

[5] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in the annexes of the Inventory report 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 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 of CO_2 equivalent (Tg CO_2 Eq.).[7] 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 2002,[8] but continue to require the use of GWPs from the IPCC Second Assessment Report (SAR). This requirement ensures that current estimates of aggregate greenhouse gas emissions for 1990 to 2004 are consistent with estimates developed prior to the publication of the IPCC Third Assessment Report (TAR). 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 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 below in Table ES-1.

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

Gas	GWP
CO_2	1
CH_4*	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.

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

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 2004, total U.S. greenhouse gas emissions were 7,074.4 Tg CO_2 Eq. Overall, total U.S. emissions have risen by 15.8 percent from 1990 to 2004, while the U.S. gross domestic product has increased by 51 percent over the same period (BEA 2005). Emissions rose from 2003 to 2004, increasing by 1.7 percent (115.3 Tg CO_2 Eq.). The following factors were primary contributors to this increase: 1) robust economic growth in 2004, leading to increased demand for electricity and fossil fuels, 2) expanding industrial production in energy-intensive industries, also increasing demand for electricity and fossil fuels, and 3) increased travel, leading to higher rates of consumption of petroleum fuels.

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 2004.

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	1998	1999	2000	2001	2002	2003	2004
CO_2	**5,005.3**	**5,620.2**	**5,695.0**	**5,864.5**	**5,795.2**	**5,815.9**	**5,877.7**	**5,988.0**
Fossil Fuel Combustion	4,696.6	5,271.8	5,342.4	5,533.7	5,486.9	5,501.8	5,571.1	5,656.6
Non-Energy Use of Fuels	117.2	152.8	160.6	140.7	131.0	136.5	133.5	153.4
Iron and Steel Production	85.0	67.7	63.8	65.3	57.8	54.6	53.3	51.3
Cement Manufacture	33.3	39.2	40.0	41.2	41.4	42.9	43.1	45.6
Waste Combustion	10.9	17.1	17.6	17.9	18.6	18.9	19.4	19.4
Ammonia Production and Urea Application	19.3	21.9	20.6	19.6	16.7	18.5	15.3	16.9
Lime Manufacture	11.2	13.9	13.5	13.3	12.8	12.3	13.0	13.7
Limestone and Dolomite Use	5.5	7.4	8.1	6.0	5.7	5.9	4.7	6.7
Natural Gas Flaring	5.8	6.6	6.9	5.8	6.1	6.2	6.1	6.0
Aluminum Production	7.0	6.4	6.5	6.2	4.5	4.6	4.6	4.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.2	4.1	4.1	4.1	4.2
Petrochemical Production	2.2	3.0	3.1	3.0	2.8	2.9	2.8	2.9
Titanium Dioxide Production	1.3	1.8	1.9	1.9	1.9	2.0	2.0	2.3
Phosphoric Acid Production	1.5	1.6	1.5	1.4	1.3	1.3	1.4	1.4
Ferroalloy Production	2.0	2.0	2.0	1.7	1.3	1.2	1.2	1.3
CO_2 Consumption	0.9	0.9	0.8	1.0	0.8	1.0	1.3	1.2
Zinc Production	0.9	1.1	1.1	1.1	1.0	0.9	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Consumption	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Net CO_2 Flux from Land Use, Land-Use Change and Forestry[a]	*(910.4)*	(744.0)	(765.7)	(759.5)	(768.0)	(768.6)	(774.8)	(780.1)

International Bunker Fuels[b]	*113.5*	*114.6*	*105.2*	*101.4*	*97.8*	*89.5*	*84.1*	*94.5*
Biomass Combustion[b]	*216.7*	*217.2*	*222.3*	*226.8*	*200.5*	*194.4*	*202.1*	*211.2*
CH_4	**618.1**	**579.5**	**569.0**	**566.9**	**560.3**	**559.8**	**564.4**	**556.7**
Landfills	172.3	144.4	141.6	139.0	136.2	139.8	142.4	140.9
Natural Gas Systems	126.7	125.4	121.7	126.7	125.6	125.4	124.7	118.8
Enteric Fermentation	117.9	116.7	116.8	115.6	114.6	114.7	115.1	112.6
Coal Mining	81.9	62.8	58.9	56.3	55.5	52.5	54.8	56.3
Manure Management	31.2	38.8	38.1	38.0	38.9	39.3	39.2	39.4
Wastewater Treatment	24.8	32.6	33.6	34.3	34.7	35.8	36.6	36.9
Petroleum Systems	34.4	29.7	28.5	27.8	27.4	26.8	25.9	25.7
Rice Cultivation	7.1	7.9	8.3	7.5	7.6	6.8	6.9	7.6
Stationary Sources	7.9	6.8	7.0	7.3	6.6	6.2	6.5	6.4
Abandoned Coal Mines	6.0	6.9	6.9	7.2	6.6	6.0	5.8	5.6
Mobile Sources	4.7	3.8	3.6	3.5	3.3	3.2	3.0	2.9
Petrochemical Production	1.2	1.7	1.7	1.7	1.4	1.5	1.5	1.6
Iron and Steel Production	1.3	1.2	1.2	1.2	1.1	1.0	1.0	1.0
Agricultural Residue Burning	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.9
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**394.9**	**440.6**	**419.4**	**416.2**	**412.8**	**407.4**	**386.1**	**386.7**
Agricultural Soil Management	266.1	301.1	281.2	278.2	282.9	277.8	259.2	261.5
Mobile Sources	43.5	54.8	54.1	53.1	50.0	47.5	44.8	42.8
Manure Management	16.3	17.4	17.4	17.8	18.1	18.0	17.5	17.7
Nitric Acid Production	17.8	20.9	20.1	19.6	15.9	17.2	16.7	16.6
Human Sewage	12.9	14.9	15.4	15.5	15.6	15.6	15.8	16.0
Stationary Sources	12.3	13.4	13.4	13.9	13.5	13.2	13.6	13.7
Settlements Remaining Settlements	5.6	6.2	6.2	6.0	5.8	6.0	6.2	6.4
Adipic Acid Production	15.2	6.0	5.5	6.0	4.9	5.9	6.2	5.7
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Waste Combustion	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5
Agricultural Residue Burning	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Forest Land Remaining Forest Land	0.1	0.4	0.5	0.4	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*
HFCs, PFCs, and SF_6	**90.8**	**133.4**	**131.5**	**134.7**	**124.9**	**132.7**	**131.0**	**143.0**
Substitution of Ozone Depleting Substances	0.4	54.5	62.8	71.2	78.6	86.2	93.5	103.3
HCFC-22 Production	35.0	40.1	30.4	29.8	19.8	19.8	12.3	15.6
Electrical Transmission and Distribution	28.6	16.7	16.1	15.3	15.3	14.5	14.0	13.8
Semiconductor Manufacture	2.9	7.1	7.2	6.3	4.5	4.4	4.3	4.7
Aluminum Production	18.4	9.1	9.0	9.0	4.0	5.3	3.8	2.8
Magnesium Production and Processing	5.4	5.8	6.0	3.2	2.6	2.6	3.0	2.7
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

+ 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.

Note: Totals may not sum due to independent rounding.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2004. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 85 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 steadily declined since 1990, resulted primarily from decomposition of wastes in landfills, natural gas systems, and enteric fermentation associated with domestic livestock. Agricultural soil management and mobile source fossil 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 from semiconductor manufacturing and as a by-product of primary aluminum production.

Figure ES-4: 2004 Greenhouse Gas Emissions by Gas

Overall, from 1990 to 2004, total emissions of CO_2 increased by 982.7 Tg CO_2 Eq. (20 percent), while CH_4 and N_2O emissions decreased by 61.3 Tg CO_2 Eq. (10 percent) and 8.2 Tg CO_2 Eq. (2 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 52.2 Tg CO_2 Eq. (58 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 11 percent of total emissions in 2004. The following sections describe each gas' contribution to total U.S. greenhouse gas emissions in more detail.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, 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 35 percent (IPCC 2001, Hofmann 2004), principally due to the combustion of fossil fuels. Within the United States, fuel combustion accounted for 94 percent of CO_2 emissions in 2004. Globally, approximately 25,575 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2002, of which the United States accounted for about 23 percent.[9] 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).

Figure ES-5: 2004 Sources of CO_2

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 80 percent of GWP weighted emissions since 1990, growing slowly from 77 percent of total GWP-weighted emissions in 1990 to 80 percent in 2004.. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 2004. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 14 years, and (2) significant growth in emissions from transportation activities and electricity generation. Between 1990 and 2004, CO_2 emissions from fossil fuel combustion increased from 4,696.6 Tg CO_2 Eq. to 5,656.6 Tg CO_2 Eq.—a 20 percent total increase over the fourteen-year period. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

From 2003 to 2004, these emissions increased by 85.5 Tg CO_2 Eq. (1.5 percent). A number of factors played a

[9] Global CO_2 emissions from fossil fuel combustion were taken from Marland et al. (2005) <http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm>.

major role in the magnitude of this increase. Strong growth in the U.S. economy and industrial production, particularly in energy-intensive industries, caused 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 in both the residential and commercial sectors. Moreover, much of the increased electricity demanded was generated by natural gas consumption and nuclear power, rather than more carbon intensive coal, moderating the increase in CO_2 emissions from electricity generation. Use of renewable fuels rose very slightly due to increases in the use of biofuels.

Figure ES-6: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure ES-7: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

The four major end-use sectors contributing to CO_2 emissions from fossil fuel combustion are industrial, transportation, residential, and commercial. Electricity generation also emits CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four 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.

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

End-Use Sector	1990	1998	1999	2000	2001	2002	2003	2004
Transportation	**1,464.4**	**1,663.4**	**1,725.6**	**1,770.3**	**1,757.0**	**1,802.2**	**1,805.4**	**1,860.2**
Combustion	1,461.4	1,660.3	1,722.4	1,766.9	1,753.6	1,798.8	1,801.0	1,855.5
Electricity	3.0	3.1	3.2	3.4	3.5	3.4	4.3	4.7
Industrial	**1,528.3**	**1,634.5**	**1,613.5**	**1,642.8**	**1,574.9**	**1,542.8**	**1,572.4**	**1,595.0**
Combustion	851.1	871.9	849.0	862.6	861.2	842.1	844.6	863.5
Electricity	677.2	762.6	764.5	780.3	713.7	700.7	727.7	731.5
Residential	**922.8**	**1,044.5**	**1,064.0**	**1,123.2**	**1,123.2**	**1,139.8**	**1,166.6**	**1,166.8**
Combustion	338.0	333.5	352.3	369.9	361.5	360.0	378.8	369.6
Electricity	584.8	711.0	711.7	753.3	761.7	779.8	787.9	797.2
Commercial	**753.1**	**895.9**	**904.8**	**961.6**	**983.3**	**973.9**	**978.1**	**983.1**
Combustion	222.6	217.7	218.6	229.3	224.9	224.3	235.8	226.0
Electricity	530.5	678.2	686.2	732.4	758.4	749.6	742.2	757.2
U.S. Territories	**28.0**	**33.5**	**34.5**	**35.8**	**48.5**	**43.1**	**48.7**	**51.4**
Total	**4,696.6**	**5,271.8**	**5,342.4**	**5,533.7**	**5,486.9**	**5,501.8**	**5,571.1**	**5,656.6**
Electricity Generation	**1,795.5**	**2,154.9**	**2,165.6**	**2,269.3**	**2,237.3**	**2,233.5**	**2,262.2**	**2,290.6**

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.

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2004.[10] Virtually all of the energy consumed in this end-

[10] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 34 percent of U.S.

use sector came from petroleum products. Over 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 28 percent of CO_2 from fossil fuel combustion in 2004. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the 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 17 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2004. Both sectors relied heavily on electricity for meeting energy demands, with 68 and 77 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking.

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 34 percent of U.S. energy from fossil fuels and emitted 40 percent of the CO_2 from fossil fuel combustion in 2004. 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 2004. 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 iron and steel production decreased to 51.3 Tg CO_2 Eq. in 2004, and have declined by 33.7 Tg CO_2 Eq. (40 percent) from 1990 through 2004, due to reduced domestic production of pig iron, sinter, and coal coke.
- CO_2 emissions from cement production increased to 45.6 Tg CO_2 Eq. in 2004, a 37 percent increase in emissions since 1990. Emissions mirror growth in the construction industry. In contrast to many other manufacturing sectors, demand for domestic cement remains strong because it is not cost-effective to transport cement far from its point of manufacture.
- CO_2 emissions from waste combustion (19.4 Tg CO_2 Eq. in 2004) increased by 8.4 Tg CO_2 Eq. (77 percent) from 1990 through 2004, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- Net CO_2 sequestration from Land Use, Land-Use Change, and Forestry decreased by 130.3 Tg CO_2 Eq. (14 percent) from 1990 through 2004. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings and food scraps also slowed over this period, while the rate of carbon accumulation in agricultural soils and 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 143 percent (IPCC 2001, Hofmann 2004). Experts believe that over half of this atmospheric increase was due to emissions from

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emissions from fossil fuel combustion in 2004.

anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-8).

Figure ES-8: 2004 U.S. Sources of CH_4

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

- Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2004, landfill CH_4 emissions were 140.9 Tg CO_2 Eq. (approximately 25 percent of total CH_4 emissions), which represents a decline of 31.4 Tg CO_2 Eq., or 18 percent, since 1990. Although the amount of solid waste landfilled each year continues to climb, the amount of CH_4 captured and burned at landfills has increased dramatically, countering this trend.
- CH_4 emissions from natural gas systems were 118.8 Tg CO_2 Eq. in 2004; emissions have declined by 7.9 Tg CO_2 Eq. (6 percent) since 1990. This decline has been due to improvements in technology and management practices, as well as some replacement of old equipment.
- Enteric fermentation was also a significant source of CH_4, accounting for 112.6 Tg CO_2 Eq. in 2004. This amount has declined by 5.3 Tg CO_2 Eq. (4 percent) since 1990, and by 10.4 Tg CO_2 Eq. (8 percent) from a high in 1995. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle.

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 2001, Hofmann 2004). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, manure management, nitric acid production, human sewage, and stationary fuel combustion (see Figure ES-9).

Figure ES-9: 2004 U.S. Sources of N_2O

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

- Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 68 percent (261.5 Tg CO_2 Eq.) of 2004 emissions. N_2O emissions from this source have not shown any significant long-term trend, as they are highly sensitive to such factors as temperature and precipitation, which have generally outweighed changes in the amount of nitrogen applied to soils.
- In 2004, N_2O emissions from mobile combustion were 42.8 Tg CO_2 Eq. (approximately 11 percent of U.S. N_2O emissions). From 1990 to 2004, N_2O emissions from mobile combustion decreased by 1 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced CH_4 emissions while increasing N_2O emissions. Since 1998, new control technologies have led to a steady decline in N_2O from this source.

HFC, PFC, and SF_6 Emissions

HFCs and PFCs are families of synthetic chemicals that are being 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).

Figure ES-10: 2004 U.S. Sources of HFCs, PFCs, and SF_6

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 103.3 Tg CO_2 Eq. in 2004. 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 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.
- The increase in ODS emissions is offset substantially by decreases in emission of HFCs, PFCs, and SF_6 from other sources. Emissions from aluminum production decreased by 85 percent (15.6 Tg CO_2 Eq.) from 1990 to 2004, due to both industry emission reduction efforts and lower domestic aluminum production.
- Emissions from the production of HCFC-22 decreased by 55 percent (19.4 Tg CO_2 Eq.), 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.
- Emissions from electric power transmission and distribution systems decreased by 52 percent (14.8 Tg CO_2 Eq.) from 1990 to 2004, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

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), the Inventory of U.S. Greenhouse Gas Emissions and Sinks report is segregated into six sector-specific chapters. Figure ES-11 and

Table ES-4 aggregate emissions and sinks by these chapters.

Figure ES-11: U.S. Greenhouse Gas Emissions by Chapter/IPCC Sector

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	1998	1999	2000	2001	2002	2003	2004
Energy	5,148.3	5,752.3	5,822.3	5,994.3	5,931.6	5,944.6	6,009.8	6,108.2
Industrial Processes	301.1	335.1	327.5	329.6	300.7	310.9	304.1	320.7
Solvent and Other Product Use	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Agriculture	439.6	483.2	463.1	458.4	463.4	457.8	439.1	440.1
Land Use, Land-Use Change, and Forestry (Emissions)	5.7	6.5	6.7	6.4	6.2	6.4	6.6	6.8
Waste	210.0	191.8	190.7	188.8	186.4	191.3	194.8	193.8

Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry*	(910.4)	(744.0)	(765.7)	(759.5)	(768.0)	(768.6)	(774.8)	(780.1)
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

* 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.

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 2004. In 2004, approximately 86 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 14 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 (39 percent and 15 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 86 percent of total U.S. greenhouse gas emissions in 2004.

Figure ES-12: 2004 U.S. Energy Consumption by Energy Source

Industrial Processes

The Industrial Processes chapter contains by-product 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. The processes include iron and steel production, lead and zinc production, cement manufacture, ammonia manufacture 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, aluminum production, petrochemical production, silicon carbide production, nitric acid production, and adipic acid production. Additionally, emissions from industrial processes release HFCs, PFCs and SF_6. Overall, emission sources in the Industrial Process chapter account for 4.5 percent of U.S. greenhouse gas emissions in 2004.

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 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 2004.

Agriculture

The Agricultural chapter contains anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy 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 20 percent and 7 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2004. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2004, accounting for 68 percent. In 2004, emission sources accounted for in the Agricultural chapters were responsible

for 6.2 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 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 carbon in the United States. Forests (including vegetation, soils, and harvested wood) accounted for approximately 82 percent of total 2004 sequestration, urban trees accounted for 11 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 6 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2004. 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 soils account for a net carbon sink that is almost two times larger than the sum of emissions from organic soils and liming. The mineral soil carbon sequestration is largely due to 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 2004 resulted in a net carbon sequestration of 780.1 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 13 percent of total U.S. CO_2 emissions, or 11 percent of total greenhouse gas emissions in 2004. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 14 percent between 1990 and 2004, which contributed to an increase in net U.S. emissions (all sources and sinks) of 21 percent from 1990 to 2004. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings and food scraps and agricultural soils also slowed over this period. However, the rate of annual carbon accumulation increased in both agricultural soils and urban trees.

Land use, land-use change, and forestry activities in 2004 also resulted in emissions of N_2O (6.8 Tg CO_2 Eq.). Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 20 percent between 1990 and 2004.

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

Sink Category	1990	1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**(773.4)**	**(618.8)**	**(637.9)**	**(631.0)**	**(634.0)**	**(634.6)**	**(635.8)**	**(637.2)**
Changes in Forest Carbon Stocks	(773.4)	(618.8)	(637.9)	(631.0)	(634.0)	(634.6)	(635.8)	(637.2)
Cropland Remaining Cropland	**(33.1)**	**(24.6)**	**(24.6)**	**(26.1)**	**(27.8)**	**(27.5)**	**(28.7)**	**(28.9)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions	(33.1)	(24.6)	(24.6)	(26.1)	(27.8)	(27.5)	(28.7)	(28.9)
Land Converted to Cropland	**1.5**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**
Changes in Agricultural Soil Carbon Stocks	1.5	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Grassland Remaining Grassland	**(4.5)**	**7.5**	**7.5**	**7.4**	**7.4**	**7.4**	**7.3**	**7.3**
Changes in Agricultural Soil Carbon Stocks	(4.5)	7.5	7.5	7.4	7.4	7.4	7.3	7.3
Land Converted to Grassland	**(17.6)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**
Changes in Agricultural Soil Carbon Stocks	(17.6)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Settlements Remaining Settlements	**(83.2)**	**(84.2)**	**(86.8)**	**(85.9)**	**(89.7)**	**(89.9)**	**(93.8)**	**(97.3)**
Urban Trees	(58.7)	(73.3)	(77.0)	(77.0)	(80.7)	(80.7)	(84.3)	(88.0)
Landfilled Yard Trimmings and Food Scraps	(24.5)	(10.9)	(9.8)	(8.9)	(9.0)	(9.3)	(9.4)	(9.3)
Total	**(910.4)**	**(744.0)**	**(765.7)**	**(759.5)**	**(768.0)**	**(768.6)**	**(774.8)**	**(780.1)**

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

Waste

The Waste chapter contains emissions from waste management activities (except waste incineration, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic CH_4 emissions, accounting for 25 percent of total U.S. CH_4 emissions.[11] Additionally, wastewater treatment accounts for 7 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, using a simplified methodology. Wastewater treatment systems are a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. N_2O emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Overall, in 2004, emission sources accounted for in the Waste chapter generated 2.7 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 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, and Agriculture, and U.S. Territories.

Table ES-6 summarizes emissions from each of these sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2004.

Figure ES-13: Emissions Allocated to Economic Sectors

Table ES-6: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq.)

Economic Sector	1990	1998	1999	2000	2001	2002	2003	2004
Electric Power Industry	1,846.4	2,202.4	2,213.3	2,315.9	2,284.4	2,280.1	2,308.5	2,337.8
Transportation	1,520.3	1,753.4	1,819.3	1,866.9	1,852.7	1,898.0	1,898.9	1,955.1
Industry	1,438.9	1,452.4	1,411.0	1,409.7	1,366.6	1,346.7	1,342.7	1,377.3
Agriculture	486.3	541.6	523.9	509.5	514.4	511.0	484.2	491.3
Commercial	433.6	428.0	430.6	443.0	439.5	447.5	466.5	459.9
Residential	349.4	353.3	372.6	390.4	381.6	380.1	399.8	391.1
U.S. Territories	33.8	42.7	44.2	46.9	54.0	52.4	58.6	61.9
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Land Use, Land-Use Change, and Forestry Sinks	-910.4	-744.0	-765.7	-759.5	-768.0	-768.6	-774.8	-780.1
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

Note: Totals may not sum due to independent rounding. Emissions include CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6.
See Table 2-14 for more detailed data.

Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2004. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2004.

[11] 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 of the Inventory report.

In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade, although there was an increase in industrial emissions in 2004 (up 3 percent from 2003 levels). 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 20 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 6 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. The commercial sector accounted for about 7 percent of emissions, while U.S. territories accounted for 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-7 presents greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electricity generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[12] 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 waste combustion, 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 2004. 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 2004.

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

Economic Sector	**1990**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Industry	2,074.6	2,210.3	2,174.4	2,186.1	2,073.6	2,042.0	2,066.0	2,103.0
Transportation	1,523.4	1,756.5	1,822.5	1,870.3	1,856.2	1,901.4	1,903.2	1,959.8
Commercial	979.2	1,102.0	1,115.8	1,171.8	1,190.8	1,191.4	1,204.3	1,211.0
Residential	950.8	1,060.0	1,083.2	1,140.0	1,136.2	1,154.1	1,182.9	1,181.9
Agriculture	547.2	602.4	575.0	567.2	582.6	574.5	544.3	556.9
U.S. Territories	33.8	42.7	44.2	46.9	54.0	52.4	58.6	61.9
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Land Use, Land-Use Change, and Forestry (Sinks)	-910.4	-744.0	-765.7	-759.5	-768.0	-768.6	-774.8	-780.1
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

See Table 2-16 for more detailed data.

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

Figure ES-14: Emissions with Electricity Distributed to Economic Sectors

[BEGIN BOX]

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 2004; 4) emissions per unit of total gross domestic product as a measure of national economic activity; or 5) emissions per capita.

Table ES-8 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the United States have grown at an average annual rate of 1.1 percent since 1990. This rate is 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 more slowly than national population since 1990 (see Figure ES-15). Overall, global atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

Table ES-8: Recent Trends in Various U.S. Data (Index 1990 = 100) and Global Atmospheric CO_2 Concentration

Variable	1991	1998	1999	2000	2001	2002	2003	2004	Growth Rate[f]
Greenhouse Gas Emissions[a]	99	111	112	114	113	113	114	116	1.1%
Energy Consumption[b]	100	112	114	117	114	116	116	118	1.2%
Fossil Fuel Consumption[b]	99	113	114	117	115	116	117	118	1.2%
Electricity Consumption[b]	102	121	123	127	125	128	129	131	2.0%
GDP[c]	100	127	133	138	139	141	145	151	3.0%
Population[d]	101	110	112	113	114	115	116	117	1.1%
Atmospheric CO_2 Concentration[e]	100	103	104	104	105	105	106	106	0.4%

[a] GWP weighted values
[b] Energy content weighted values (EIA 2004a)
[c] Gross Domestic Product in chained 2000 dollars (BEA 2005)
[d] U.S. Census Bureau (2005)
[e] Hofmann (2004)
[f] Average annual growth rate

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product
Source: BEA (2005), U.S. Census Bureau (2005), and emission estimates in this report.

[END BOX]

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

The reporting requirements of the UNFCCC[13] 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.

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2005),[14] which are regulated under the Clean Air Act. Table ES-9 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs.

Table ES-9: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1998	1999	2000	2001	2002	2003	2004
NO_x	**22,860**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**17,995**	**17,076**
Stationary Fossil Fuel Combustion	9,884	9,419	8,344	8,002	7,667	7,522	7,138	6,662
Mobile Fossil Fuel Combustion	12,134	11,592	11,300	11,395	10,823	10,389	9,916	9,465
Oil and Gas Activities	139	130	109	111	113	135	135	135
Waste Combustion	82	145	143	114	114	134	134	134
Industrial Processes	591	637	595	626	656	630	631	632
Solvent Use	1	3	3	3	3	6	6	6
Agricultural Burning	28	35	34	35	35	33	34	39
Waste	0	3	3	2	2	2	2	2
CO	**130,580**	**98,984**	**94,361**	**92,895**	**89,329**	**87,428**	**87,518**	**87,599**
Stationary Fossil Fuel Combustion	4,999	3,927	5,024	4,340	4,377	4,020	4,020	4,020
Mobile Fossil Fuel Combustion	119,482	87,940	83,484	83,680	79,972	78,574	78,574	78,574
Oil and Gas Activities	302	332	145	146	147	116	116	116
Waste Combustion	978	2,826	2,725	1,670	1,672	1,672	1,672	1,672
Industrial Processes	4,124	3,163	2,156	2,217	2,339	2,286	2,286	2,286
Solvent Use	4	1	46	46	45	46	46	46
Agricultural Burning	689	789	767	790	770	706	796	877
Waste	1	5	13	8	8	8	8	8
NMVOCs	**20,937**	**16,403**	**15,869**	**15,228**	**15,048**	**14,217**	**13,877**	**13,556**
Stationary Fossil Fuel Combustion	912	1,016	1,045	1,077	1,080	923	922	922
Mobile Fossil Fuel Combustion	10,933	7,742	7,586	7,230	6,872	6,560	6,212	5,882
Oil and Gas Activities	555	440	414	389	400	340	341	341
Waste Combustion	222	326	302	257	258	281	282	282
Industrial Processes	2,426	2,047	1,813	1,773	1,769	1,723	1,725	1,727
Solvent Use	5,217	4,671	4,569	4,384	4,547	4,256	4,262	4,267
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	673	161	140	119	122	133	134	134
SO_2	**20,936**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,208**	**13,910**
Stationary Fossil Fuel Combustion	18,407	15,191	13,915	12,848	12,461	11,946	12,220	11,916
Mobile Fossil Fuel Combustion	793	665	704	632	624	631	637	644

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

[14] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2004).

Oil and Gas Activities	390	310	283	286	289	315	315	315
Waste Combustion	39	30	30	29	30	24	24	24
Industrial Processes	1,306	991	984	1,031	1,047	1,009	1,009	1,009
Solvent Use	0	1	1	1	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	0	1	1	1	1	1	1	1

Source: (EPA 2005) except for estimates from field burning of agricultural residues.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

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."[15] 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 2004 emission estimates for the 2004 key categories as defined by a level analysis (i.e., the contribution of each source or sink category to the total inventory level). The UNFCCC reporting guidelines request that key category analyses be reported at an appropriate level of disaggregation, which may lead to source and sink category names which differ from those used elsewhere in the Inventory report. For more information regarding key categories, see section 1.5 and Annex 1 of the Inventory report.

Figure ES-16: 2004 Key Categories—Tier 1 Level Assessment

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency and credibility of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. To assist in these efforts, the United States implemented a systematic approach to QA/QC. While QA/QC has always been an integral part of the U.S. national system for inventory development, the procedures followed for the current inventory have been formalized in accordance with the 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

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

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.

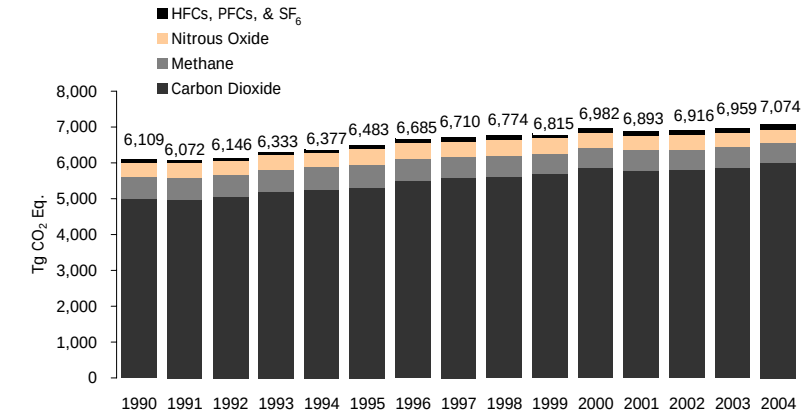


Figure ES-1: U.S. GHG Emissions by Gas

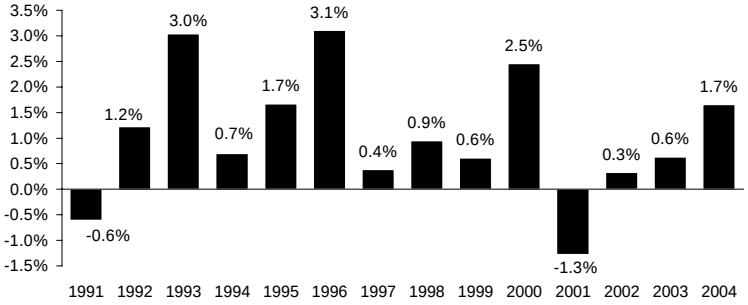


Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

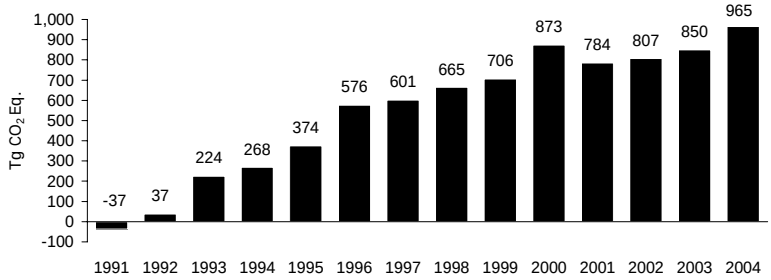


Figure ES-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

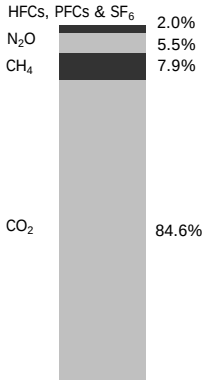


Figure ES-4: 2004 Greenhouse Gas Emissions by Gas

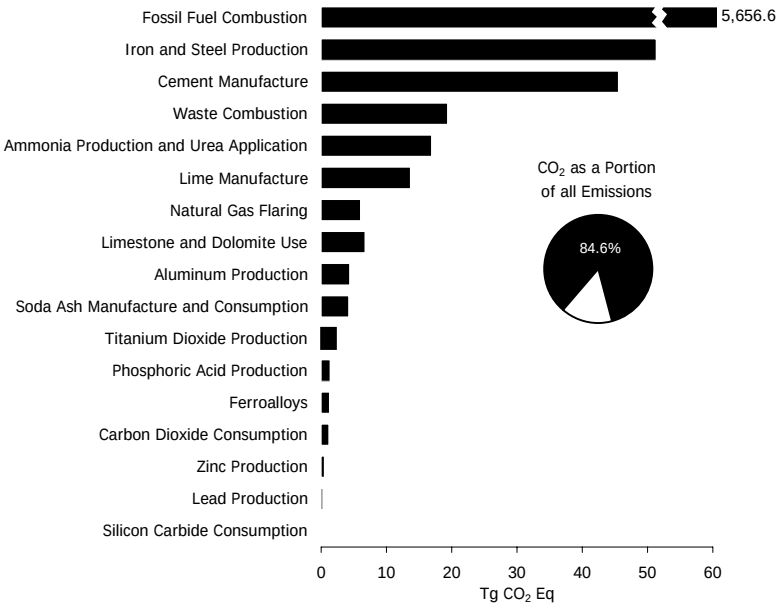


Figure ES-5: 2004 Sources of CO_2

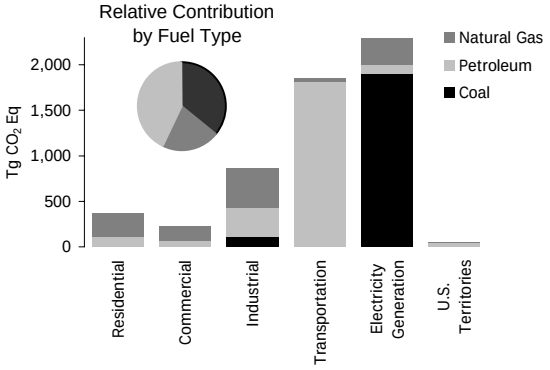


Figure ES-6: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricity generation.

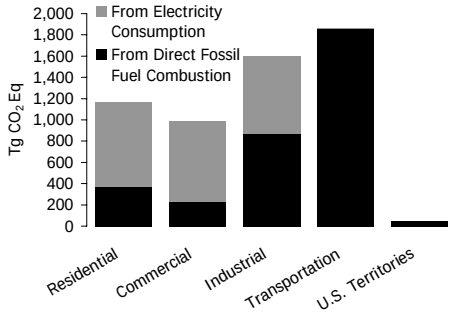


Figure ES-7: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

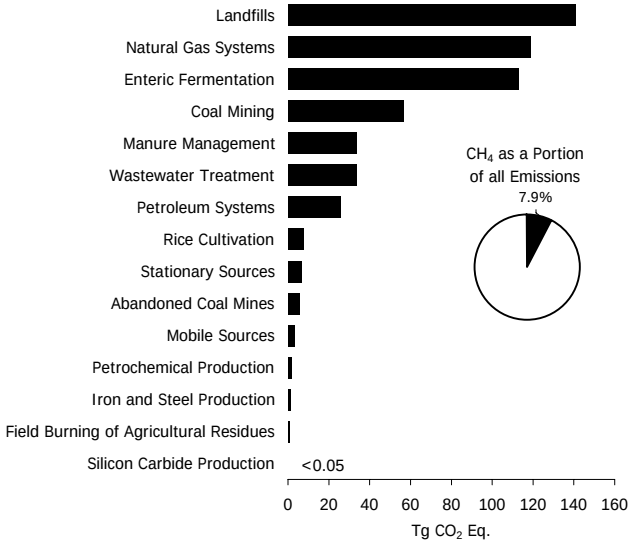


Figure ES-8: 2004 Sources of CH_4

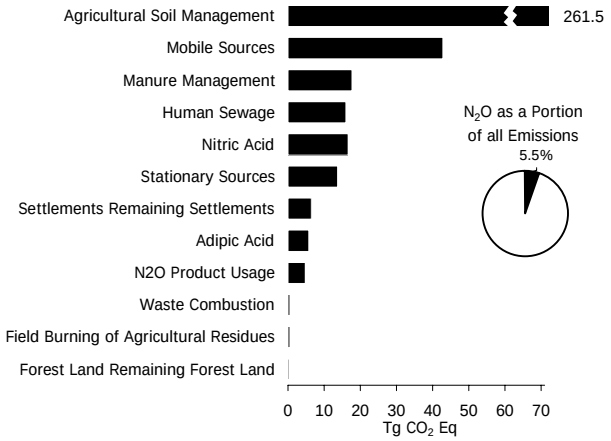


Figure ES-9: 2004 Sources of N_2O

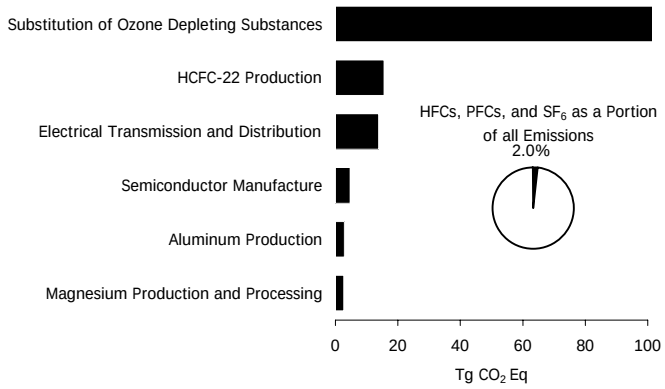
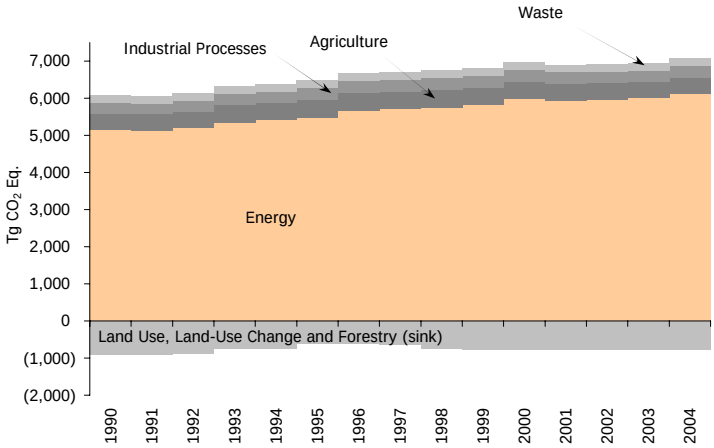


Figure ES-10: 2004 Sources of HFCs, PFCs, and SF_6



Note: Relatively smaller amounts of GWP-weighted emissions are also emitted from the Land-Use Change and Forestry sector and the Solvent and Other Product
Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

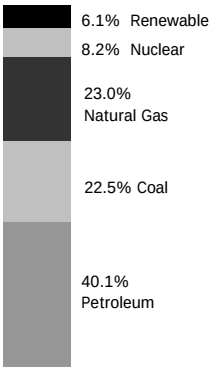


Figure ES-12: 2004 U.S. Energy Consumption by Energy Source

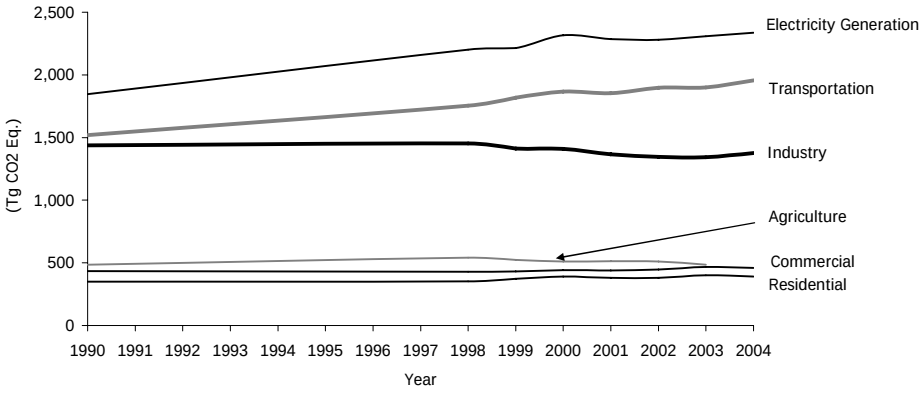


Figure ES-13: Emissions Allocated to Economic Sectors
Note: Does not include U.S. territories.

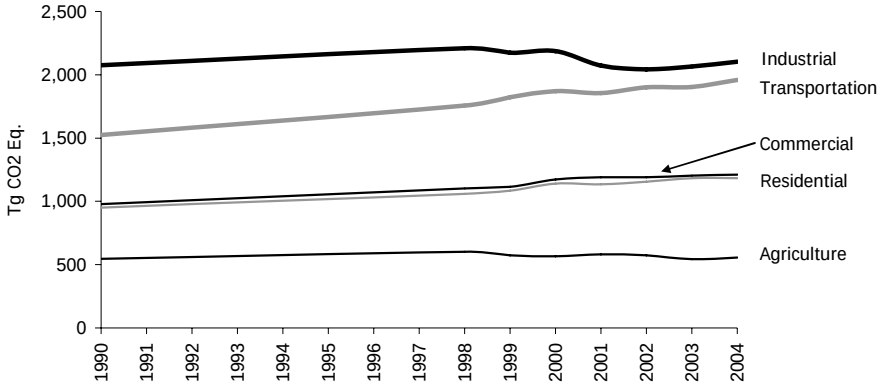


Figure ES-14: Emissions with Electricity Distributed to Economic Sectors
Note: Does not include U.S. territories.

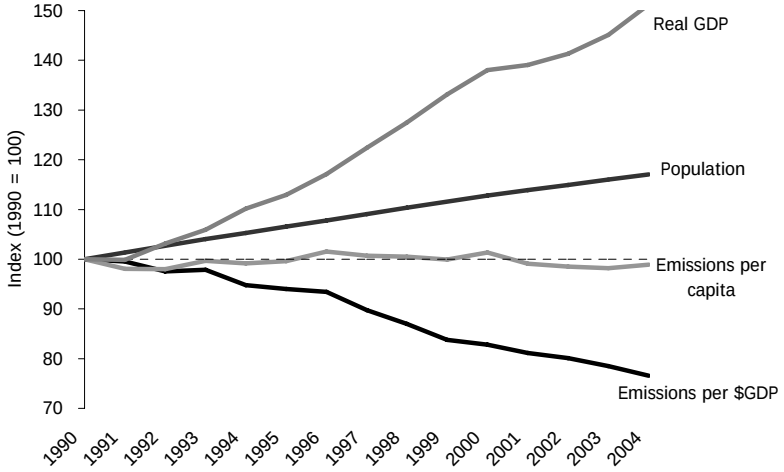


Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

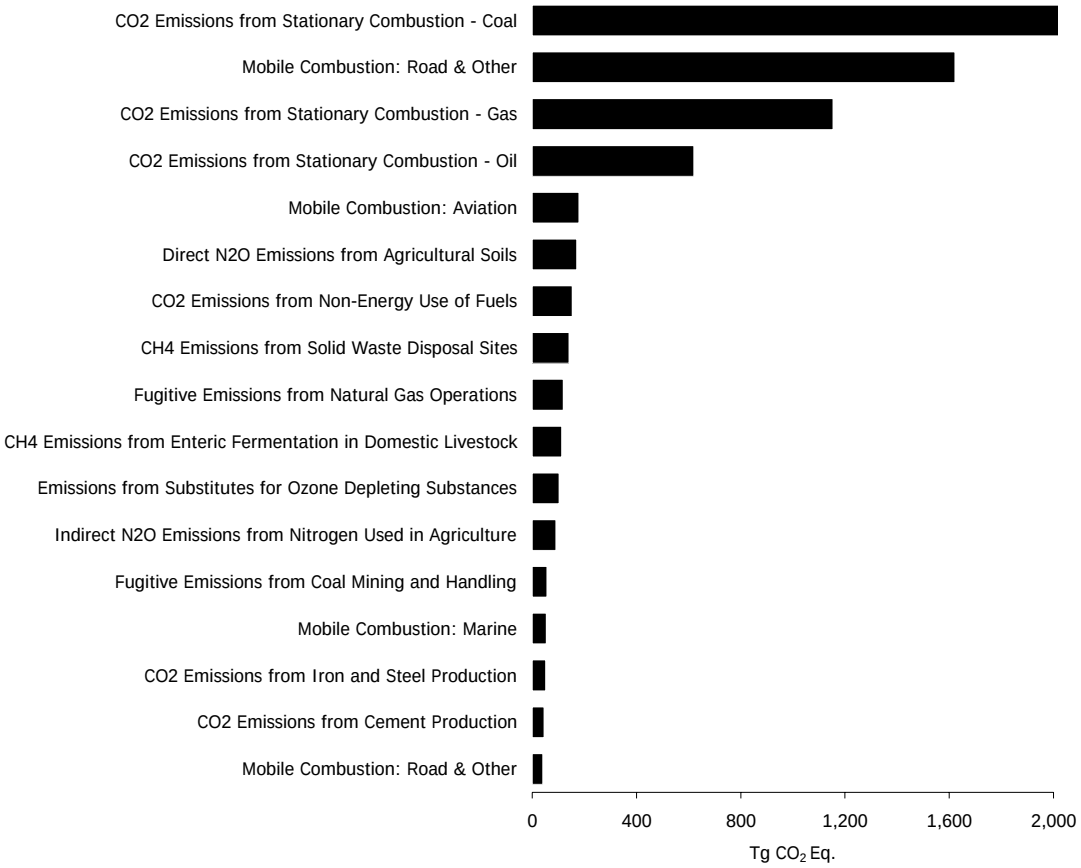


Figure ES-16: 2004 Key Categories - Tier 1 Level Assessment
Note: For a complete discussion of the key source analysis see Annex 1.

Descriptions of Figures: Executive Summary

Figure ES-1 illustrates U.S. greenhouse gas emissions by gas, with a cumulative total of CO_2 equivalent. There is generally an upward trend, starting from 6,109 Tg CO_2 eq. in 1990 and ending with 7,074 Tg CO_2 eq. in 2004. The only exception to this trend is 1991, where emissions were 6,072 Tg CO_2 eq, down from 6,109 Tg CO_2 eq in 1990. They increased again in 1992 to 6,146 Tg CO_2 eq.

Figure ES-2 depicts the annual percent change in U.S. greenhouse gas emissions since 1990. The change in 1991 was -0.6%. In 1992, it was 1.2%. In 1993, it was 3.0%. In 1994, it was 0.7%. In 1995, it was 1.7%. In 1996, it was 3.1%. In 1997, it was 0.4%. In 1998, it was 0.9%. In 1999, it was 0.6%. In 2000, it was 2.5%. In 2001, it was -1.3%. In 2002, it was 0.3%, in 2003, it was 0.6%, and in 2004, it was 1.7%.

Figure ES-3 depicts the absolute change in U.S. greenhouse gas emissions since 1990. The change in 1991 was -37 Tg CO_2 Eq. In 1992, it was 37 Tg CO_2 Eq. In 1993, it was 224 Tg CO_2 Eq. In 1994, it was 268 Tg CO_2 Eq . In 1995, it was 374 Tg CO_2 Eq . In 1996, it was 576 Tg CO_2 Eq. In 1997, it was 601 Tg CO_2 Eq. In 1998, it was 665 Tg CO_2 Eq. In 1999, it was 706 Tg CO_2 Eq. In 2000, it was 873 Tg CO_2 Eq. In 2001, it was 784 Tg CO_2 Eq. In 2002, it was 807 Tg CO_2 Eq. In 2003, it was 850 Tg CO_2 Eq. and in 2004, it was 965 Tg CO_2 Eq.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2004. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing 84.6 % of total greenhouse gas emissions. CH_4 represented 7.9 % of total greenhouse gas emissions, while N_2O represented 5.5 % and HFCs along with PFCs represented 2.0%.

Figure ES-5 illustrates sources of CO_2 emissions for 2004. Fossil fuel combustion is the greatest source with 5,656.6 Tg CO_2 Eq, The next greatest is iron and steel production which accounts for 51.3 Tg CO_2 Eq. The smallest source in Figure ES-5 is Silicon Carbide Consumption, which accounts for 0.1 Tg CO_2 Eq. There is also a pie chart indicating that CO_2 represents 84.6% of all greenhouse gas emissions.

Figure ES-6 illustrates 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type. There is also a pie chart indicating petroleum represents 43% of all fossil fuel combustion.

Figure ES-7 illustrates 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion. Transportation is the largest sector with 1855.5 teragrams of CO_2 emissions, all from direct fossil fuel combustion. Industrial is next with 731.5 teragrams of CO_2 from electricity consumption and 863.5 teragrams of CO_2 from direct fossil fuel combustion.

Figure ES-8 illustrates sources of CH_4 emissions for 2004. There is also a pie chart indicating that CH_4 represents 7.9% of all greenhouse gas emissions.

Figure ES-9 illustrates sources of N_2O emissions for 2004. There is also a pie chart indicating that N_2O represents 5.5% of all greenhouse gas emissions.

Figure ES-10 illustrates sources of HFCs, PFCs, and SF_6 emissions for 2004. There is also a pie chart indicating that HFCs, PFCs, and SF_6 represent 2.0 percent of all greenhouse gas emissions.

Figure ES-11 depicts 2004 CO_2 emissions from fossil fuel combustion by sector and fuel type using the data presented in Table 3-3. In addition, there is a pie chart that indicates that petroleum accounted for 43% of emissions from fossil fuel combustion.

Figure ES-12 illustrates the data presented in Table 3-6, CO_2 emissions from fossil fuel combustion by end use sector.

For a detailed description of Figure ES-13, refer to the description of Figure 2-13 in Chapter 2.

For a detailed description of Figure ES-14, refer to the description of Figure 2-14 in Chapter 2.

For a detailed description of Figure ES-15, refer to the description of Figure 2-4 in Chapter 2.

Figure ES-16 illustrates sources identified as key using the Tier 1 Level assessment for 2004.

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 2004. A summary of these estimates is provided in Table 2-3 and Table 2-4 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 June of 1992, the United States signed, and later ratified in October, 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 Management in National Greenhouse Gas Inventories*, which further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines.* The IPCC has also accepted the *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* at its Twenty-First Session (Vienna, November 3-7, 2003), as an elaboration of the *Revised 1996 Guidelines.*

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 Reporting and Review (UNFCCC 2003).

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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>.

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 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).

CO_2, 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.

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

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

Table 1-1: Global Atmospheric Concentration (ppm unless otherwise specified), Rate of Concentration Change (ppb/year), and Atmospheric Lifetime (years) of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6[a]	CF_4[a]
Pre-industrial atmospheric concentration	280	0.722	0.270	0	40
Atmospheric concentration[b]	376.7	1.756	0.319	5.4	80
Rate of concentration change[c]	1.6	0.005	0.0007	0.23	1.0
Atmospheric lifetime	50-200[d]	12[e]	114[e]	3,200	>50,000

Source: Current atmospheric concentrations and rate of concentration changes for all gases but CF_4 are from Hofmann (2004), data for CF_4 are from IPCC (2001). Pre-industrial atmospheric concentration and atmospheric lifetime taken from IPCC (2001).
[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.
[b] Concentration for CF_4 was measured in 2000. Concentrations for all other gases were measured in 2004.
[c] Rate is calculated over the period 1990 to 2004 for CO_2, CH_4, and N_2O; 1996 to 2004 for SF_6; and 1990 to 1999 for CF_4.
[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.

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. CO_2 concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 376.7 ppmv in 2004, a 35 percent increase (IPCC 2001 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.

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. CH_4 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. CH_4 is also emitted during the

[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).

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 1,756 ppb in 2004, 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 2001).

CH_4 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 combustion; 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 2004, a concentration that has not been exceeded during the last thousand years. N_2O is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2001).

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.

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 [HBFCs]) result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and

[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.

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

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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.

droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect 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 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 produces 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.

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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 sulfur dioxide 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 12/44^{ths} of carbon dioxide by weight.

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 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.

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

Source: (IPCC 1996)

[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.

[Begin Box]

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

In 2001, the IPCC published its Third Assessment Report (TAR), 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 IPCC's Second Assessment Report (SAR), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved

[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)

CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where significantly different new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. In addition, the values for radiative forcing and lifetimes have been calculated 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	Change	
CO_2	1	1	NC	NC
CH_4*	21	23	2	10%
N_2O	310	296	(14)	(5%)
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	(100)	(15%)
HFC-125	2,800	3,400	600	21%
HFC-134a	1,300	1,300	NC	NC
HFC-143a	3,800	4,300	500	13%
HFC-152a	140	120	(20)	(14%)
HFC-227ea	2,900	3,500	600	21%
HFC-236fa	6,300	9,400	3,100	49%
HFC-4310mee	1,300	1,500	200	15%
CF_4	6,500	5,700	(800)	(12%)
C_2F_6	9,200	11,900	2,700	29%
C_4F_{10}	7,000	8,600	1,600	23%
C_6F_{14}	7,400	9,000	1,600	22%
SF_6	23,900	22,200	(1,700)	(7%)

Source: (IPCC 2001)
NC (No Change)
Note: Parentheses indicate negative values.
* 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.

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 2004 are consistent and comparable with estimates developed prior to the publication of the TAR. For informational purposes, emission estimates that use the updated GWPs are presented below and in even more detail in Annex 6.1 of this report. All estimates provided throughout this report are also presented in unweighted units.

[END BOX]

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.

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

Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format 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 source category and the unique characteristics of its emissions profile. The individual source leads determine the most appropriate methodology and collect the best activity data to use in the emission calculations, based upon their expertise in the source category, as well as coordinating with researchers and contractors familiar with the sources. A multi-stage process for collecting information from the individual source leads and producing the Inventory is undertaken annually to compile all information and data.

Methodology Development, Data Collection, and Emissions and Sink Estimation

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

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

Summary Spreadsheet Compilation and Data Storage

The inventory coordinator at EPA collects the source categories' descriptive text and Annexes, and also aggregates

the emission estimates into a summary spreadsheet that links the individual source category spreadsheets together. This summary sheet contains all of the essential data in one central location, in formats commonly used in the Inventory document. In addition to the data from each source category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Recent Trends sections of the Inventory report. Electronic copies of each year's summary spreadsheet, which contains all the emission and sink estimates for the United States, are kept on a central server at EPA under the jurisdiction of the Inventory coordinator.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the 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 complete CRF tables 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 tables, 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 coordinator, who has 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). The QA/QC coordinator works closely with the source leads to ensure 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.

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 Tables. 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) and *IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003). 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.

[BEGIN BOX]

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.

[END BOX]

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]

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

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 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.

In addition to conducting Tier 1 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.

Table 1-4 presents the key categories for the United States based on the Tier 1 approach (including and excluding LULUCF categories) using emissions data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2004. The table also indicates the criteria used in identifying these categories (i.e., level, trend, and/or qualitative assessments). Annex 1 of this report provides additional information regarding the key categories in the United States and the methodologies used to identify them.

Table 1-4: Key Categories for the United States (1990-2004) Based on Tier 1 Approach

IPCC Source Category	Gas	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Qual[a]	2004 Emissions (Tg CO_2 Eq.)
Energy							
CO_2 Emissions from Stationary Combustion—Coal	CO_2	✓	✓	✓	✓		2,027.0
Mobile Combustion: Road & Other	CO_2	✓	✓	✓	✓		1,621.5
CO_2 Emissions from Stationary Combustion—Gas	CO_2	✓	✓	✓	✓		1,153.8
CO_2 Emissions from Stationary Combustion—Oil	CO_2	✓	✓	✓	✓		619.9
Mobile Combustion: Aviation	CO_2	✓	✓	✓	✓		179.6
Fugitive Emissions from Natural Gas Operations	CH_4	✓	✓	✓	✓		153.4
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	✓	✓	✓	✓		118.8
International Bunker Fuels[b]	Several					✓	95.5
Fugitive Emissions from Coal Mining and Handling	CH_4	✓	✓	✓	✓		56.3
Mobile Combustion: Marine	CO_2	✓		✓			54.4
Mobile Combustion: Road & Other	N_2O	✓	✓	✓			40.6
Fugitive Emissions from Oil	CH_4	✓	✓	✓	✓		25.7

Operations						
Industrial Processes						
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓	✓	✓	103.3
CO_2 Emissions from Iron and Steel Production	CO_2	✓	✓	✓	✓	51.3
CO_2 Emissions from Cement Production	CO_2	✓	✓	✓	✓	45.6
CO_2 Emissions from Ammonia Production and Urea Application	CO_2		✓			16.9
SF_6 Emissions from Electrical Equipment	SF_6		✓		✓	15.6
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	✓	✓	✓	✓	13.8
N_2O Emissions from Adipic Acid Production	N_2O		✓		✓	5.7
PFC Emissions from Aluminum Production	PFCs		✓		✓	2.8
Agriculture						
Direct N_2O Emissions from Agricultural Soils	N_2O	✓		✓		170.9
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	✓	✓	✓	✓	112.6
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	✓	✓	✓	✓	90.6
CH_4 Emissions from Manure Management	CH_4			✓		39.4
Waste						
CH_4 Emissions from Solid Waste Disposal Sites	CH_4	✓	✓	✓	✓	140.9
CH_4 Emissions from Wastewater Handling	CH_4		✓		✓	36.9
CO_2 Emissions from Waste Incineration	CO_2		✓		✓	19.4
Land Use, Land Use Change, and Forestry						
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			✓	✓	(637.2)
CO_2 Emissions from Settlement Remaining Settlements	CO_2			✓		(97.3)
CO_2 Emissions from Cropland Remaining Cropland	CO_2			✓	✓	(28.8)
Subtotal Without LULUCF						**6,918.2**
Total Emissions Without LULUCF[c]						**7,067.6**
Percent of Total Without LULUCF						**97.9%**
Subtotal With LULUCF						**6,154.8**
Total Emissions With LULUCF						**6,294.3**
Percent of Total With LULUCF						**97.8%**

[a]Qualitative criteria.

[b]Emissions from this source not included in totals.
[c]Does not include LULUCF sources (i.e., N_2O emissions) or sinks.
Note: The Tier 1 approach for identifying key source categories does not directly include assessment of uncertainty in emission estimates.

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:

- The plan includes specific detailed procedures (or protocols) and templates (or 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.
- The plan includes 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.
- The QC process includes both Tier 1 (general) and Tier 2 (source-specific) quality controls and checks, as recommended by IPCC *Good Practice Guidance*.
- Investigations of secondary data quality and source-specific quality checks (Tier 2 QC) are considered 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.
- The plan contains 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.
- The plan is designed so that QA/QC procedures are implemented throughout the whole inventory development process—from initial data collection, through preparation of the emission estimates, to publication of the Inventory.
- The plan includes a schedule for multi-year implementation.
- The plan promotes and involves 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 the current Inventory, source-specific plans have been developed and implemented for the majority of sources within the Energy and Industrial Process sectors. Throughout 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 checking and 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.

QA/QC procedures guide 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 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. A preliminary estimate of the overall quantitative uncertainty is shown below, 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 and add a quantitative estimates of uncertainty for the one remaining source for which a quantitative estimate does not exist—CO_2 from Natural Gas Flaring.

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

	2004 Emission	Uncertainty Range Relative to Emission		Mean[b]	Standard

Gas	Estimate ($Tg CO_2$ Eq.)	Estimate[a] ($Tg CO_2$ Eq.)		Estimate[a] (%)		Deviation ($Tg CO_2$ Eq.)	
		Lower Bound[c]	Upper Bound[c]	Lower Bound[c]	Upper Bound[c]		
CO_2	5,988.0	5,920.5	6,329.8	-1.1%	5.7%	6,120.6	105.3
CH_4	556.7	495.3	620.2	-11.0%	11.4%	556.5	31.8
N_2O	386.7	235.1	571.5	-39.2%	47.7%	403.1	88.3
PFC, HFC & SF_6[d]	143.2	130.1	164.8	-9.2%	15.1%	147.2	8.9
Total	**7,074.7**	**6,966.8**	**7,518.9**	**-1.5%**	**6.3%**	**7,245.2**	**142.2**

Notes:
[a] Range of emission estimates for 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 add up 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 2004.

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.

1.8. Completeness

This report, along with its accompanying CRF tables, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2004. 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.

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	By-product 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 usage.
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 from forest management, other land-use activities, and land-use change.
Waste	Emissions from waste management activities.

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

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.

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 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CO_2 and N_2O Emissions from Municipal Solid Waste Combustion
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
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. Uncertainty Estimation as a Process
7.4. Planned Improvements

2. Trends in Greenhouse Gas Emissions

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

In 2004, total U.S. greenhouse gas emissions were 7,074.4 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.)[1]. Overall, total U.S. emissions have risen by 15.8 percent from 1990 to 2004, while the U.S. gross domestic product has increased by 51 percent over the same period (BEA 2005). Emissions rose from 2003 to 2004, increasing by 1.7 percent (115.3 Tg CO_2 Eq.). The following factors were primary contributors to this increase: 1) robust economic growth in 2004, leading to increased demand for electricity and fossil fuels, 2) expanding industrial production in energy-intensive industries, also increasing demand for electricity and fossil fuels, and 3) increased travel, requiring higher rates of consumption of petroleum fuels.[2] Figure 2-1 through Figure 2-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

Figure 2-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

As the largest source of U.S. greenhouse gas emissions, carbon dioxide (CO_2) from fossil fuel combustion has accounted for approximately 80 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 2003 and 2004. Emissions from this source category grew by 20.4 percent (960.0 Tg CO_2 Eq.) from 1990 to 2004 and were responsible for most of the increase in national emissions during this period. From 2003 to 2004, these emissions increased by 85.5 Tg CO_2 Eq. (1.5 percent), slightly greater than the source's average annual growth rate of 1.3 percent from 1990 through 2004. 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 precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

In the 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).

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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, Chapter 1.)

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

Energy-related CO_2 emissions also depend on the type of fuel or energy consumed and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 because of the lower carbon content of natural gas. Table 2-1 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 2-1: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2000 to 2001		2001 to 2002		2002 to 2003		2003 to 2004	
Electricity Generation	Coal	-50.7	-3%	3.8	0%	37.5	2%	9.9	1%
Electricity Generation	Natural Gas	8.2	3%	16.1	6%	-28.0	-9%	18.2	7%
Electricity Generation	Petroleum	10.5	12%	-23.7	-23%	19.2	25%	0.3	0%
Transportation[a]	Petroleum	-11.7	-1%	42.0	2%	2.0	0%	54.3	3%
Residential	Natural Gas	-10.2	-4%	6.6	3%	11.4	4%	-11.4	-4%
Commercial	Natural Gas	-6.9	-4%	5.9	4%	4.6	3%	-12.7	-7%
Industrial	Coal	-1.1	-1%	-9.7	-8%	1.4	1%	-0.7	-1%
Industrial	Natural Gas	-36.8	-8%	6.3	1%	-15.0	-3%	12.3	3%
All Sectors[b]	**All Fuels[b]**	**-46.8**	**-1%**	**14.9**	**0%**	**69.3**	**1%**	**85.5**	**2%**

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

In 2001, economic growth in the United States slowed considerably for the second time since 1990, contributing to a decrease in CO_2 emissions from fossil fuel combustion, also for the second time since 1990. A significant reduction in industrial output contributed to weak economic growth, primarily in manufacturing, and led to lower emissions from the industrial sector. Several other factors also played a role in this decrease in emissions. Warmer winter conditions compared to 2000, along with higher natural gas prices, reduced demand for heating fuels. Additionally, nuclear facilities operated at a very high capacity, offsetting electricity produced from fossil fuels. Since there are no greenhouse gas emissions associated with electricity production from nuclear plants, this substitution reduces the overall carbon intensity of electricity generation.

Emissions from fuel combustion resumed a modest growth in 2002, slightly less than the average annual growth rate since 1990. There were a number of reasons behind this increase. The U.S. economy experienced moderate growth, recovering from weak conditions in 2001. Prices for fuels remained at or below 2001 levels; the cost of natural gas, motor gasoline, and electricity were all lower–triggering an increase in demand for fuel. In addition, the United States experienced one of the hottest summers on record, causing a significant increase in electricity use in the residential sector as the use of air-conditioners increased. Partially offsetting this increased consumption of fossil fuels, however, were increases in the use of nuclear and renewable fuels. Nuclear facilities operated at the highest capacity on record in 2002. Furthermore, there was a considerable increase in the use of hydroelectric power in 2002 after a very low output the previous year.

Emissions from fuel combustion continued growing in 2003, at about the average annual growth rate since 1990. 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. Use of nuclear and renewable fuels remained relatively stable. Nuclear capacity decreased slightly, and 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 increased at a rate slightly higher than the average growth rate since 1990. A number of factors played a major role in the magnitude of this increase. 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 consumption 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.

Other significant trends in emissions from additional source categories over the fourteen-year period from 1990 through 2004 included the following:

- CO_2 emissions from waste combustion increased by 8.4 Tg CO_2 Eq. (77 percent), as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- Net CO_2 sequestration from land use change and forestry decreased by 130.3 Tg CO_2 Eq. (14 percent), primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. This decline largely resulted from a decrease in the estimated rate of forest soil sequestration caused by a slowing rate of increase in forest area after 1997.
- Methane (CH_4) emissions from coal mining declined by 25.6 Tg CO_2 Eq. (31 percent) from 1990 to 2004, as a result of the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- From 1990 to 2004, nitrous oxide (N_2O) emissions from mobile combustion decreased by 1 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced CH_4 emissions while increasing N_2O emissions. Since 1998, new control technologies have led to a steady decline in N_2O from this source.
- Emissions resulting from the substitution of ozone depleting substances (ODS, e.g., chlorofluorocarbons [CFCs]) have increased dramatically from small amounts in 1990 to 102.9 Tg CO_2 Eq. in 2004. These emissions have been increasing as phase-outs of ODS required under the Montreal Protocol come into effect.
- The increase in ODS emissions is offset substantially by decreases in emission of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from other sources. Emissions from aluminum production decreased by 85 percent (15.6 Tg CO_2 Eq.) from 1990 to 2004, due to both industry emission reduction efforts and lower domestic aluminum production. Emissions from the production of HCFC-22 decreased by 55 percent (19.4 Tg CO_2 Eq.) from 1990 to 2004, 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. Emissions from electric power transmission and distribution systems decreased by 52 percent (14.8 Tg CO_2 Eq.) from 1990 to 2004, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

Overall, from 1990 to 2004, total emissions of CO_2 increased by 982.7 Tg CO_2 Eq. (20 percent), while CH_4 and N_2O emissions decreased by 61.3 Tg CO_2 Eq. (10 percent) and 8.2 Tg CO_2 Eq. (2 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 52.2 Tg CO_2 Eq. (58 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, which was estimated to be 11 percent of total emissions in 2004.

[BEGIN BOX]

Box 2-1: 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 2004; 4) emissions per unit of total gross domestic product as a measure of national economic activity; or 5) emissions per capita.

Table 2-2 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 1.1 percent since 1990. This rate is 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 more slowly than national population since 1990 (see Figure 2-4). Overall, global atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

Table 2-2: Recent Trends in Various U.S. Data (Index 1990 = 100) and Global Atmospheric CO_2 Concentration

Variable	1991	1998	1999	2000	2001	2002	2003	2004	Growth Rate[f]
Greenhouse Gas Emissions[a]	99	111	111	114	112	113	114	116	1.1%
Energy Consumption[b]	100	112	114	117	114	116	116	118	1.2%
Fossil Fuel Consumption[b]	99	113	114	117	115	116	117	118	1.2%
Electricity Consumption[b]	102	121	123	127	125	128	129	131	2.0%
GDP[c]	100	127	133	138	139	141	145	151	3.0%
Population[d]	101	110	112	113	114	115	116	117	1.1%
Atmospheric CO_2 Concentration[e]	100	103	104	104	105	105	106	106	0.4%

[a] GWP weighted values
[b] Energy content weighted values (EIA 2004a)
[c] Gross Domestic Product in chained 2000 dollars (BEA 2005)
[d] (U.S. Census Bureau 2005)
[e] Hofmann (2004)
[f] Average annual growth rate

Figure 2-4: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product
Source: BEA (2005), U.S. Census Bureau (2005), and emission estimates in this report.

[END BOX]

As an alternative, emissions of all gases can be totaled for each of the Intergovernmental Panel on Climate Change (IPCC) sectors. Over the fourteen year period of 1990 to 2004, total emissions in the Energy, Industrial Processes, Agriculture, and Solvent and Other Product Use sectors climbed by 959.9 Tg CO_2 Eq. (19 percent), 19.5 Tg CO_2 Eq. (6 percent), 0.6 Tg CO_2 Eq. (less than 1 percent), and 0.5 Tg CO_2 Eq. (11 percent), respectively, while emissions from the Waste sector decreased 16.2 Tg CO_2 Eq. (8 percent). Over the same period, estimates of net carbon sequestration in the Land Use, Land-Use Change, and Forestry sector declined by 130.3 Tg CO_2 Eq. (14 percent).

Table 2-3 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 Figure 2-4. Alternatively, emissions and sinks are aggregated by sector/chapter in Table 2-5 and Figure 2-5.

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

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**5,005.3**	**5,620.2**	**5,695.0**	**5,864.5**	**5,795.2**	**5,815.9**	**5,877.7**	**5,988.0**
Fossil Fuel Combustion	4,696.6	5,271.8	5,342.4	5,533.7	5,486.9	5,501.8	5,571.1	5,656.6
Non-Energy Use of Fuels	117.2	152.8	160.6	140.7	131.0	136.5	133.5	153.4
Iron and Steel Production	85.0	67.7	63.8	65.3	57.8	54.6	53.3	51.3
Cement Manufacture	33.3	39.2	40.0	41.2	41.4	42.9	43.1	45.6

Waste Combustion	10.9	17.1	17.6	17.9	18.6	18.9	19.4	19.4
Ammonia Production and Urea Application	19.3	21.9	20.6	19.6	16.7	18.5	15.3	16.9
Lime Manufacture	11.2	13.9	13.5	13.3	12.8	12.3	13.0	13.7
Limestone and Dolomite Use	5.5	7.4	8.1	6.0	5.7	5.9	4.7	6.7
Natural Gas Flaring	5.8	6.6	6.9	5.8	6.1	6.2	6.1	6.0
Aluminum Production	7.0	6.4	6.5	6.2	4.5	4.6	4.6	4.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.2	4.1	4.1	4.1	4.2
Petrochemical Production	2.2	3.0	3.1	3.0	2.8	2.9	2.8	2.9
Titanium Dioxide Production	1.3	1.8	1.9	1.9	1.9	2.0	2.0	2.3
Phosphoric Acid Production	1.5	1.6	1.5	1.4	1.3	1.3	1.4	1.4
Ferroalloys	2.0	2.0	2.0	1.7	1.3	1.2	1.2	1.3
CO_2 Consumption	0.9	0.9	0.8	1.0	0.8	1.0	1.3	1.2
Zinc Production	0.9	1.1	1.1	1.1	1.0	0.9	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Consumption	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Net CO_2 flux from Land Use, Land-Use Change, and Forestry[a]	*(910.4)*	(744.0)	(765.7)	(759.5)	(768.0)	(768.6)	(774.8)	(780.1)
International Bunker Fuels[b]	*113.5*	*114.6*	*105.2*	*101.4*	*97.8*	*89.5*	*84.1*	*94.5*
Biomass Combustion[b]	*216.7*	*217.2*	*222.3*	*226.8*	*200.5*	*194.4*	*202.1*	*211.2*
CH_4	**618.1**	**579.5**	**569.0**	**566.9**	**560.3**	**559.8**	**564.4**	**556.7**
Landfills	172.3	144.4	141.6	139.0	136.2	139.8	142.4	140.9
Natural Gas Systems	126.7	125.4	121.7	126.7	125.6	125.4	124.7	118.8
Enteric Fermentation	117.9	116.7	116.8	115.6	114.6	114.7	115.1	112.6
Coal Mining	81.9	62.8	58.9	56.3	55.5	52.5	54.8	56.3
Manure Management	31.2	38.8	38.1	38.0	38.9	39.3	39.2	39.4
Wastewater Treatment	24.8	32.6	33.6	34.3	34.7	35.8	36.6	36.9
Petroleum Systems	34.4	29.7	28.5	27.8	27.4	26.8	25.9	25.7
Rice Cultivation	7.1	7.9	8.3	7.5	7.6	6.8	6.9	7.6
Stationary Sources	7.9	6.8	7.0	7.3	6.6	6.2	6.5	6.4
Abandoned Coal Mines	6.0	6.9	6.9	7.2	6.6	6.0	5.8	5.6
Mobile Sources	4.7	3.8	3.6	3.5	3.3	3.2	3.0	2.9
Petrochemical Production	1.2	1.7	1.7	1.7	1.4	1.5	1.5	1.6
Iron and Steel Production	1.3	1.2	1.2	1.2	1.1	1.0	1.0	1.0
Agricultural Residue Burning	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.9
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**394.9**	**440.6**	**419.4**	**416.2**	**412.8**	**407.4**	**386.1**	**386.7**
Agricultural Soil Management	266.1	301.1	281.2	278.2	282.9	277.8	259.2	261.5
Mobile Sources	43.5	54.8	54.1	53.1	50.0	47.5	44.8	42.8
Manure Management	16.3	17.4	17.4	17.8	18.1	18.0	17.5	17.7
Nitric Acid	17.8	20.9	20.1	19.6	15.9	17.2	16.7	16.6
Human Sewage	12.9	14.9	15.4	15.5	15.6	15.6	15.8	16.0
Stationary Sources	12.3	13.4	13.4	13.9	13.5	13.2	13.6	13.7
Settlements Remaining Settlements	5.6	6.2	6.2	6.0	5.8	6.0	6.2	6.4
Adipic Acid	15.2	6.0	5.5	6.0	4.9	5.9	6.2	5.7
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Waste Combustion	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5
Agricultural Residue Burning	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Forest Land Remaining Forest Land	0.1	0.4	0.5	0.4	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*

HFCs, PFCs, and SF_6	**90.8**	**133.4**	**131.5**	**134.7**	**124.9**	**132.7**	**131.0**	**143.0**
Substitution of Ozone Depleting Substances	0.4	54.5	62.8	71.2	78.6	86.2	93.5	103.3
HCFC-22 Production	35.0	40.1	30.4	29.8	19.8	19.8	12.3	15.6
Electrical Transmission and Distribution	28.6	16.7	16.1	15.3	15.3	14.5	14.0	13.8
Semiconductor Manufacture	2.9	7.1	7.2	6.3	4.5	4.4	4.3	4.7
Aluminum Production	18.4	9.1	9.0	9.0	4.0	5.3	3.8	2.8
Magnesium Production and Processing	5.4	5.8	6.0	3.2	2.6	2.6	3.0	2.7
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

+ 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 Biomass Combustion are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 2-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**5,005,255**	**5,620,176**	**5,695,039**	**5,864,465**	**5,795,192**	**5,815,889**	**5,877,677**	**5,987,984**
Fossil Fuel Combustion	4,696,571	5,271,819	5,342,446	5,533,710	5,486,908	5,501,763	5,571,088	5,656,554
Non-Energy Use of Fuels	117,168	152,800	160,569	140,687	131,028	136,455	133,489	153,386
Iron and Steel Production	85,023	67,689	63,821	65,316	57,822	54,550	53,335	51,334
Cement Manufacture	33,278	39,218	39,991	41,190	41,357	42,898	43,082	45,559
Waste Combustion	10,919	17,094	17,632	17,921	18,634	18,862	19,360	19,360
Ammonia Production and Urea Application	19,306	21,934	20,615	19,616	16,719	18,510	15,278	16,894
Lime Manufacture	11,242	13,919	13,473	13,322	12,828	12,309	12,987	13,698
Limestone and Dolomite Use	5,533	7,449	8,057	5,960	5,733	5,885	4,720	6,702
Natural Gas Flaring	5,805	6,566	6,943	5,769	6,094	6,204	6,091	6,034
Aluminum Production	7,045	6,359	6,458	6,244	4,505	4,596	4,608	4,346
Soda Ash Manufacture and Consumption	4,141	4,325	4,217	4,181	4,147	4,139	4,111	4,205
Petrochemical Production	2,221	3,015	3,054	3,004	2,787	2,857	2,777	2,895
Titanium Dioxide Production	1,308	1,819	1,853	1,918	1,857	1,997	2,013	2,259
Phosphoric Acid Production	1,529	1,593	1,539	1,382	1,264	1,338	1,382	1,395
Ferroalloys	1,980	2,027	1,996	1,719	1,329	1,237	1,159	1,287
CO_2 Consumption	860	912	849	957	818	968	1,293	1,183
Zinc Production	939	1,140	1,080	1,129	976	927	502	502
Lead Production	285	308	310	311	293	290	289	259
Silicon Carbide Consumption	100	190	137	130	94	105	111	133
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry[a]	(910,373)	(744,042)	(765,692)	(759,507)	(767,987)	(768,639)	(774,848)	(780,094)
International Bunker Fuels[b]	*113,503*	*114,557*	*105,228*	*101,366*	*97,815*	*89,489*	*84,083*	*94,499*
Biomass Combustion[b]	*216,702*	*217,201*	*222,340*	*226,765*	*200,479*	*194,351*	*202,111*	*211,230*
CH_4	**29,432**	**27,594**	**27,094**	**26,997**	**26,679**	**26,657**	**26,875**	**26,511**
Landfills	8,206	6,874	6,743	6,619	6,484	6,659	6,782	6,709
Natural Gas Systems	6,034	5,973	5,797	6,033	5,981	5,971	5,939	5,658
Enteric Fermentation	5,612	5,559	5,563	5,507	5,459	5,463	5,481	5,362

Coal Mining	3,900	2,990	2,807	2,679	2,644	2,500	2,611	2,682
Manure Management	1,484	1,848	1,816	1,811	1,850	1,871	1,865	1,875
Wastewater Treatment	1,180	1,550	1,602	1,635	1,651	1,705	1,742	1,758
Petroleum Systems	1,640	1,414	1,358	1,325	1,303	1,274	1,236	1,222
Rice Cultivation	339	376	395	357	364	325	328	360
Stationary Sources	374	325	335	346	316	295	311	307
Abandoned Coal Mines	286	328	330	343	313	288	277	269
Mobile Sources	224	181	173	167	159	152	144	140
Petrochemical Production	56	80	81	80	68	72	72	77
Iron and Steel Production	63	57	56	57	51	48	49	50
Field Burning of Agricultural Residues	33	38	37	38	37	34	38	42
Silicon Carbide Production	1	1	1	1	+	+	+	+
International Bunker Fuels[b]	*8*	*7*	*6*	*6*	*5*	*4*	*4*	*5*
N_2O	**1,274**	**1,421**	**1,353**	**1,343**	**1,332**	**1,314**	**1,245**	**1,247**
Agricultural Soil Management	858	971	907	897	913	896	836	844
Mobile Sources	140	177	174	171	161	153	144	138
Manure Management	52	56	56	58	58	58	57	57
Nitric Acid	58	67	65	63	51	56	54	54
Human Sewage	42	48	50	50	50	50	51	52
Stationary Sources	40	43	43	45	44	43	44	44
Settlements Remaining Settlements	18	20	20	19	19	19	20	21
Adipic Acid	49	19	18	19	16	19	20	19
N_2O Product Usage	14	15	15	15	15	15	15	15
Waste Combustion	2	1	1	1	1	2	2	2
Field Burning of Agricultural Residues	1	1	1	1	1	1	1	2
Forest Land Remaining Forest Land	+	1	2	1	1	1	1	1
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*	*2*	*3*
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production	3	3	3	3	2	2	1	1
Electrical Transmission and Distribution	1	1	1	1	1	1	1	1
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
Magnesium Production and Processing[d]	+	+	+	+	+	+	+	+
SO_2	**20,936**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,208**	**13,910**
NO_x	**22,860**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**17,995**	**17,076**
CO	**130,580**	**98,984**	**94,361**	**92,895**	**89,329**	**87,428**	**87,518**	**87,599**
NMVOCs	**20,937**	**16,403**	**15,869**	**15,228**	**15,048**	**14,217**	**13,877**	**13,556**

+ Does not exceed 0.5 Gg.
M Mixture of multiple gases
[a] Sinks are not included in CO_2 emissions total, and are based partially on projected activity data.
[b] Emissions from International Bunker Fuels and Biomass Combustion are not included in totals.
[c] HFC-23 emitted
[d] SF_6 emitted
Note: Totals may not sum due to independent rounding.
Note: Parentheses indicate negative values or sequestration.

Figure 2-5: U.S. Greenhouse Gas Emissions by Chapter/IPCC Sector

Table 2-5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

Chapter/IPCC Sector	1990	1998	1999	2000	2001	2002	2003	2004
Energy	5,148.3	5,752.3	5,822.3	5,994.3	5,931.6	5,944.6	6,009.8	6,108.2
Industrial Processes	301.1	335.1	327.5	329.6	300.7	310.9	304.1	320.7
Solvent and Other Product Use	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Agriculture	439.6	483.2	463.1	458.4	463.4	457.8	439.1	440.1
Land Use, Land-Use Change, and Forestry (Emissions)	5.7	6.5	6.7	6.4	6.2	6.4	6.6	6.8
Waste	210.0	191.8	190.7	188.8	186.4	191.3	194.8	193.8
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry*	(910.4)	(744.0)	(765.7)	(759.5)	(768.0)	(768.6)	(774.8)	(780.1)
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**

* 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.

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 2004. In 2004, approximately 86 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 14 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-6 and Figure 2-7). A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy consumption is presented below. Energy related activities are also responsible for CH_4 and N_2O emissions (39 percent and 15 percent of total U.S. emissions of each gas, respectively). Table 2-6 presents greenhouse gas emissions from the Energy sector, by source and gas.

Figure 2-6: 2004 Energy Sector Greenhouse Gas Sources

Figure 2-7: 2004 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

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

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**4,830.5**	**5,448.3**	**5,527.6**	**5,698.1**	**5,642.7**	**5,663.3**	**5,730.0**	**5,835.3**
Fossil Fuel Combustion	4,696.6	5,271.8	5,342.4	5,533.7	5,486.9	5,501.8	5,571.1	5,656.6
Non-Energy Use of Fuels	117.2	152.8	160.6	140.7	131.0	136.5	133.5	153.4
Waste Combustion	10.9	17.1	17.6	17.9	18.6	18.9	19.4	19.4
Natural Gas Flaring	5.8	6.6	6.9	5.8	6.1	6.2	6.1	6.0
*Biomass-Wood**	*212.5*	*209.5*	*214.3*	*217.6*	*190.8*	*182.9*	*186.3*	*191.7*
*International Bunker Fuels**	*113.5*	*114.6*	*105.2*	*101.4*	*97.8*	*89.5*	*84.1*	*94.5*
*Biomass-Ethanol**	*4.2*	*7.7*	*8.0*	*9.2*	*9.7*	*11.5*	*15.8*	*19.5*
CH_4	**261.6**	**235.4**	**226.8**	**228.7**	**225.0**	**220.1**	**220.9**	**215.8**
Natural Gas Systems	126.7	125.4	121.7	126.7	125.6	125.4	124.7	118.8
Coal Mining	81.9	62.8	58.9	56.3	55.5	52.5	54.8	56.3
Petroleum Systems	34.4	29.7	28.5	27.8	27.4	26.8	25.9	25.7
Stationary Sources	7.9	6.8	7.0	7.3	6.6	6.2	6.5	6.4

Abandoned Coal Mines	6.0	6.9	6.9	7.2	6.6	6.0	5.8	5.6
Mobile Sources	4.7	3.8	3.6	3.5	3.3	3.2	3.0	2.9
*International Bunker Fuels**	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.2**	**68.6**	**67.9**	**67.5**	**63.9**	**61.3**	**58.9**	**57.0**
Mobile Sources	43.5	54.8	54.1	53.1	50.0	47.5	44.8	42.8
Stationary Sources	12.3	13.4	13.4	13.9	13.5	13.2	13.6	13.7
Waste Combustion	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5
*International Bunker Fuels**	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*
Total	**5,148.3**	**5,752.3**	**5,822.3**	**5,994.3**	**5,931.6**	**5,944.6**	**6,009.8**	**6,108.2**

* 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.

Fossil Fuel Combustion (5,656.6 Tg CO_2 Eq.)

As fossil fuels are combusted, the carbon stored in them is emitted almost entirely as CO_2. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum and natural gas have about 25 percent and 45 percent less carbon than coal, respectively. From 1990 through 2004, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption with natural gas and coal accounting for 24 and 23 percent of total energy consumption, respectively. Petroleum was consumed primarily in the transportation end-use sector, the vast majority of coal was used by electric power generators, and natural gas was consumed largely in the industrial and residential end-use sectors.

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 2004. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 14 years, and (2) significant growth in emissions from transportation activities and electricity generation. Between 1990 and 2004, CO_2 emissions from fossil fuel combustion increased from 4,696.6 Tg CO_2 Eq. to 5,656.6 Tg CO_2 Eq.—a 20.4 percent total increase over the fourteen-year period.

The four major end-use sectors contributing to CO_2 emissions from fossil fuel combustion are industrial, transportation, residential, and commercial. Electricity generation also emits CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four 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.

Table 2-7, Figure 2-8, and Figure 2-9 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Table 2-7: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1998	1999	2000	2001	2002	2003	2004
Transportation	**1,464.4**	**1,663.4**	**1,725.6**	**1,770.3**	**1,757.0**	**1,802.2**	**1,805.4**	**1,860.2**
Combustion	1,461.4	1,660.3	1,722.4	1,766.9	1,753.6	1,798.8	1,801.0	1,855.5
Electricity	3.0	3.1	3.2	3.4	3.5	3.4	4.3	4.7
Industrial	**1,528.3**	**1,634.5**	**1,613.5**	**1,642.8**	**1,574.9**	**1,542.8**	**1,572.4**	**1,595.0**
Combustion	851.1	871.9	849.0	862.6	861.2	842.1	844.6	863.5
Electricity	677.2	762.6	764.5	780.3	713.7	700.7	727.7	731.5
Residential	**922.8**	**1,044.5**	**1,064.0**	**1,123.2**	**1,123.2**	**1,139.8**	**1,166.6**	**1,166.8**
Combustion	338.0	333.5	352.3	369.9	361.5	360.0	378.8	369.6
Electricity	584.8	711.0	711.7	753.3	761.7	779.8	787.9	797.2
Commercial	**753.1**	**895.9**	**904.8**	**961.6**	**983.3**	**973.9**	**978.1**	**983.1**

Combustion	222.6	217.7	218.6	229.3	224.9	224.3	235.8	226.0
Electricity	530.5	678.2	686.2	732.4	758.4	749.6	742.2	757.2
U.S. Territories	**28.0**	**33.5**	**34.5**	**35.8**	**48.5**	**43.1**	**48.7**	**51.4**
Total	**4,696.6**	**5,271.8**	**5,342.4**	**5,533.7**	**5,486.9**	**5,501.8**	**5,571.1**	**5,656.6**
Electricity Generation	**1,795.5**	**2,154.9**	**2,165.6**	**2,269.3**	**2,237.3**	**2,233.5**	**2,262.2**	**2,290.6**

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.

Figure 2-8: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure 2-9: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2004.[3] Virtually all of the energy consumed in this end-use sector came from petroleum products. Over 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 28 percent of CO_2 from fossil fuel combustion in 2004. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the 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 17 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2004. Both sectors relied heavily on electricity for meeting energy demands, with 68 and 77 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking.

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 34 percent of U.S. energy from fossil fuels and emitted 40 percent of the CO_2 from fossil fuel combustion in 2004. 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 2004. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Non-Energy Use of Fossil Fuels (153.4 Tg CO_2 Eq.)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEUs). Fuels are used in the industrial and transportation end-use sectors for a variety of NEUs, including application as solvents, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, and synthetic fibers. CO_2

[3] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 34 percent of U.S. emissions from fossil fuel combustion in 2004.

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. Where appropriate data and methodologies are available, NEUs of fossil fuels used for industrial processes are reported in the Industrial Processes sector. Emissions in 2004 for non-energy uses of fossil fuels were 153.4 Tg CO_2 Eq., which constituted 3 percent of overall fossil fuel CO_2 emissions and 3 percent of total national CO_2 emissions, approximately the same proportion as in 1990.

Waste Combustion (19.4 Tg CO_2 Eq.)

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes generated in the United States. The burning of garbage and non-hazardous solids, referred to as municipal solid waste, as well as the burning of hazardous waste, is usually performed to recover energy from the waste materials. CO_2 and N_2O emissions arise from the organic materials found in these wastes. The CO_2 emissions from municipal solid waste containing carbon of biogenic origin (e.g., paper, yard trimmings) are not accounted for in this inventory, since they are presumed to be offset by regrowth of the original living source, and are ultimately accounted for in the Land Use, Land-Use Change, and Forestry sector. Several components of municipal solid waste, such as plastics, synthetic rubber, synthetic fibers, and carbon black, are of fossil fuel origin, and are included as sources of CO_2 and N_2O emissions. In 2004, CO_2 emissions from waste combustion amounted to 19.4 Tg CO_2 Eq., while N_2O emissions amounted to 0.5 Tg CO_2 Eq.

Natural Gas Flaring (6.0 Tg CO_2 Eq.)

The flaring of natural gas from oil wells results in the release of CO_2 emissions. Natural gas is flared from both on-shore and off-shore oil wells to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 2004, flaring accounted for approximately 0.1 percent of U.S. CO_2 emissions (6.0 Tg CO_2 Eq.).

Natural Gas Systems (118.8 Tg CO_2 Eq.)

CH_4 is the major component of natural gas. Fugitive emissions of CH_4 occur throughout the production, processing, transmission, and distribution of natural gas. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment conditions. In 2004, CH_4 emissions from U.S. natural gas systems accounted for approximately 21 percent of U.S. CH_4 emissions.

Coal Mining (56.3 Tg CO_2 Eq.)

Produced millions of years ago during the formation of coal, CH_4 trapped within coal seams and surrounding rock strata is released when the coal is mined. The quantity of CH_4 released to the atmosphere during coal mining operations depends primarily upon the type of coal and the method and rate of mining.

CH_4 from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because CH_4 in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this CH_4, typically to the atmosphere. At some mines, CH_4-recovery systems may supplement these ventilation systems. During 2004, coal mining activities emitted 10 percent of U.S. CH_4 emissions. From 1990 to 2004, emissions from this source decreased by 31 percent due to increased use of the CH_4 collected by mine degasification systems and a general shift toward surface mining.

Petroleum Systems (25.7 Tg CO_2 Eq.)

Petroleum is often found in the same geological structures as natural gas, and the two are often retrieved together. Crude oil is saturated with many lighter hydrocarbons, including CH_4. When the oil is brought to the surface and processed, many of the dissolved lighter hydrocarbons (as well as water) are removed through a series of high-pressure and low-pressure separators. The remaining hydrocarbons in the oil are emitted at various points along the system. CH_4 emissions from the components of petroleum systems generally occur as a result of system leaks,

disruptions, and routine maintenance. In 2004, emissions from petroleum systems were about 5 percent of U.S. CH_4 emissions.

Mobile Combustion (45.8 Tg CO_2 Eq.)

Mobile combustion results in N_2O and CH_4 emissions. N_2O is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. The quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, some types of catalytic converters installed to reduce motor vehicle pollution can promote the formation of N_2O. In 2004, N_2O emissions from mobile combustion were 42.8 Tg CO_2 Eq. (11 percent of U.S. N_2O emissions). From 1990 to 2004, N_2O emissions from mobile combustion decreased by about 1 percent.

In 2004, CH_4 emissions were estimated to be 2.9 Tg CO_2 Eq. The combustion of gasoline in highway vehicles was responsible for the majority of the CH_4 emitted from mobile combustion.

Stationary Combustion (20.1 Tg CO_2 Eq.)

Stationary combustion results in N_2O and CH_4 emissions. In 2004, N_2O emissions from stationary combustion accounted for 13.7 Tg CO_2 Eq. (4 percent of U.S. N_2O emissions). From 1990 to 2004, N_2O emissions from stationary combustion increased by 11 percent, due to increased fuel consumption. In 2004, CH_4 emissions were 6.4 Tg CO_2 Eq. (1 percent of U.S. CH_4 emissions). The majority of CH_4 emissions from stationary combustion resulted from the burning of wood in the residential end-use sector.

Abandoned Coal Mines (5.6 Tg CO_2 Eq.)

Coal mining activities result in the emission of CH_4 into the atmosphere. However, the closure of a coal mine does not correspond with an immediate cessation in the release of emissions. 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. In 2004, the emissions from abandoned coal mines constituted 1 percent of U.S. CH_4 emissions.

CO_2 from Biomass Combustion (211.2 Tg CO_2 Eq.)

Biomass refers to organically-based carbon fuels (as opposed to fossil-based). Biomass in the form of fuel wood and wood waste was used primarily in the industrial sector, while the transportation sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops.

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 carbon emitted is offset by the growth of new biomass. For example, fuel wood burned one year but re-grown the next only recycles carbon, rather than creating a net increase in total atmospheric carbon. Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or croplands are accounted for in the estimates for the Land Use, Land-Use Change, and Forestry sector. 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. CH_4 emissions from biomass combustion are included in the Stationary combustion source described above.

The consumption of wood biomass in the industrial, residential, electric power, and commercial end-use sectors accounted for 64, 16, 8, and 2 percent of gross CO_2 emissions from biomass combustion, respectively. Ethanol consumption in the transportation end-use sector accounted for the remaining 9 percent.

International Bunker Fuels (95.5 Tg CO_2 Eq.)

Greenhouse gases emitted from the combustion of fuels used for international transport activities, termed international bunker fuels under the UNFCCC, include CO_2, CH_4, and N_2O. Emissions from these activities 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. These decisions are reflected in the *Revised 1996 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).

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine. 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. Emissions of CO_2, CH_4, and N_2O from international bunker fuel combustion were 94.5, 0.1, and 0.9 Tg CO_2 Eq. in 2004, respectively.

Industrial Processes

Emissions are produced as a by-product 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. The processes include iron and steel production, cement manufacture, ammonia manufacture 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 2-10). Additionally, emissions from industrial processes release HFCs, PFCs and SF_6. Table 2-8 presents greenhouse gas emissions from Industrial Processes by source category.

Figure 2-10: 2004 Industrial Processes Chapter Greenhouse Gas Sources

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

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	**174.8**		**171.9**	**167.5**	**166.4**	**152.5**	**152.6**	**147.6**	**152.6**
Iron and Steel Production	85.0		67.7	63.8	65.3	57.8	54.6	53.3	51.3
Cement Manufacture	33.3		39.2	40.0	41.2	41.4	42.9	43.1	45.6
Ammonia Manufacture & Urea Application	19.3		21.9	20.6	19.6	16.7	18.5	15.3	16.9
Lime Manufacture	11.2		13.9	13.5	13.3	12.8	12.3	13.0	13.7
Limestone and Dolomite Use	5.5		7.4	8.1	6.0	5.7	5.9	4.7	6.7
Aluminum Production	7.0		6.4	6.5	6.2	4.5	4.6	4.6	4.3
Soda Ash Manufacture and Consumption	4.1		4.3	4.2	4.2	4.1	4.1	4.1	4.2
Petrochemical Production	2.2		3.0	3.1	3.0	2.8	2.9	2.8	2.9
Titanium Dioxide Production	1.3		1.8	1.9	1.9	1.9	2.0	2.0	2.3
Phosphoric Acid Production	1.5		1.6	1.5	1.4	1.3	1.3	1.4	1.4
Ferroalloy Production	2.0		2.0	2.0	1.7	1.3	1.2	1.2	1.3
CO_2 Consumption	0.9		0.9	0.8	1.0	0.8	1.0	1.3	1.2
Zinc Production	0.9		1.1	1.1	1.1	1.0	0.9	0.5	0.5
Lead Production	0.3		0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Consumption	0.1		0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	**2.5**		**2.9**	**2.9**	**2.9**	**2.5**	**2.5**	**2.5**	**2.7**
Petrochemical Production	1.2		1.7	1.7	1.7	1.4	1.5	1.5	1.6
Iron and Steel Production	1.3		1.2	1.2	1.2	1.1	1.0	1.0	1.0
Silicon Carbide Production	+		+	+	+	+	+	+	+
N_2O	**33.0**		**26.9**	**25.6**	**25.6**	**20.8**	**23.1**	**22.9**	**22.4**
Nitric Acid Production	17.8		20.9	20.1	19.6	15.9	17.2	16.7	16.6
Adipic Acid Production	15.2		6.0	5.5	6.0	4.9	5.9	6.2	5.7
HFCs, PFCs, and SF_6	**90.8**		**133.4**	**131.5**	**134.7**	**124.9**	**132.7**	**131.0**	**143.0**
Substitution of Ozone Depleting Substances	0.4		54.5	62.8	71.2	78.6	86.2	93.5	103.3
HCFC-22 Production	35.0		40.1	30.4	29.8	19.8	19.8	12.3	15.6

Electrical Transmission and Distribution	28.6		16.7	16.1	15.3	15.3	14.5	14.0	13.8
Semiconductor Manufacture	2.9		7.1	7.2	6.3	4.5	4.4	4.3	4.7
Aluminum Production	18.4		9.1	9.0	9.0	4.0	5.3	3.8	2.8
Magnesium Production and Processing	5.4		5.8	6.0	3.2	2.6	2.6	3.0	2.7
Total	**301.1**		**335.1**	**327.5**	**329.6**	**300.7**	**310.9**	**304.1**	**320.7**

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

Iron and Steel Production (52.4 Tg CO_2 Eq.)

Pig iron is the product of combining iron oxide (i.e., iron ore) and sinter with metallurgical coke in a blast furnace. The pig iron production process, as well as the thermal processes used to create sinter and metallurgical coke, resulted in emissions of CO_2 and CH_4. In 2004, iron and steel production resulted in 1.0 Tg CO_2 Eq. of CH_4 emissions, with the majority of the emissions coming from the pig iron production process. The majority of CO_2 emissions from iron and steel processes come from the production of coke for use in pig iron creation, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel. CO_2 emissions from iron and steel amounted to 51.3 Tg CO_2 Eq. in 2004. From 1990 to 2004, overall emissions from this source decreased by 39 percent.

Cement Manufacture (45.6 Tg CO_2 Eq.)

Clinker is an intermediate product in the formation of finished Portland and masonry cement. Heating calcium carbonate ($CaCO_3$) in a cement kiln forms lime and CO_2. The lime combines with other materials to produce clinker, and the CO_2 is released into the atmosphere. From 1990 to 2004, emissions from this source increased by 37 percent.

Ammonia Manufacture and Urea Application (16.9 Tg CO_2 Eq.)

In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (i.e., a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. This carbon monoxide is transformed into CO_2 in the presence of a catalyst. The CO_2 is generally released into the atmosphere, but some of the CO_2, together with ammonia, is used as a raw material in the production of urea [$CO(NH_2)_2$], which is a type of nitrogenous fertilizer. The carbon in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2.

Lime Manufacture (13.7 Tg CO_2 Eq.)

Lime is used in steel making, construction, flue gas desulfurization, and water and sewage treatment. It is manufactured by heating limestone (mostly calcium carbonate, $CaCO_3$) in a kiln, creating quicklime (calcium oxide, CaO) and CO_2, which is normally emitted to the atmosphere.

Limestone and Dolomite Use (6.7 Tg CO_2 Eq.)

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are basic raw materials used in a wide variety of industries, including construction, agriculture, chemical, and metallurgy. For example, limestone can be used as a purifier in refining metals. In the case of iron ore, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating CO_2 as a by-product. Limestone is also used in flue gas desulfurization systems to remove sulfur dioxide from the exhaust gases.

Aluminum Production (7.2 Tg CO_2 Eq.)

Aluminum production results in emissions of CO_2, CF_4 and C_2F_6. CO_2 is emitted when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite. The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from

petroleum coke. During reduction, some of this carbon is oxidized and released to the atmosphere as CO_2. In 2004, CO_2 emissions from aluminum production amounted to 4.3 Tg CO_2 Eq.

During the production of primary aluminum, CF_4 and C_2F_6 are emitted as intermittent by-products of the smelting process. These PFCs are formed when fluorine from the cryolite bath combines with carbon from the electrolyte anode. PFC emissions from aluminum production have decreased by 85 percent between 1990 and 2004 due to emission reduction efforts by the industry and falling domestic aluminum production. In 2004, CF_4 and C_2F_6 emissions from aluminum production amounted to 2.8 Tg CO_2 Eq.

Soda Ash Manufacture and Consumption (4.2 Tg CO_2 Eq.)

Commercial soda ash (sodium carbonate, Na_2CO_3) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of soda ash, some natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which CO_2 is generated as a by-product. In addition, CO_2 is often released when the soda ash is consumed.

Petrochemical Production (4.5 Tg CO_2 Eq.)

The production process for carbon black results in the release CO_2 emissions to the atmosphere. Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock production. The majority of carbon black produced in the United States is consumed by the tire industry, which adds it to rubber to increase strength and abrasion resistance. Small amounts of CH_4 are also released during the production of five petrochemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. These production processes resulted in emissions of 2.9 Tg CO_2 Eq. of CO_2 and 1.6 Tg CO_2 Eq. of CH_4 in 2004.

Titanium Dioxide Production (2.3 Tg CO_2 Eq.)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. It is used in white paint and as a pigment in the manufacture of white paper, foods, and other products. Two processes, the chloride process and the sulfate process, are used for making TiO_2. CO_2 is emitted from the chloride process, which uses petroleum coke and chlorine as raw materials.

Phosphoric Acid Production (1.4 Tg CO_2 Eq.)

Phosphoric acid is a basic raw material in the production of phosphate-based fertilizers. The phosphate rock consumed in the United States originates from both domestic mines, located primarily in Florida, North Carolina, Idaho, and Utah, and foreign mining operations in Morocco. The primary use of this material is as a basic component of a series of chemical reactions that lead to the production of phosphoric acid, as well as the by-products CO_2 and phosphogypsum.

Ferroalloy Production (1.3 Tg CO_2 Eq.)

CO_2 is 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.

Carbon Dioxide Consumption (1.2 Tg CO_2 Eq.)

Many segments of the economy consume CO_2, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. CO_2 may be produced as a by-product from the production of certain chemicals (e.g., ammonia), from select natural gas wells, or by separating it from crude oil and natural gas. The majority of the CO_2 used in these applications is eventually released to the atmosphere.

Zinc Production (0.5 Tg CO_2 Eq.)

CO_2 emissions from the production of zinc in the United States occur through the primary production of zinc in the electro-thermic production process, or through the secondary production of zinc using a Waelz Kiln furnace or the electro-thermic production process. Both the electro-thermic and Waelz Kiln processes are emissive due to the use of a carbon-based material (often metallurgical coke); however, zinc is also produced in the United States using non-emissive processes. Due to the closure of an electro-thermic plant in 2003, the only emissive zinc production process remaining occurs through the recycling of electric-arc-furnace (EAF) dust in a Waelz Kiln furnace (secondary production) at a plant in Palmerton, Pennsylvania.

Lead Production (0.3 Tg CO_2 Eq.)

Primary and secondary production of lead in the United States results in CO_2 emissions when carbon-based materials (often metallurgical coke) are used as a reducing agent. Primary production involves the direct smelting of lead concentrates while secondary production largely occurs through the recycling of lead-acid batteries. In 2004, emissions from primary lead production decreased by 40 percent due to the closure of one of two primary lead production plants located in Missouri. Secondary lead production accounted for 85 percent of total lead production emissions in 2004.

Silicon Carbide Production and Consumption (0.1 Tg CO_2 Eq.)

Small amounts of CH_4 are released during the production of silicon carbide (SiC), a material used as an industrial abrasive. Additionally, small amounts of CO_2 are released when SiC is consumed for metallurgical and other non-abrasive purposes (e.g., iron and steel production). Silicon carbide is made through a reaction of quartz (SiO_2) and carbon (in the form of petroleum coke). CH_4 is produced during this reaction from volatile compounds in the petroleum coke. CH_4 emissions from silicon carbide production have declined significantly due to a 67 percent decrease in silicon carbide production since 1990. CO_2 emissions from SiC consumption have fluctuated significantly between years dependent on consumption, but overall have increased by 33 percent since 1990.

Nitric Acid Production (16.6 Tg CO_2 Eq.)

Nitric acid production is an industrial source of N_2O emissions. Used primarily to make synthetic commercial fertilizer, this raw material is also a major component in the production of adipic acid and explosives.

Virtually all of the nitric acid manufactured in the United States is produced by the oxidation of ammonia, during which N_2O is formed and emitted to the atmosphere. In 2004, N_2O emissions from nitric acid production accounted for 4 percent of U.S. N_2O emissions. From 1990 to 2004, emissions from this source category decreased by 7 percent with the trend in the time series closely tracking the changes in production.

Adipic Acid Production (5.7 Tg CO_2 Eq.)

Most adipic acid produced in the United States is used to manufacture nylon 6,6. Adipic acid is also used to produce some low-temperature lubricants and to add a "tangy" flavor to foods. N_2O is emitted as a by-product of the chemical synthesis of adipic acid.

In 2004, U.S. adipic acid plants emitted 1.5 percent of U.S. N_2O emissions. Even though adipic acid production has increased in recent years, by 1998 all three major adipic acid plants in the United States had voluntarily implemented N_2O abatement technology. As a result, emissions have decreased by 62 percent since 1990.

Substitution of Ozone Depleting Substances (103.3 Tg CO_2 Eq.)

The use and subsequent emissions of HFCs and PFCs as substitutes for ODSs have increased from small amounts in 1990 to account for 72 percent of aggregate HFC, PFC, and SF_6 emissions. This increase was in large part the result of efforts to phase-out CFCs and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration and air-conditioning applications. In the short term, this trend is expected to continue, and will likely accelerate over the coming 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.

HCFC-22 Production (15.6 Tg CO_2 Eq.)

HFC-23 is a by-product of the production of HCFC-22. Emissions from this source have decreased by 55 percent since 1990. The HFC-23 emission rate (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990, although production has been increasing.

Electrical Transmission and Distribution Systems (13.8 Tg CO_2 Eq.)

The primary use of SF_6 is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of SF_6 occur from leaks in and servicing of substations and circuit breakers, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Estimated emissions from this source decreased by 52 percent since 1990, primarily due to higher SF_6 prices and industrial efforts to reduce emissions.

Semiconductor Manufacture (4.7 Tg CO_2 Eq.)

The semiconductor industry uses combinations of HFCs, PFCs, SF_6, and other gases for plasma etching and to clean chemical vapor deposition tools. Emissions from this source category have increased 62 percent since 1990 with the growth in the semiconductor industry and the rising intricacy of chip designs. However, the growth rate in emissions has slowed since 1997, and emissions actually declined between 1999 and 2004. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

Magnesium Production (2.7 Tg CO_2 Eq.)

Sulfur hexafluoride is also used as a protective cover gas for the casting of molten magnesium. Emissions from primary magnesium production and magnesium casting have decreased by 50 percent since 1990. This decrease has primarily taken place since 1999, due to a decline in the quantity of magnesium die cast and the closure of a U.S. primary magnesium production facility.

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 N_2O Product Usage, the only source of greenhouse gas emissions from this sector, accounted for 4.8 Tg CO_2 Eq. of N_2O, or less than 0.1 percent of total U.S. emissions in 2004 (see Table 2-9).

Table 2-9: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq.)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
N_2O	**4.3**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Total	**4.3**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**

N_2O Product Usage (4.8 Tg CO_2 Eq.)

N_2O is 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. In 2004, N_2O emissions from product usage constituted approximately 1 percent of U.S. N_2O emissions. From 1990 to 2004, emissions from this source category increased by 11 percent.

Agriculture

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

In 2004, agricultural activities were responsible for emissions of 440.1 Tg CO_2 Eq., or 6.2 percent of total U.S. greenhouse gas emissions. 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 20 percent and 7 percent of total CH_4 emissions from anthropogenic activities, respectively in 2004. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2004, accounting for 68 percent. Table 2-10 presents emission estimates for the Agriculture sector.

Figure 2-11: 2004 Agriculture Chapter Greenhouse Gas Sources

Table 2-10: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**156.8**		**164.2**	**164.0**	**162.0**	**161.9**	**161.5**	**161.8**	**160.4**
Enteric Fermentation	117.9		116.7	116.8	115.6	114.5	114.7	115.1	112.6
Manure Management	31.2		38.8	38.1	38.0	38.9	39.3	39.2	39.4
Rice Cultivation	7.1		7.9	8.3	7.5	7.6	6.8	6.9	7.6
Field Burning of Agricultural Residues	0.7		0.8	0.8	0.8	0.8	0.7	0.8	0.9
N_2O	**282.7**		**319.0**	**299.1**	**296.5**	**301.5**	**296.2**	**277.1**	**279.7**
Agricultural Soil Management	266.1		301.1	281.2	278.2	282.9	277.8	259.2	261.5
Manure Management	16.3		17.4	17.4	17.8	18.1	18.0	17.5	17.7
Field Burning of Agricultural Residues	0.4		0.5	0.4	0.5	0.5	0.4	0.4	0.5
Total	**439.6**		**483.2**	**463.1**	**458.4**	**463.4**	**457.8**	**439.1**	**440.1**

Note: Totals may not sum due to independent rounding.

Enteric Fermentation (112.6 Tg CO_2 Eq.)

During animal digestion, CH_4 is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down food. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest CH_4 emissions among all animal types because they have a rumen, or large fore-stomach, in which CH_4-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower CH_4 emissions. In 2004, enteric fermentation was the source of about 20 percent of U.S. CH_4 emissions, and more than 70 percent of the CH_4 emissions from agriculture. From 1990 to 2004, emissions from this source decreased by 4 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle.

Manure Management (57.1 Tg CO_2 Eq.)

Both CH_4 and N_2O result from manure management. The decomposition of organic animal waste in an anaerobic environment produces CH_4. The most important factor affecting the amount of CH_4 produced is how the manure is managed, because certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems tend to encourage anaerobic conditions and produce significant quantities of CH_4, whereas solid waste management approaches produce little or no CH_4. Higher temperatures and moist climatic conditions also promote CH_4 production.

Emissions from manure management were 39.4 Tg CO_2 Eq., or about 7 percent of U.S. CH_4 emissions in 2004 and 25 percent of the CH_4 emissions from the agriculture sector. From 1990 to 2004, emissions from this source increased by 26 percent. The bulk of this increase was from swine and dairy cow manure, and is attributed to the

shift in the composition of the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid management systems.

N_2O is also produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure. Emissions from unmanaged manure are accounted for within the agricultural soil management source category. Total N_2O emissions from managed manure systems in 2004 accounted for 17.7 Tg CO_2 Eq., or 5 percent of U.S. N_2O emissions. From 1990 to 2004, emissions from this source category increased by 9 percent, primarily due to increases in swine and poultry populations over the same period.

Rice Cultivation (7.6 Tg CO_2 Eq.)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing CH_4 to the atmosphere, primarily through the rice plants. In 2004, rice cultivation was the source of 1 percent of U.S. CH_4 emissions, and about 5 percent of U.S. CH_4 emissions from agriculture. Emission estimates from this source have increased about 6 percent since 1990.

Field Burning of Agricultural Residues (1.4 Tg CO_2 Eq.)

Burning crop residue releases N_2O and CH_4. Because field burning is not a common debris clearing method used in the United States, it was responsible for only 0.2 percent of U.S. CH_4 (0.9 Tg CO_2 Eq.) and 0.1 percent of U.S. N_2O (0.5 Tg CO_2 Eq.) emissions in 2004.

Agricultural Soil Management (261.5 Tg CO_2 Eq.)

N_2O is produced naturally in soils through microbial nitrification and denitrification processes. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by microbial processes. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through the application of synthetic and organic fertilizers; production of nitrogen-fixing crops and forages; the application of livestock manure, crop residues, and sewage sludge; cultivation of high-organic-content soils; and direct excretion by animals onto soil. Indirect additions result from volatilization and subsequent atmospheric deposition, and from leaching and surface run-off of some of the nitrogen applied to or deposited on soils as fertilizer, livestock manure, and sewage sludge.

In 2004, agricultural soil management accounted for 68 percent of U.S. N_2O emissions. From 1990 to 2004, emissions from this source decreased slightly as fertilizer consumption, manure production, and production of nitrogen-fixing and other crops rose. Year-to-year fluctuations are largely a reflection of annual variations in climate, synthetic fertilizer consumption, and crop production.

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 a net uptake (sequestration) of carbon in the United States, which offset about 11 percent of total U.S. greenhouse gas emissions in 2004. Forests (including vegetation, soils, and harvested wood) accounted for approximately 82 percent of total 2004 sequestration, urban trees accounted for 11 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 6 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2004. 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 soils account for a net carbon sink that is almost two times larger than the sum of emissions from organic soils and liming. The mineral soil carbon sequestration is largely due to 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 2004 resulted in a net carbon sequestration of 780.1 Tg CO_2 Eq. (Table 2-11). This represents an offset of approximately 13 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 14 percent between 1990 and 2004, which contributed to an increase in net U.S. emissions (all sources and sinks) of 21 percent from 1990 to 2004. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings and food scraps and agricultural soils also slowed over this period, while the rate of carbon accumulation in agricultural soils and urban trees increased.

Table 2-11: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**(773.4)**	**(618.8)**	**(637.9)**	**(631.0)**	**(634.0)**	**(634.6)**	**(635.8)**	**(637.2)**
Changes in Forest Carbon Stocks	(773.4)	(618.8)	(637.9)	(631.0)	(634.0)	(634.6)	(635.8)	(637.2)
Cropland Remaining Cropland	**(33.1)**	**(24.6)**	**(24.6)**	**(26.1)**	**(27.8)**	**(27.5)**	**(28.7)**	**(28.9)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions	(33.1)	(24.6)	(24.6)	(26.1)	(27.8)	(27.5)	(28.7)	(28.9)
Land Converted to Cropland	**1.5**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**
Changes in Agricultural Soil Carbon Stocks	1.5	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Grassland Remaining Grassland	**(4.5)**	**7.5**	**7.5**	**7.4**	**7.4**	**7.4**	**7.3**	**7.3**
Changes in Agricultural Soil Carbon Stocks	(4.5)	7.5	7.5	7.4	7.4	7.4	7.3	7.3
Land Converted to Grassland	**(17.6)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**
Changes in Agricultural Soil Carbon Stocks	(17.6)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Settlements Remaining Settlements	**(83.2)**	**(84.2)**	**(86.8)**	**(85.9)**	**(89.7)**	**(89.9)**	**(93.8)**	**(97.3)**
Urban Trees	(58.7)	(73.3)	(77.0)	(77.0)	(80.7)	(80.7)	(84.3)	(88.0)
Landfilled Yard Trimmings and Food Scraps	(24.5)	(10.9)	(9.8)	(8.9)	(9.0)	(9.3)	(9.4)	(9.3)
Total	**(910.4)**	**(744.0)**	**(765.7)**	**(759.5)**	**(768.0)**	**(768.6)**	**(774.8)**	**(780.1)**

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

Land use, land-use change, and forestry activities in 2004 also resulted in emissions of N_2O (6.8 Tg CO_2 Eq., Table 2-12). Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 20 percent between 1990 and 2004.

Table 2-12: N_2O Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**0.1**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
N_2O Fluxes from Soils	0.1	0.4	0.5	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements	**5.6**	**6.2**	**6.2**	**6.0**	**5.8**	**6.0**	**6.2**	**6.4**
N_2O Fluxes from Soils	5.6	6.2	6.2	6.0	5.8	6.0	6.2	6.4
Total	**5.7**	**6.5**	**6.7**	**6.4**	**6.2**	**6.4**	**6.6**	**6.8**

Note: Totals may not sum due to independent rounding.

Forest Land Remaining Forest Land (0.4 Tg CO_2 Eq.)

As with other agricultural applications, forests may be fertilized to stimulate growth rates. The relative magnitude of the impact of this practice is limited, however, because forests are generally only fertilized twice during their life cycles, and applications account for no more than one percent of total U.S. fertilizer applications annually. In terms of trends, however, N_2O emissions from forest soils for 2004 were almost 7 times higher than in 1990, primarily the result of an increase in the fertilized area of pine plantations in the southeastern U.S. This source accounts for approximately 0.1 percent of total U.S. N_2O emissions.

Settlements Remaining Settlements (6.4 Tg CO_2 Eq.)

Of the fertilizers applied to soils in the United States, approximately 10 percent are applied to lawns, golf courses, and other landscaping within settled areas. In 2004, N_2O emissions from settlement soils constituted approximately 1.7 percent of total U.S. N_2O emissions. There has been an overall increase in emissions of 15 percent since 1990, a result of a general increase in the applications of synthetic fertilizers.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-12). Landfills were the largest source of anthropogenic CH_4 emissions, accounting for 25 percent of total U.S. CH_4 emissions.[4] Additionally, wastewater treatment accounts for 7 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, using a simplified methodology. Wastewater treatment systems are a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. N_2O emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are also emitted by waste activities. A summary of greenhouse gas emissions from the Waste sector is presented in Table 2-13.

Figure 2-12: 2004 Waste Sector Greenhouse Gas Sources

Overall, in 2004, waste activities generated emissions of 193.8 Tg CO_2 Eq., or 2.7 percent of total U.S. greenhouse gas emissions.

Table 2-13: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**197.1**		**176.9**	**175.3**	**173.3**	**170.8**	**175.6**	**179.0**	**177.8**
Landfills	172.3		144.4	141.6	139.0	136.2	139.8	142.4	140.9
Wastewater Treatment	24.8		32.6	33.6	34.3	34.7	35.8	36.6	36.9
N_2O	**12.9**		**14.9**	**15.4**	**15.5**	**15.6**	**15.6**	**15.8**	**16.0**
Human Sewage	12.9		14.9	15.4	15.5	15.6	15.6	15.8	16.0
Total	**210.0**		**191.8**	**190.7**	**188.8**	**186.4**	**191.3**	**194.8**	**193.8**

Note: Totals may not sum due to independent rounding.

Landfills (140.9 Tg CO_2 Eq.)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States, accounting for approximately 25 percent of total CH_4 emissions in 2004. In an environment where the oxygen content is low or zero, anaerobic bacteria can decompose organic materials, such as yard waste, household waste, food waste, and paper, resulting in the generation of CH_4 and biogenic CO_2. Site-specific factors, such as waste composition, moisture, and landfill size, influence the level of CH_4 generation.

From 1990 to 2004, net CH_4 emissions from landfills decreased by approximately 18 percent, with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

[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.

Wastewater Treatment (36.9 Tg CO_2 Eq.)

Wastewater from domestic sources (i.e., municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms and chemical contaminants. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, with the latter condition producing 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. Untreated wastewater may also produce CH_4 if contained under anaerobic conditions. In 2004, wastewater treatment was the source of approximately 7 percent of U.S. CH_4 emissions.

Human Sewage (Domestic Wastewater) (16.0 Tg CO_2 Eq.)

Domestic human sewage is usually mixed with other household wastewater, which includes drainage from showers and sinks, washing machine effluent, etc., and transported by a collection system to either a direct discharge, or an on-site, decentralized, or centralized wastewater treatment system. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the surface. N_2O may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. Emissions of N_2O from treated human sewage discharged into aquatic environments accounted for 4 percent of U.S. N_2O emissions in 2004. From 1990 to 2004, emissions from this source category increased by 24 percent.

2.2. Emissions by Economic Sector

Throughout this 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 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, and Agriculture, as well as U.S. Territories. Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2004. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Additional discussion and data on these two economic sectors is provided below.

Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2004. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade, although there was an increase in industrial emissions in 2004 (up 3 percent from 2003 levels). 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 residential, agriculture, commercial economic sectors, and U.S. territories, contributed the remaining 20 percent of emissions. The residential economic sector accounted for approximately 6 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, but unlike all other economic sectors these emissions were dominated by non-CO_2 emissions. The commercial sector accounted for about 7 percent of emissions, while U.S. territories accounted for 1 percent of total emissions.

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.

Table 2-14 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-13 shows the trend in emissions by sector from 1990 to 2004.

Figure 2-13: Emissions Allocated to Economic Sectors

Table 2-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2004)

Sector/Source	1990	1998	1999	2000	2001	2002	2003	2004	Percent[a]
Electricity Generation	**1,846.4**	**2,202.4**	**2,213.3**	**2,315.9**	**2,284.4**	**2,280.1**	**2,308.5**	**2,337.8**	**33.0%**
CO_2 from Fossil Fuel Combustion	1,795.5	2,154.9	2,165.6	2,269.3	2,237.3	2,233.5	2,262.2	2,290.6	32.4%
Stationary Combustion[d]	8.1	9.6	9.6	10.0	9.8	9.8	10.0	10.1	0.1%
Electrical Transmission and Distribution[c]	28.6	16.7	16.1	15.3	15.3	14.5	14.0	13.8	0.2%
Waste Combustion[b]	11.4	17.5	18.0	18.3	19.1	19.4	19.9	19.9	0.3%
Limestone and Dolomite Use	2.8	3.7	4.0	3.0	2.9	2.9	2.4	3.4	+
Transportation	**1,520.3**	**1,753.4**	**1,819.3**	**1,866.9**	**1,852.7**	**1,898.0**	**1,898.9**	**1,955.1**	**27.6%**
CO_2 from Fossil Fuel Combustion	1,461.4	1,660.3	1,722.4	1,766.9	1,753.6	1,798.8	1,801.0	1,855.5	26.2%
Mobile Combustion[d]	47.1	57.4	56.4	55.4	52.0	49.4	46.5	44.4	0.6%
Substitution of ODS[e]	+	23.5	28.2	32.6	36.1	38.9	41.2	45.0	0.6%
Non-Energy Use of Fuels	11.9	12.1	12.3	12.1	11.1	10.9	10.1	10.2	0.1%
Industry	**1,438.9**	**1,452.4**	**1,411.0**	**1,409.7**	**1,366.6**	**1,346.7**	**1,342.7**	**1,377.3**	**19.5%**
CO_2 from Fossil Fuel Combustion	804.8	814.5	789.2	812.3	811.0	789.8	800.3	813.1	11.5%
Non-Energy Use of Fuels	99.6	131.6	138.8	117.7	114.7	116.4	113.7	132.8	1.9%
Stationary Combustion	5.3	5.4	5.4	5.5	5.1	4.9	4.9	5.1	0.1%
Mobile Combustion	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.0	+
Coal Mining	81.9	62.8	58.9	56.3	55.5	52.5	54.8	56.3	0.8%
Abandoned Coal Mines	6.0	6.9	6.9	7.2	6.6	6.0	5.8	5.6	0.1%
Natural Gas Systems	126.7	125.4	121.7	126.7	125.6	125.4	124.7	118.8	1.7%
Petroleum Systems	34.4	29.7	28.5	27.8	27.4	26.8	25.9	25.7	0.4%
Natural Gas Flaring	5.8	6.6	6.9	5.8	6.1	6.2	6.1	6.0	0.1%
Titanium Dioxide Production	1.3	1.8	1.9	1.9	1.9	2.0	2.0	2.3	+
Aluminum Production[h]	25.5	15.4	15.4	15.2	8.5	9.9	8.4	7.2	0.1%
Iron and Steel Production[f]	86.3	68.9	65.0	66.5	58.9	55.6	54.4	52.4	0.7%
Ferroalloy Production	2.0	2.0	2.0	1.7	1.3	1.2	1.2	1.3	+
Ammonia Manufacture	19.3	21.9	20.6	19.6	16.7	18.5	15.3	16.9	0.2%
Cement Manufacture	33.3	39.2	40.0	41.2	41.4	42.9	43.1	45.6	0.6%
Lime Manufacture	11.2	13.9	13.5	13.3	12.8	12.3	13.0	13.7	0.2%
Limestone and Dolomite Use	2.8	3.7	4.0	3.0	2.9	2.9	2.4	3.4	+
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.2	4.1	4.1	4.1	4.2	0.1%
CO_2 Consumption	0.9	0.9	0.8	1.0	0.8	1.0	1.3	1.2	+
Silicon Carbide Consumption	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	+
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	+
Zinc Production	0.9	1.1	1.1	1.1	1.0	0.9	0.5	0.5	+
Petrochemical Production	3.4	4.7	4.8	4.7	4.2	4.4	4.3	4.5	0.1%
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
Phosphoric Acid Production	1.5	1.6	1.5	1.4	1.3	1.3	1.4	1.4	+
Adipic Acid	15.2	6.0	5.5	6.0	4.9	5.9	6.2	5.7	0.1%
Nitric Acid	17.8	20.9	20.1	19.6	15.9	17.2	16.7	16.6	0.2%
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8	0.1%
HCFC-22 Production[g]	35.0	40.1	30.4	29.8	19.8	19.8	12.3	15.6	0.2%
Semiconductor Manufacture[e]	2.9	7.1	7.2	6.3	4.5	4.4	4.3	4.7	0.1%
Magnesium Production and Processing[c]	5.4	5.8	6.0	3.2	2.6	2.6	3.0	2.7	+
Substitution of ODS[e]	0.1	3.9	4.4	4.7	5.1	5.7	6.5	7.9	0.1%
Agriculture	**486.3**	**541.6**	**523.9**	**509.5**	**514.4**	**511.0**	**484.2**	**491.3**	**6.9%**
CO_2 from Fossil Fuel	46.3	57.4	59.8	50.2	50.2	52.3	44.3	50.3	0.7%

Combustion									
Stationary Combustion[d]	+	+	+	+	+	+	+	+	+
Mobile Combustion[d]	0.4	0.5	0.5	0.4	0.4	0.5	0.4	0.4	+
Enteric Fermentation	117.9	116.7	116.8	115.6	114.6	114.7	115.1	112.6	1.6%
Manure Management[d]	47.4	56.2	55.6	55.9	56.9	57.3	56.7	57.1	0.8%
Rice Cultivation	7.1	7.9	8.3	7.5	7.6	6.8	6.9	7.6	0.1%
Agricultural Residue Burning[d]	1.1	1.2	1.2	1.2	1.2	1.1	1.2	1.4	+
Agricultural Soil Management	266.1	301.1	281.2	278.2	282.9	277.8	259.2	261.5	3.7%
Forest Soil Fertilization	0.1	0.4	0.5	0.4	0.4	0.4	0.4	0.4	+
Commercial	**433.6**	**428.0**	**430.6**	**443.0**	**439.5**	**447.5**	**466.5**	**459.9**	**6.5%**
CO_2 from Fossil Fuel Combustion	222.6	217.7	218.6	229.3	224.9	224.3	235.8	226.0	3.2%
Stationary Combustion[d]	1.1	1.1	1.1	1.1	1.0	1.0	1.1	1.1	+
Substitution of ODS[e]	+	17.4	20.3	23.8	27.1	30.9	34.8	39.0	0.6%
Landfills	172.3	144.4	141.6	139.0	136.2	139.8	142.4	140.9	2.0%
Human Sewage	12.9	14.9	15.4	15.5	15.6	15.6	15.8	16.0	0.2%
Wastewater Treatment	24.8	32.6	33.6	34.3	34.7	35.8	36.6	36.9	0.5%
Residential	**349.4**	**353.3**	**372.6**	**390.4**	**381.6**	**380.1**	**399.8**	**391.1**	**5.5%**
CO_2 from Fossil Fuel Combustion	338.0	333.5	352.3	369.9	361.5	360.0	378.8	369.6	5.2%
Stationary Combustion[d]	5.5	4.0	4.2	4.4	3.9	3.5	3.9	3.7	0.1%
Substitution of ODS[e]	0.3	9.6	9.8	10.1	10.3	10.6	11.0	11.3	0.2%
Settlement Soil Fertilization	5.6	6.2	6.2	6.0	5.8	6.0	6.2	6.4	0.1%
U.S. Territories	**33.8**	**42.7**	**44.2**	**46.9**	**54.0**	**52.4**	**58.6**	**61.9**	**0.9%**
CO_2 from Fossil Fuel Combustion	33.8	42.7	44.2	46.9	54.0	52.4	58.6	61.9	0.9%
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**	**100.0%**
Sinks	**(910.4)**	**(744.0)**	**(765.7)**	**(759.5)**	**(768.0)**	**(768.6)**	**(774.8)**	**(780.1)**	**-11.0%**
Forests	(773.4)	(618.8)	(637.9)	(631.0)	(634.0)	(634.6)	(635.8)	(637.2)	-9.0%
Urban Trees	(58.7)	(73.3)	(77.0)	(77.0)	(80.7)	(80.7)	(84.3)	(88.0)	-1.2%
Agricultural Soils	(53.8)	(41.0)	(41.1)	(42.6)	(44.3)	(44.1)	(45.3)	(45.6)	-0.6%
Landfilled Yard Trimmings	(24.5)	(10.9)	(9.8)	(8.9)	(9.0)	(9.3)	(9.4)	(9.3)	-0.1%
Net Emissions (Sources and Sinks)	**5,198.6**	**6,029.6**	**6,049.2**	**6,222.8**	**6,125.1**	**6,147.2**	**6,184.3**	**6,294.3**	**89.0%**

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.
ODS (Ozone Depleting Substances)
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05%.
[a] Percent of total emissions for year 2004.
[b] Includes both CO_2 and N_2O.
[c] SF_6 emitted.
[d] Includes both CH_4 and N_2O.
[e] May include a mixture of HFCs, PFCs, and SF_6.
[f] Includes both CH_4 and CO_2.
[g] HFC-23 emitted.
[h] Includes both CO_2 and PFCs.

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 33 percent of total U.S. greenhouse gas

emissions in 2004. Emissions increased by 27 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and nonutility 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 2-15 provides a detailed summary of emissions from electricity generation-related activities.

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

Gas/Fuel Type or Source	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**1,809.2**	**2,175.7**	**2,187.2**	**2,290.2**	**2,258.8**	**2,255.3**	**2,283.9**	**2,313.3**
CO_2 from Fossil Fuel Combustion	1,795.5	2,154.9	2,165.6	2,269.3	2,237.3	2,233.5	2,262.2	2,290.6
Coal	*1,517.3*	*1,801.2*	*1,807.7*	*1,896.6*	*1,845.9*	*1,849.6*	*1,887.2*	*1,897.1*
Natural Gas	*176.9*	*249.1*	*260.9*	*281.4*	*289.5*	*305.6*	*277.6*	*295.8*
Petroleum	*100.9*	*104.2*	*96.6*	*91.0*	*101.6*	*77.8*	*97.0*	*97.3*
Geothermal	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Waste Combustion	10.9	17.1	17.6	17.9	18.6	18.9	19.4	19.4
Limestone and Dolomite Use	2.8	3.7	4.0	3.0	2.9	2.9	2.4	3.4
CH_4	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Stationary Combustion*	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
N_2O	**8.0**	**9.3**	**9.3**	**9.7**	**9.6**	**9.6**	**9.8**	**9.9**
Stationary Combustion*	7.6	8.9	8.9	9.3	9.1	9.1	9.3	9.4
Waste Combustion	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5
SF_6	**28.6**	**16.7**	**16.1**	**15.3**	**15.3**	**14.5**	**14.0**	**13.8**
Electrical Transmission and Distribution	28.6	16.7	16.1	15.3	15.3	14.5	14.0	13.8
Total	**1,846.4**	**2,202.4**	**2,213.3**	**2,315.9**	**2,284.4**	**2,280.1**	**2,308.5**	**2,337.8**

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

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electricity generation sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity (EIA 2005a and Duffield 2005). These three source categories include CO_2 from fossil fuel combustion, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.[5]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (30 percent). 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. 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.

Table 2-16 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electricity generation distributed to them. Figure 2-14 shows the trend in these emissions by sector from 1990 to 2004.

Figure 2-14: Emissions with Electricity Distributed to Economic Sectors

[5] 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 2-16: U.S Greenhouse Gas Emissions by "Economic Sector" and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2004

Sector/Gas	1990	1998	1999	2000	2001	2002	2003	2004	Percent[a]
Industry	**2,074.6**	**2,210.3**	**2,174.4**	**2,186.1**	**2,073.6**	**2,042.0**	**2,066.0**	**2,103.0**	**29.7%**
Direct Emissions	1,438.9	1,452.4	1,411.0	1,409.7	1,366.6	1,346.7	1,342.7	1,377.3	19.5%
CO_2	1,082.3	1,120.8	1,098.4	1,099.2	1,081.4	1,062.0	1,065.4	1,101.3	15.6%
CH_4	253.8	230.0	221.3	223.2	219.7	215.3	216.0	211.3	3.0%
N_2O	41.1	35.5	34.2	34.3	29.4	31.6	31.4	31.0	0.4%
HFCs, PFCs, and SF_6	61.8	66.1	57.1	53.0	36.0	37.7	30.0	33.7	0.5%
Electricity-Related	635.7	757.9	763.4	776.5	707.0	695.4	723.3	725.7	10.3%
CO_2	622.9	748.7	754.4	767.9	699.1	687.8	715.6	718.1	10.2%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.8	3.2	3.2	3.3	3.0	2.9	3.1	3.1	+
SF_6	9.9	5.8	5.5	5.1	4.7	4.4	4.4	4.3	0.1%
Transportation	**1,523.4**	**1,756.5**	**1,822.5**	**1,870.3**	**1,856.2**	**1,901.4**	**1,903.2**	**1,959.8**	**27.7%**
Direct Emissions	1,520.3	1,753.4	1,819.3	1,866.9	1,852.7	1,898.0	1,898.9	1,955.1	27.6%
CO_2	1,473.2	1,672.5	1,734.6	1,778.9	1,764.6	1,809.7	1,811.1	1,865.7	26.4%
CH_4	4.5	3.6	3.4	3.3	3.1	2.9	2.8	2.7	0.0%
N_2O	42.6	53.8	53.0	52.1	48.9	46.4	43.7	41.7	0.6%
HFCs[b]	+	23.5	28.2	32.57	36.10	38.95	41.22	45.03	0.6%
Electricity-Related	3.1	3.1	3.2	3.38	3.44	3.38	4.30	4.69	0.1%
CO_2	3.0	3.1	3.1	3.3	3.4	3.3	4.3	4.6	0.1%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+	+	+
Commercial	**979.2**	**1,102.0**	**1,115.8**	**1,171.8**	**1,190.8**	**1,191.4**	**1,204.3**	**1,211.0**	**17.1%**
Direct Emissions	433.6	428.0	430.6	443.0	439.5	447.5	466.5	459.9	6.5%
CO_2	222.6	217.7	218.6	229.3	224.9	224.3	235.8	226.0	3.2%
CH_4	197.8	177.7	176.0	174.1	171.6	176.4	179.7	178.5	2.5%
N_2O	13.3	15.2	15.7	15.8	15.9	15.9	16.1	16.3	0.2%
HFCs	+	17.4	20.3	23.8	27.1	30.9	34.8	39.0	0.6%
Electricity-Related	545.6	674.0	685.1	728.8	751.3	743.9	737.8	751.1	10.6%
CO_2	534.6	665.9	677.1	720.7	742.9	735.8	729.9	743.3	10.5%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.4	2.8	2.9	3.1	3.2	3.1	3.1	3.2	+
SF_6	8.5	5.1	5.0	4.8	5.0	4.7	4.5	4.4	0.1%
Residential	**950.8**	**1,060.0**	**1,083.2**	**1,140.0**	**1,136.2**	**1,154.1**	**1,182.9**	**1,181.9**	**16.7%**
Direct Emissions	349.4	353.3	372.6	390.4	381.6	380.1	399.8	391.1	5.5%
CO_2	338.0	333.5	352.3	369.9	361.5	360.0	378.8	369.6	5.2%
CH_4	4.4	3.1	3.3	3.5	3.1	2.7	3.0	2.9	+
N_2O	6.7	7.0	7.1	7.0	6.7	6.8	7.0	7.3	0.1%
HFCs	0.3	9.6	9.8	10.1	10.3	10.6	11.0	11.3	0.2%
Electricity-Related	601.4	706.7	710.7	749.6	754.6	773.9	783.1	790.8	11.2%
CO_2	589.2	698.1	702.3	741.3	746.1	765.5	774.8	782.6	11.1%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.6	3.0	3.0	3.2	3.2	3.3	3.3	3.3	+
SF_6	9.3	5.4	5.2	4.9	5.1	4.9	4.8	4.7	0.1%
Agriculture	**547.1**	**602.4**	**575.0**	**567.2**	**582.6**	**574.5**	**544.3**	**556.9**	**7.9%**
Direct Emissions	486.3	541.6	523.9	509.5	514.4	511.0	484.2	491.3	6.9%
CO_2	46.3	57.4	59.8	50.2	50.2	52.3	44.3	50.3	0.7%
CH_4	157.0	164.4	164.2	162.1	162.1	161.7	162.1	160.6	2.3%
N_2O	283.1	319.7	299.9	297.2	302.2	297.0	277.8	280.4	4.0%
Electricity-Related	60.7	60.7	50.9	57.6	68.0	63.4	60.0	65.4	**0.9%**
CO_2	59.5	59.9	50.3	56.9	67.3	62.8	59.3	64.7	0.9%
CH_4	+	+	+	+	+	+	+	+	+

N_2O	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.3	+
SF_6	0.9	0.5	0.4	0.4	0.5	0.4	0.4	0.4	+
U.S. Territories	**33.8**	**42.7**	**44.2**	**46.9**	**54.0**	**52.4**	**58.6**	**61.9**	**0.9%**
CO_2	33.8	42.7	44.2	46.9	54.0	52.4	58.6	61.9	0.9%
Total	**6,109.0**	**6,773.7**	**6,814.9**	**6,982.3**	**6,893.1**	**6,915.8**	**6,959.1**	**7,074.4**	**100.0%**

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.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05%.
[a] Percents for year 2004.
[b] Includes primarily HFC-134a.

Transportation

Transportation activities accounted for 28 percent of U.S. greenhouse gas emissions in 2004. Table 2-17 provides a detailed summary of greenhouse gas emissions from transportation-related activities. Total emissions in Table 2-17 differ slightly from those shown in Table 2-16 primarily because the table below excludes a few minor non-transportation mobile sources, such as construction and industrial equipment.

From 1990 to 2004, transportation emissions rose by 29 percent due, in part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration (FHWA). Likewise, the number of miles driven (up 38 percent from 1990 to 2004) and the gallons of gasoline consumed each year in the United States have increased steadily since the 1980s, according to the FHWA and Energy Information Administration, respectively. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, urban sprawl, low fuel prices, and increasing popularity of sport utility vehicles and other light-duty trucks that tend to have lower fuel efficiency. 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 nearly two-thirds 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 27 percent from 1990 to 2004. This rise in CO_2 emissions, combined with an increase of 45.0 Tg CO_2 Eq. in HFC emissions over the same period, led to an increase in overall emissions from transportation activities of 29 percent.

Table 2-17: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**1,476.2**	**1,675.6**	**1,737.8**	**1,782.3**	**1,768.1**	**1,813.1**	**1,815.5**	**1,870.4**
Passenger Cars	618.9	621.5	631.2	633.4	636.5	651.6	631.3	636.4
Light-Duty Trucks	315.8	437.3	455.0	458.3	462.2	474.8	509.6	526.0
Other Trucks	225.3	306.5	322.4	337.9	337.0	351.0	347.3	365.3
Buses	8.2	9.8	11.0	10.8	9.9	9.5	10.3	10.3
Aircraft[a]	177.2	181.3	186.8	193.2	183.5	174.9	171.8	179.6
Ships and Boats	43.6	27.3	37.5	55.1	48.1	57.0	49.7	54.4
Locomotives	37.8	43.0	44.6	44.6	44.8	45.2	47.1	49.8
Other[b]	49.5	48.8	49.4	48.9	46.2	49.0	48.4	48.7
International Bunker Fuels[c]	*93.6*	*103.3*	*102.6*	*102.2*	*98.5*	*89.5*	*84.1*	*94.5*
CH_4	**4.5**	**3.6**	**3.4**	**3.3**	**3.1**	**2.9**	**2.8**	**2.7**
Passenger Cars	2.6	1.8	1.7	1.6	1.5	1.4	1.3	1.3
Light-Duty Trucks	1.4	1.3	1.2	1.1	1.1	1.0	0.9	0.9
Other Trucks and Buses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Aircraft	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1
Ships and Boats	0.1	+	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Motorcycles	+		+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*		*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**42.7**		**53.9**	**53.1**	**52.1**	**48.9**	**46.4**	**43.7**	**41.6**
Passenger Cars	25.4		26.7	25.9	25.1	23.9	22.9	21.8	21.0
Light-Duty Trucks	14.1		23.7	23.5	23.1	21.2	19.7	18.1	16.7
Other Trucks and Buses	0.8		1.2	1.2	1.2	1.3	1.3	1.3	1.3
Aircraft	1.7		1.8	1.8	1.9	1.8	1.7	1.7	1.8
Ships and Boats	0.4		0.2	0.3	0.4	0.4	0.5	0.4	0.4
Locomotives	0.3		0.3	0.3	0.3	0.3	0.3	0.3	0.4
Motorcycles	+		+	+	+	+	+	+	+
International Bunker Fuels[c]	*1.0*		*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*
HFCs	+		23.5	28.2	32.6	36.1	38.9	41.2	45.0
Mobile Air Conditioners[d]	+		16.5	19.7	22.8	25.3	27.4	28.9	31.9
Refrigerated Transport	+		7.0	8.5	9.8	10.8	11.5	12.3	13.1
Total	**1,523.4**		**1,756.6**	**1,822.6**	**1,870.3**	**1,856.2**	**1,901.4**	**1,903.1**	**1,959.8**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

[b] "Other" CO_2 emissions include motorcycles, pipelines, and lubricants.

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

[d] Includes primarily HFC-134a.

[BEGIN BOX]

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

In order to aggregate emissions by economic sector, source category emission estimates were generated according to the methodologies outlined in the appropriate sections of this report. Those emissions were then simply reallocated into economic sectors. In most cases, the IPCC subcategories distinctly fit into an apparent economic sector category. Several exceptions exist, and the methodologies used to disaggregate these subcategories are described below:

- *Agricultural CO_2 Emissions from Fossil Fuel Combustion, and non-CO_2 emissions from Stationary and Mobile Combustion.* Emissions from on-farm energy use were accounted for in the Energy chapter as part of the industrial and transportation end-use sectors. To calculate agricultural emissions related to fossil fuel combustion, energy consumption estimates were obtained from economic survey data from the U.S. Department of Agriculture (Duffield 2005) and fuel sales data (EIA 1991 through 2005). To avoid double-counting, emission estimates of CO_2 from fossil fuel combustion and non-CO_2 from stationary and mobile sources were subtracted from the industrial economic sector, although some of these fuels may have been originally accounted for under the transportation end-use sector.

- *Landfills, Wastewater Treatment, and Human Sewage.* CH_4 emissions from landfills and wastewater treatment, as well as N_2O emissions from human sewage, were allocated to the commercial sector.

- *Waste Combustion.* CO_2 and N_2O emissions from waste combustion were allocated completely to the electricity generation sector since nearly all waste combustion occurs in waste-to-energy facilities.

- *Limestone and Dolomite Use.* CO_2 emissions from limestone and dolomite use are allocated to the electricity generation (50 percent) and industrial (50 percent) sectors, because 50 percent of the total emissions for this source are used in flue gas desulfurization.

- *Substitution of Ozone Depleting Substances.* All greenhouse gas emissions resulting from the substitution of ozone depleting substances were placed in the industrial economic sector, with the exception of emissions from domestic, commercial, mobile and transport refrigeration/air-conditioning systems, which were placed in the residential, commercial, and transportation sectors, respectively. Emissions from non-MDI aerosols were attributed to the residential economic sector.

- *Settlement Soil Fertilization, Forest Soil Fertilization.* Emissions from settlement soil fertilization were allocated to the residential economic sector; forest soil fertilization was allocated to the agriculture economic sector.

[END BOX]

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

The reporting requirements of the UNFCCC[6] 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 nitrous oxide (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 carbon monoxide'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),[7] which are regulated under the Clean Air Act. Table 2-18 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs.

Table 2-18: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1998	1999	2000	2001	2002	2003	2004
NO_x	**22,860**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**17,995**	**17,076**
Stationary Fossil Fuel Combustion	9,884	9,419	8,344	8,002	7,667	7,522	7,138	6,662
Mobile Fossil Fuel Combustion	12,134	11,592	11,300	11,395	10,823	10,389	9,916	9,465
Oil and Gas Activities	139	130	109	111	113	135	135	135

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

[7] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2004).

Waste Combustion	82	145	143	114	114	134	134	134
Industrial Processes	591	637	595	626	656	630	631	632
Solvent Use	1	3	3	3	3	6	6	6
Agricultural Burning	28	35	34	35	35	33	34	39
Waste	+	3	3	2	2	2	2	2
CO	**130,580**	**98,984**	**94,361**	**92,895**	**89,329**	**87,428**	**87,518**	**87,599**
Stationary Fossil Fuel Combustion	4,999	3,927	5,024	4,340	4,377	4,020	4,020	4,020
Mobile Fossil Fuel Combustion	119,482	87,940	83,484	83,680	79,972	78,574	78,574	78,574
Oil and Gas Activities	302	332	145	146	147	116	116	116
Waste Combustion	978	2,826	2,725	1,670	1,672	1,672	1,672	1,672
Industrial Processes	4,124	3,163	2,156	2,217	2,339	2,286	2,286	2,286
Solvent Use	4	1	46	46	45	46	46	46
Agricultural Burning	689	789	767	790	770	706	796	877
Waste	1	5	13	8	8	8	8	8
NMVOCs	**20,937**	**16,403**	**15,869**	**15,228**	**15,048**	**14,217**	**13,877**	**13,556**
Stationary Fossil Fuel Combustion	912	1,016	1,045	1,077	1,080	923	922	922
Mobile Fossil Fuel Combustion	10,933	7,742	7,586	7,230	6,872	6,560	6,212	5,882
Oil and Gas Activities	555	440	414	389	400	340	341	341
Waste Combustion	222	326	302	257	258	281	282	282
Industrial Processes	2,426	2,047	1,813	1,773	1,769	1,723	1,725	1,727
Solvent Use	5,217	4,671	4,569	4,384	4,547	4,256	4,262	4,267
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	673	161	140	119	122	133	134	134
SO_2	**20,936**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,208**	**13,910**
Stationary Fossil Fuel Combustion	18,407	15,191	13,915	12,848	12,461	11,946	12,220	11,916
Mobile Fossil Fuel Combustion	793	665	704	632	624	631	637	644
Oil and Gas Activities	390	310	283	286	289	315	315	315
Waste Combustion	39	30	30	29	30	24	24	24
Industrial Processes	1,306	991	984	1,031	1,047	1,009	1,009	1,009
Solvent Use	+	1	1	1	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	+	1	1	1	1	1	1	1

Source: (EPA 2005) except for estimates from field burning of agricultural residues.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

[BEGIN BOX]

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 86 percent in 2004. 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.

[END BOX]

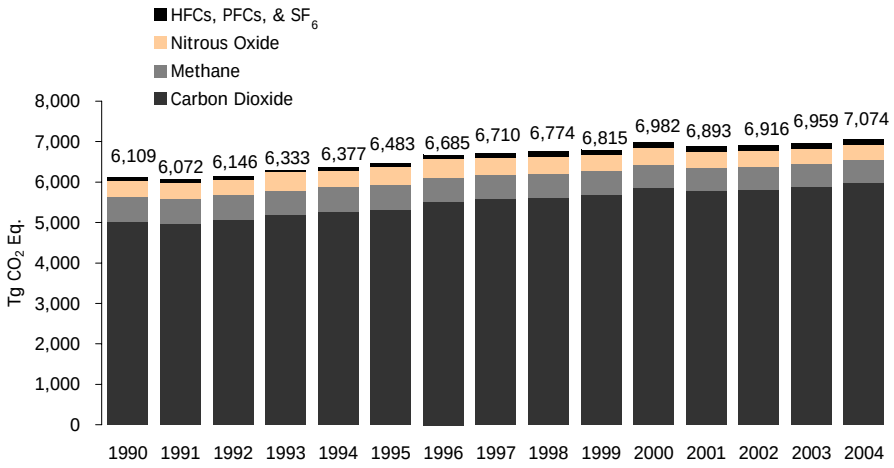


Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

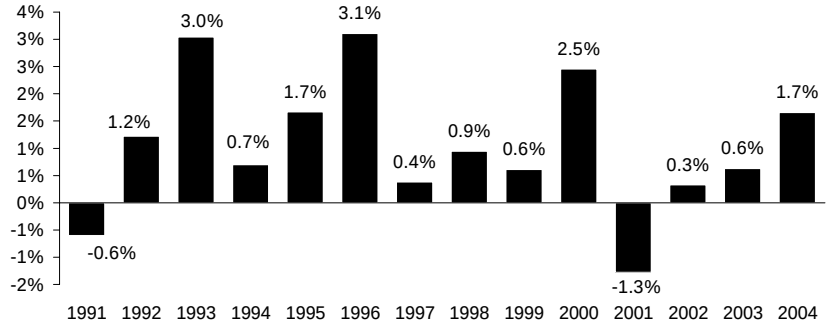


Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

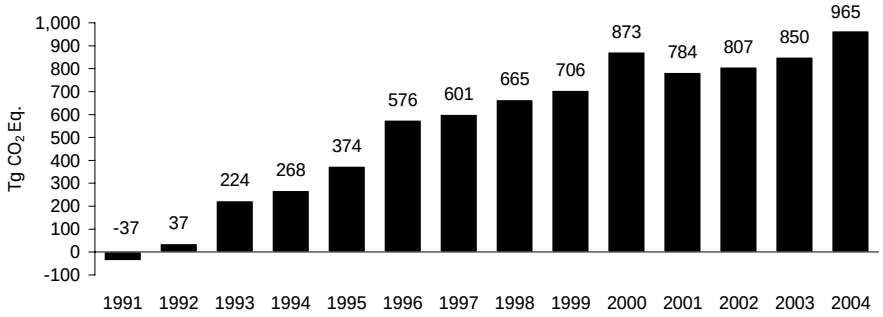


Figure 2-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

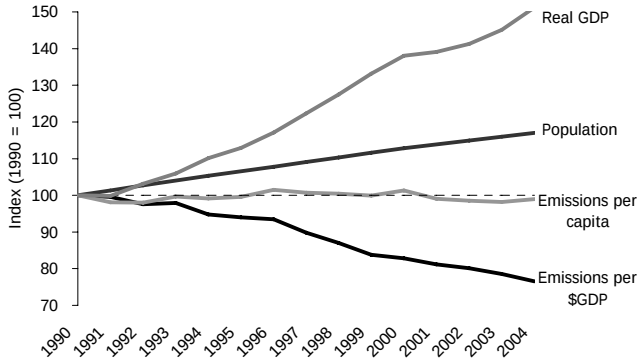
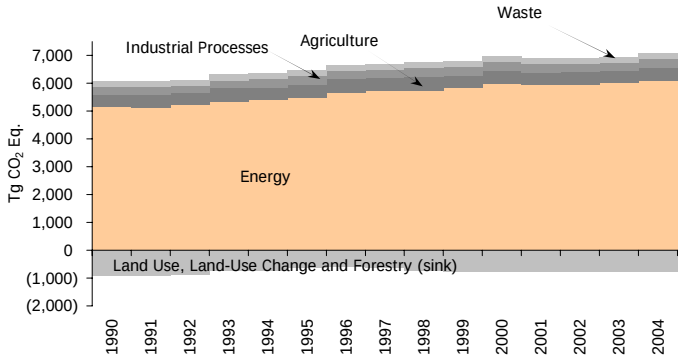


Figure 2-4: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



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

Figure 2-5: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

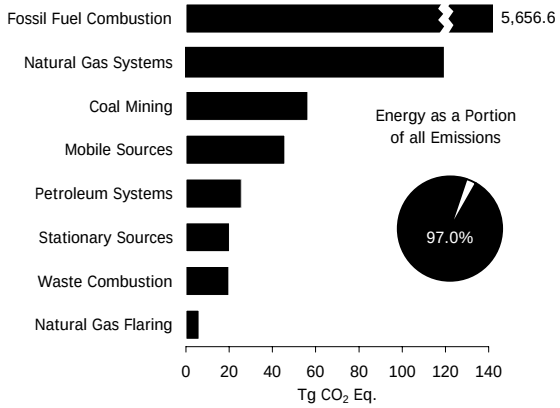
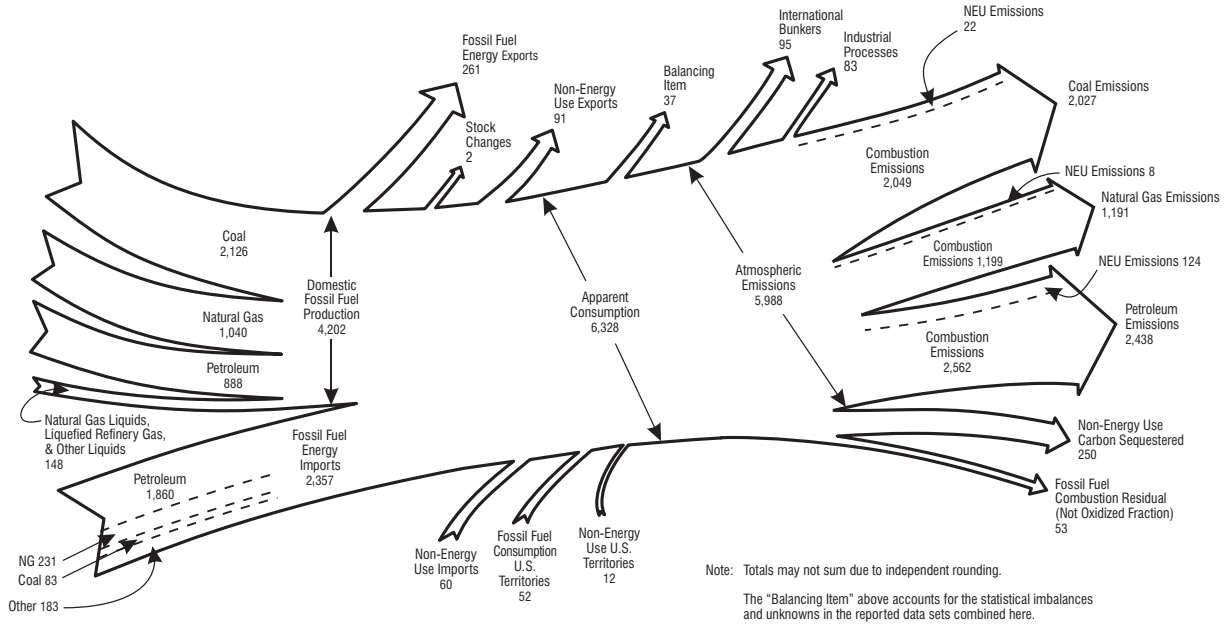


Figure 2-6: 2004 Energy Sector Greenhouse Gas Sources

Figure 2-7

2004 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

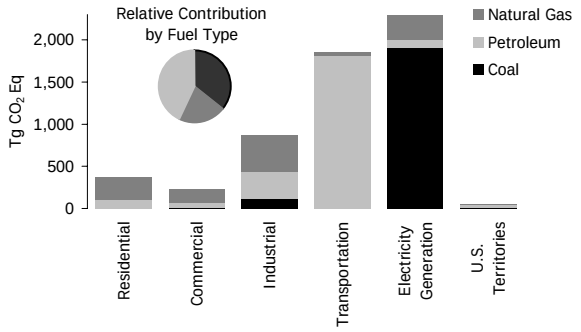


Figure 2-8: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricit

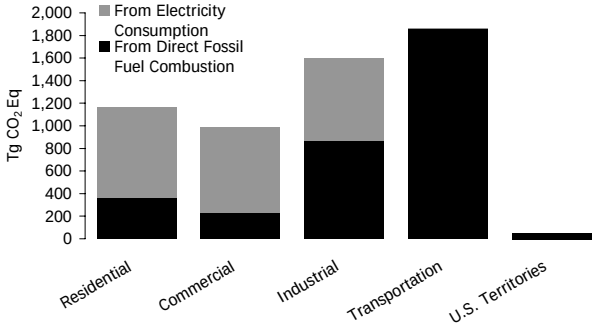


Figure 2-9: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

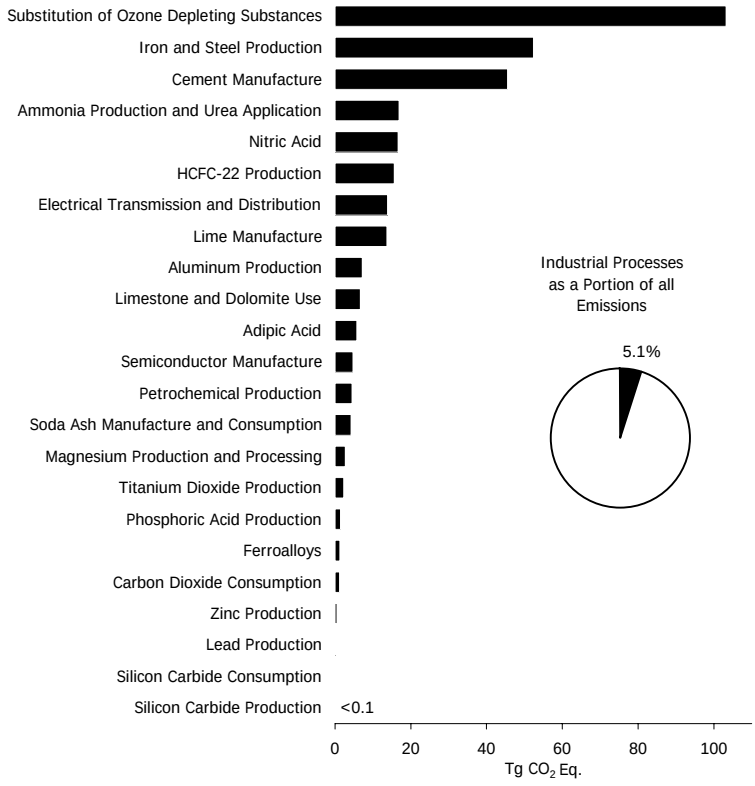


Figure 2-10: 2004 Industrial Processes Chapter Greenhouse Gas Sources

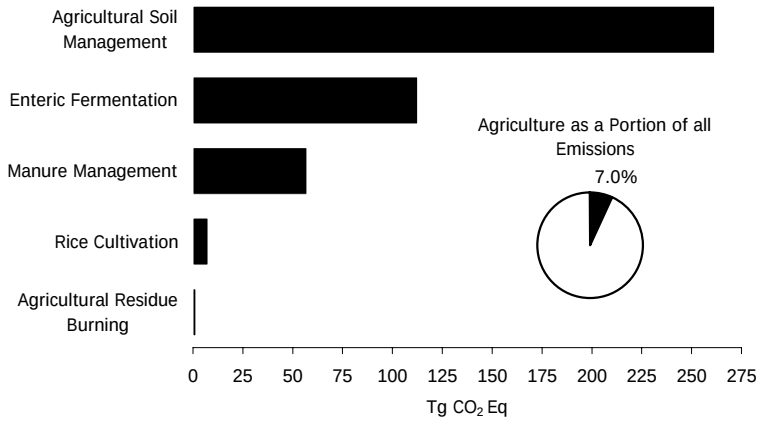


Figure 2-11: 2004 Agriculture Chapter GHG Sources

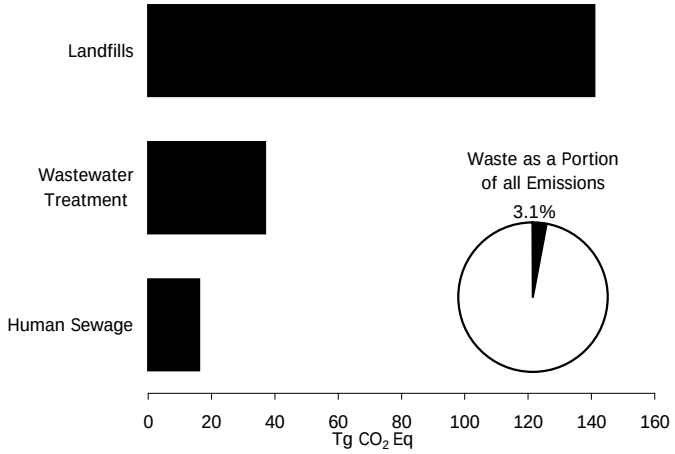


Figure 2-12: 2004 Waste Chapter Greenhouse Gas Sources

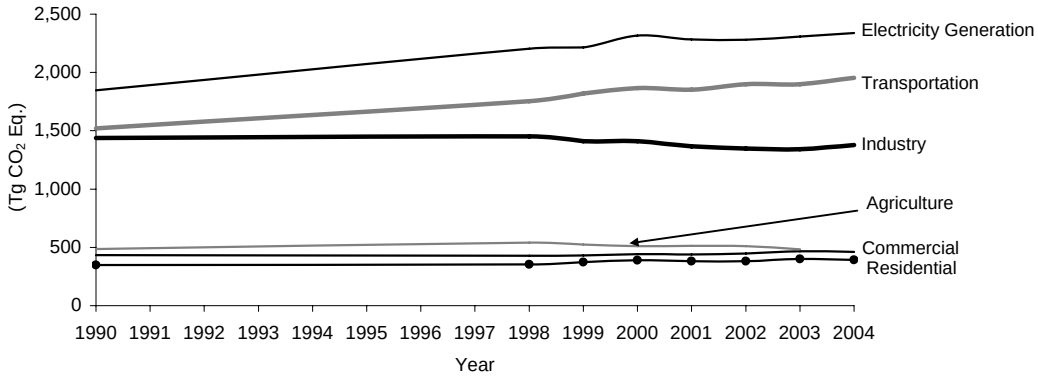


Figure 2-13: Emissions Allocated to Economic Sectors

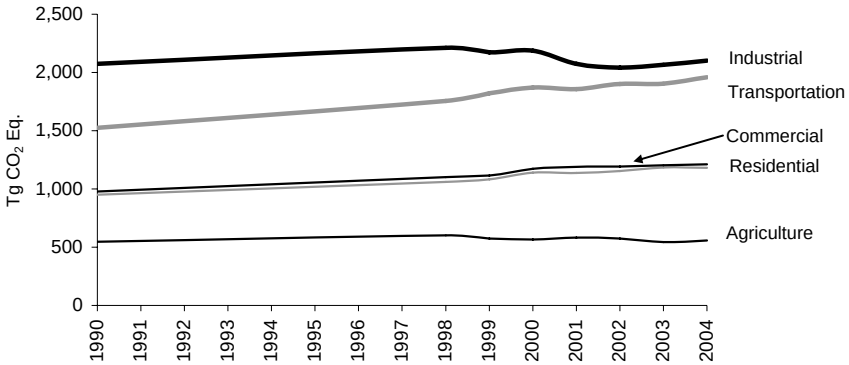


Figure 2-14: Emissions with Electricity Distributed to Economic Sectors

Descriptions of Figures: Trends in Greenhouse Gas Emissions

Figure 2-1 illustrates U.S. greenhouse gas emissions by gas, with a cumulative total of CO_2 equivalent. There is generally an upward trend, starting from 6,109 Tg CO_2 eq. in 1990 and ending with 7,074 Tg CO_2 eq. in 2004. The only exception to this trend is 1991, where emissions were 6,072 Tg CO_2 eq, down from 6,109 Tg CO_2 eq in 1990. They increased again in 1992 to 6,146 Tg CO_2 eq.

Figure 2-2 depicts the annual percent change in U.S. greenhouse gas emissions since 1990. The change in 1991 was -0.6%. In 1992, it was 1.2%. In 1993, it was 3.0%. In 1994, it was 0.7%. In 1995, it was 1.7%. In 1996, it was 3.1%. In 1997, it was 0.4%. In 1998, it was 0.9%. In 1999, it was 0.6%. In 2000, it was 2.5%. In 2001, it was -1.3%. In 2002, it was 0.3%, in 2003, it was 0.6%, and in 2004, it was 1.7%.

Figure 2-3 depicts the absolute change in U.S. greenhouse gas emissions since 1990. The change in 1991 was -37 Tg CO_2 Eq. In 1992, it was 37 Tg CO_2 Eq. In 1993, it was 224 Tg CO_2 Eq. In 1994, it was 268 Tg CO_2 Eq . In 1995, it was 374 Tg CO_2 Eq . In 1996, it was 576 Tg CO_2 Eq. In 1997, it was 601 Tg CO_2 Eq. In 1998, it was 665 Tg CO_2 Eq. In 1999, it was 706 Tg CO_2 Eq. In 2000, it was 873 Tg CO_2 Eq. In 2001, it was 784 Tg CO_2 Eq. In 2002, it was 807 Tg CO_2 Eq. In 2003, it was 850 Tg CO_2 Eq. and in 2004, it was 965 Tg CO_2 Eq.

Figure 2-4 illustrates U.S. greenhouse gas emissions per capita and per dollar of gross domestic product. Emissions per dollar GDP have gradually decreased from 1990 until 2004. Emissions per capita have remained relatively steady from 1990 until 2003. Population has steadily increased from 1990 until 2004. Real GDP from 1990 through 2004 has increased at a higher rate than population, with the graph illustrating an upward sloping line with a short plateau in 2000 and 2001.

Figure 2-5 illustrates the data presented in Table 2-5, Recent Trends in U.S. greenhouse gas emissions and sinks by chapter/IPCC sector.

Figure 2-6 illustrates U.S. energy sector greenhouse gas sources for 2004. Fossil fuel combustion is the greatest contributor, followed by natural gas systems and coal mining. This figure also includes a pie chart, which illustrates that the energy sector represents 97.0% of all emissions.

For a detailed description of Figure 2-7, refer to the description of Figure 3-2 in Chapter 3.

For a detailed description of Figure 2-8, refer to the description of Figure 3-5 in Chapter 3.

For a detailed description of Figure 2-9, refer to the description of Figure 3-9 in Chapter 3.

For a detailed description of Figure 2-11, refer to the description of Figure 6-1 in Chapter 6.

For a detailed description of Figure 2-12, refer to the description of Figure 8-1 in Chapter 8.

Figure 2-13 illustrates the data presented in Table 2-14, U.S. greenhouse gas emissions allocated to economic Sectors from 1990 through 2004.

Figure 2-14 illustrates the data presented in Table 2-16, U.S Greenhouse Gas Emissions by “Economic Sector” and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and percent of total in 2004.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 86 percent of total emissions on a carbon equivalent basis in 2004. This included 97, 39, and 15 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 82 percent of national emissions from all sources on a carbon 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 25,575 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2002, of which the United States accounted for about 23 percent.[1] Due to the relative importance of fossil fuel combustion-related CO_2 emissions, they 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.

Figure 3-1: 2004 Energy Sector Greenhouse Gas Sources

Figure 3-2: 2004 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive 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. CO_2 emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the carbon 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 carbon cycle are accounted for within the Land Use, Land-Use Change, and Forestry chapter. Emissions of other greenhouse gases from the combustion 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 teragrams 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 6,108.2 Tg CO_2 Eq. in 2004, 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		1998	1999	2000	2001	2002	2003	2004
CO_2	**4,830.5**		**5,448.3**	**5,527.6**	**5,698.1**	**5,642.7**	**5,663.3**	**5,730.0**	**5,835.3**
Fossil Fuel Combustion	4,696.6		5,271.8	5,342.4	5,533.7	5,486.9	5,501.8	5,571.1	5,656.6
Non-Energy Use of Fuels	117.2		152.8	160.6	140.7	131.0	136.5	133.5	153.4
Waste Combustion	10.9		17.1	17.6	17.9	18.6	18.9	19.4	19.4

[1] Global CO_2 emissions from fossil fuel combustion were taken from Marland *et al.* (2003) <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>.

Natural Gas Flaring	5.8	6.6	6.9	5.8	6.1	6.2	6.1	6.0
*Biomass-Wood**	*212.5*	*209.5*	*214.3*	*217.6*	*190.8*	*182.9*	*186.3*	*191.7*
*International Bunker Fuels**	*113.5*	*114.6*	*105.2*	*101.4*	*97.8*	*89.5*	*84.1*	*94.5*
*Biomass-Ethanol**	*4.2*	*7.7*	*8.0*	*9.2*	*9.7*	*11.5*	*15.8*	*19.5*
CH_4	**261.6**	**235.4**	**226.8**	**228.7**	**225.0**	**220.1**	**220.9**	**215.8**
Natural Gas Systems	126.7	125.4	121.7	126.7	125.6	125.4	124.7	118.8
Coal Mining	81.9	62.8	58.9	56.3	55.5	52.5	54.8	56.3
Petroleum Systems	34.4	29.7	28.5	27.8	27.4	26.8	25.9	25.7
Stationary Sources	7.9	6.8	7.0	7.3	6.6	6.2	6.5	6.4
Mobile Sources	6.0	6.9	6.9	7.2	6.6	6.0	5.8	5.6
Abandoned Coal Mines	4.7	3.8	3.6	3.5	3.3	3.2	3.0	2.9
*International Bunker Fuels**	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.2**	**68.6**	**67.9**	**67.5**	**63.9**	**61.3**	**58.9**	**57.0**
Mobile Sources	43.5	54.8	54.1	53.1	50.0	47.5	44.8	42.8
Stationary Sources	12.3	13.4	13.4	13.9	13.5	13.2	13.6	13.7
Waste Combustion	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5
*International Bunker Fuels**	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*
Total	**5,148.3**	**5,752.3**	**5,822.3**	**5,994.3**	**5,931.6**	**5,944.6**	**6,009.8**	**6,108.2**

* 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	1998	1999	2000	2001	2002	2003	2004
CO_2	**4,830,464**	**5,448,279**	**5,527,589**	**5,698,086**	**5,642,664**	**5,663,284**	**5,730,029**	**5,835,335**
Fossil Fuel Combustion	4,696,571	5,271,819	5,342,446	5,533,710	5,486,908	5,501,763	5,571,088	5,656,554
Non-Energy Use of Fuels	117,168	152,800	160,569	140,687	131,028	136,455	133,489	153,386
Waste Combustion	10,919	17,094	17,632	17,921	18,634	18,862	19,360	19,360
Natural Gas Flaring	5,805	6,566	6,943	5,769	6,094	6,204	6,091	6,034
*Biomass-Wood**	*212,547*	*209,490*	*214,323*	*217,577*	*190,778*	*182,878*	*186,339*	*191,737*
*International Bunker Fuels**	*113,503*	*114,557*	*105,228*	*101,366*	*97,815*	*89,489*	*84,083*	*94,499*
*Biomass-Ethanol**	*4,155*	*7,711*	*8,017*	*9,188*	*9,701*	*11,473*	*15,771*	*19,493*
CH_4	**12,459**	**11,211**	**10,800**	**10,893**	**10,715**	**10,480**	**10,517**	**10,277**
Natural Gas Systems	6,034	5,973	5,797	6,033	5,981	5,971	5,939	5,658
Coal Mining	3,900	2,990	2,807	2,679	2,644	2,500	2,611	2,682
Petroleum Systems	1,640	1,414	1,358	1,325	1,303	1,274	1,236	1,222
Stationary Sources	374	325	335	346	316	295	311	307
Mobile Sources	286	328	330	343	313	288	277	269
Abandoned Coal Mines	224	181	173	167	159	152	144	140
*International Bunker Fuels**	*8*	*7*	*6*	*6*	*5*	*4*	*4*	*5*
N_2O	**181**	**221**	**219**	**218**	**206**	**198**	**190**	**184**
Mobile Combustion	140	177	174	171	161	153	144	138
Stationary Combustion	40	43	43	45	44	43	44	44
Waste Combustion	2	1	1	1	1	2	2	2
*International Bunker Fuels**	*3*	*3*	*3*	*3*	*3*	*3*	*2*	*3*

* 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. Carbon Dioxide Emissions from Fossil Fuel Combustion (IPCC Source Category 1A)

CO_2 emissions from fossil fuel combustion in 2004 increased by 1.5 percent from the previous year. This increase is primarily a result of increased demand for fuels due to a growing economy, expanding industrial production, and increased demand for transportation. In 2004, CO_2 emissions from fossil fuel combustion were 5,656.6 Tg CO_2 Eq.,

or 20 percent above emissions in 1990 (see Table 3-3).[2]

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

Fuel/Sector	1990	1998	1999	2000	2001	2002	2003	2004
Coal	**1,683.8**	**1,944.0**	**1,946.2**	**2,033.8**	**1,982.5**	**1,976.8**	**2,017.4**	**2,027.0**
Residential	2.9	1.2	1.3	1.0	1.1	1.0	0.9	1.0
Commercial	11.6	9.5	9.6	8.1	8.6	8.6	7.9	8.2
Industrial	151.3	131.1	126.7	127.2	126.1	116.4	117.7	117.1
Transportation	NE	NE	NE	NE	NE	NE	NE	NE
Electricity Generation	1,517.3	1,801.2	1,807.7	1,896.6	1,845.9	1,849.6	1,887.2	1,897.1
U.S. Territories	0.6	1.0	0.9	0.9	0.9	1.2	3.6	3.6
Natural Gas	**1,006.9**	**1,168.4**	**1,172.2**	**1,220.2**	**1,173.4**	**1,211.4**	**1,184.8**	**1,191.2**
Residential	238.6	246.6	256.4	269.2	259.0	265.6	276.9	265.5
Commercial	142.4	163.6	165.3	171.8	164.9	170.8	175.4	162.7
Industrial	413.2	474.1	453.9	461.7	424.8	431.2	416.1	428.4
Transportation	35.9	35.1	35.6	35.5	33.9	37.1	37.3	37.4
Electricity Generation	176.9	249.1	260.9	281.4	289.5	305.6	277.6	295.8
U.S. Territories	NO	NO	NO	0.7	1.2	1.2	1.4	1.3
Petroleum	**2,005.5**	**2,159.0**	**2,223.7**	**2,279.3**	**2,330.6**	**2,313.2**	**2,368.5**	**2,438.0**
Residential	96.5	85.8	94.6	99.7	101.4	93.3	100.9	103.0
Commercial	68.5	44.6	43.7	49.3	51.4	45.0	52.5	55.1
Industrial	286.7	266.7	268.4	273.7	310.2	294.6	310.8	318.0
Transportation	1,425.5	1,625.2	1,686.8	1,731.4	1,719.7	1,761.7	1,763.8	1,818.1
Electricity Generation	100.9	104.2	96.6	91.0	101.6	77.8	97.0	97.3
U.S. Territories	27.4	32.5	33.6	34.2	46.4	40.7	43.7	46.5
Geothermal*	**0.40**	**0.38**	**0.38**	**0.36**	**0.35**	**0.37**	**0.37**	**0.37**
Total	**4,696.6**	**5,271.8**	**5,342.4**	**5,533.7**	**5,486.9**	**5,501.8**	**5,571.1**	**5,656.6**

NE (Not estimated)
NO (Not occurring)
+ Does not exceed 0.05 Tg CO_2 Eq.
* 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.

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

Longer-term changes in energy 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, and size 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).

CO_2 emissions also depend on the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55

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

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 3-4 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-4: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2000 to 2001		2001 to 2002		2002 to 2003		2003 to 2004	
Electricity Generation	Coal	-50.7	-3%	3.8	0%	37.5	2%	9.9	1%
Electricity Generation	Natural Gas	8.2	3%	16.1	6%	-28.0	-9%	18.2	7%
Electricity Generation	Petroleum	10.5	12%	-23.7	-23%	19.2	25%	0.3	0%
Transportation[a]	Petroleum	-11.7	-1%	42.0	2%	2.0	0%	54.3	3%
Residential	Natural Gas	-10.2	-4%	6.6	3%	11.4	4%	-11.4	-4%
Commercial	Natural Gas	-6.9	-4%	5.9	4%	4.6	3%	-12.7	-7%
Industrial	Coal	-1.1	-1%	-9.7	-8%	1.4	1%	-0.7	-1%
Industrial	Natural Gas	-36.8	-8%	6.3	1%	-15.0	-3%	12.3	3%
All Sectors[b]	**All Fuels[b]**	**-46.8**	**-1%**	**14.9**	**0%**	**69.3**	**1%**	**85.5**	**2%**

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

In the United States, 86 percent of the energy consumed in 2004 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 (6 percent), primarily hydroelectric power and biofuels (EIA 2005a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 39 percent of total energy consumption from 1990 through 2004. Natural gas and coal followed in order of importance, accounting for 24 and 23 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 2005a).

Figure 3-3: 2004 U.S. Energy Consumption by Energy Source

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

Figure 3-5: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the carbon 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 carbon 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, except for the soot and ash left behind during the combustion process, all the carbon in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

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

[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.

[BEGIN BOX]

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

In 2004, weather conditions became milder in both the winter and summer. Warmer winter conditions led to a decrease in demand for heating fuels. Though the summer of 2004 was cooler than the previous year, demand for electricity still increased, likely due to the growing economy. The winter was warmer than usual, with heating degree days in the United States 5 percent below normal (see Figure 3-6). Summer temperatures were slightly warmer than usual, with cooling degree days 1 percent above normal (see Figure 3-7) (EIA 2005f).[5]

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1949-2004)

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1949-2004)

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[6]) of existing plants reached record levels in 2004, at over 90 percent. Electricity output by hydroelectric power plants increased in 2004 by approximately 10 percent. Electricity generated by nuclear plants in 2004 provided almost 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2005a). 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 (1973-2004)

[END BOX]

For the purpose of international reporting, the Intergovernmental Panel on Climate Change (IPCC) (IPCC/UNEP/OECD/IEA 1997) recommends that particular adjustments be made to national fuel consumption statistics. Certain fossil fuels can be manufactured into plastics, asphalt, lubricants, or other products. A portion of the carbon consumed for these non-energy products can be stored (i.e., sequestered) indefinitely. To account for the fact that the carbon in these fuels ends up in products instead of being combusted (i.e., oxidized and released into the atmosphere), consumption of fuels for non-energy purposes is estimated and subtracted from total fuel consumption estimates. Emissions from non-energy uses of fuels are estimated in the Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter.

According to the UNFCCC reporting guidelines, CO_2 emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) should be reported separately, and not included in national emission totals. Estimates of international bunker fuel emissions for the United States are

[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 affect 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 2005a).

provided in Table 3-5.

Table 3-5: CO_2 Emissions from International Bunker Fuels (Tg CO_2 Eq.)*

Vehicle Mode	1990		1998	1999	2000	2001	2002	2003	2004
Aviation	46.2		56.7	58.8	60.5	59.3	61.8	59.4	59.9
Marine	67.3		57.9	46.4	40.9	38.5	27.7	24.6	34.6
Total	**113.5**		**114.6**	**105.2**	**101.4**	**97.8**	**89.5**	**84.1**	**94.5**

* See International Bunker Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

End-Use Sector Consumption

An alternative method of presenting CO_2 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. For the discussion below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption. This method of distributing emissions assumes that each sector consumes electricity generated from an equally carbon-intensive mix of fuels and other energy sources. After the end-use sectors are discussed, emissions from electricity generation are addressed separately. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table 3-6 and Figure 3-9 summarize CO_2 emissions from direct fossil fuel combustion and pro-rated electricity generation emissions from electricity consumption by end-use sector.

Table 3-6: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990		1998	1999	2000	2001	2002	2003	2004
Transportation	**1,464.4**		**1,663.4**	**1,725.6**	**1,770.3**	**1,757.0**	**1,802.2**	**1,805.4**	**1,860.2**
Combustion	1,461.4		1,660.3	1,722.4	1,766.9	1,753.6	1,798.8	1,801.0	1,855.5
Electricity	3.0		3.1	3.2	3.4	3.5	3.4	4.3	4.7
Industrial	**1,528.3**		**1,634.5**	**1,613.5**	**1,642.8**	**1,574.9**	**1,542.8**	**1,572.4**	**1,595.0**
Combustion	851.1		871.9	849.0	862.6	861.2	842.1	844.6	863.5
Electricity	677.2		762.6	764.5	780.3	713.7	700.7	727.7	731.5
Residential	**922.8**		**1,044.5**	**1,064.0**	**1,123.2**	**1,123.2**	**1,139.8**	**1,166.6**	**1,166.8**
Combustion	338.0		333.5	352.3	369.9	361.5	360.0	378.8	369.6
Electricity	584.8		711.0	711.7	753.3	761.7	779.8	787.9	797.2
Commercial	**753.1**		**895.9**	**904.8**	**961.6**	**983.3**	**973.9**	**978.1**	**983.1**
Combustion	222.6		217.7	218.6	229.3	224.9	224.3	235.8	226.0
Electricity	530.5		678.2	686.2	732.4	758.4	749.6	742.2	757.2
U.S. Territories	**28.0**		**33.5**	**34.5**	**35.8**	**48.5**	**43.1**	**48.7**	**51.4**
Total	**4,696.6**		**5,271.8**	**5,342.4**	**5,533.7**	**5,486.9**	**5,501.8**	**5,571.1**	**5,656.6**
Electricity Generation	**1,795.5**		**2,154.9**	**2,165.6**	**2,269.3**	**2,237.3**	**2,233.5**	**2,262.2**	**2,290.6**

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.

Figure 3-9: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Transportation End-Use Sector

Using this allocation method, the transportation end-use sector accounted for 1,860.2 Tg CO_2 in 2004, or

approximately 33 percent of total CO_2 emissions from fossil fuel combustion, the largest share of any end-use economic sector.[7] Between 1990 and 2004, transportation CO_2 emissions increased by 395.8 Tg CO_2, representing approximately 40 percent of the growth in energy-related CO_2 emissions from all sectors. Almost all of the energy consumed in the transportation sector was petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil.

Table 3-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. As detailed in the table, overall transportation CO_2 emissions increased by 27 percent from 1990 to 2004, representing an average annual increase of 1.7 percent. Between 2003 and 2004 transportation CO_2 emissions increased by just over 3.0 percent.

Transportation fuel consumption is broadly affected by travel activity and the amount of energy vehicles use to move people and goods by various travel modes. In the short-term, changes transportation energy consumption and CO_2 emissions primarily reflect variation in travel activity that accompanies year-to-year economic fluctuations. Long-term factors, especially the cost of fuel (see Figure 3-10), can impact travel patterns and vehicle energy efficiency. Since 1990, there has been a significant increase in vehicle miles traveled (VMT) by light-duty trucks, freight trucks and aircraft. At the same time, the fuel economy of light-duty trucks and freight trucks has remained roughly constant. By contrast, commercial aircraft have become noticeably more fuel efficient.

As shown in Table 3-7, automobiles and light-duty trucks (consuming both gasoline and diesel) accounted for approximately 63 percent of transportation CO_2 emissions in 2004. From 1990 to 2004, carbon dioxide emissions from automobiles and light-duty trucks increased roughly 24 percent (227.7 Tg CO_2). Over this period, VMT by automobile and light-duty trucks increased by 37 percent, outweighing a small increase in overall fleet fuel economy (see Figure 3-11). Much of the small increase in overall fleet fuel economy resulted from the retirement of older, less fuel efficient vehicles.

Carbon dioxide emissions from freight trucks[8] increased by 62 percent (140 Tg) from 1990 to 2004, representing the largest emissions rate increase of any major transportation mode. Fuel economy for the freight truck fleet was relatively constant over this period, while truck VMT increased by 53 percent. Aircraft[9] CO_2 emissions increased by just over one percent (2.3 Tg CO_2) between 1990 and 2004, reflecting a relatively small increase in emissions from commercial aircraft emissions and a decrease in domestic military aircraft emissions. While CO_2 emissions from commercial aircraft grew by approximately 10 percent (11.9 Tg CO_2) from 1990 to 2004, passenger miles traveled increased by 61 percent over the same period, reflecting improvements in the fuel efficiency of planes and an increasing percentage of occupied seats per plane. For further information on all greenhouse gas emissions from transportation sources, please refer to Table A-104 in Annex 3.2.

Figure 3-10: Motor Gasoline Retail Prices (Real)

Figure 3-11: Personal Vehicle Fuel Economy

Table 3-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-eight percent of the emissions from this end-use sector in 2004 were the result of the combustion of motor gasoline in passenger cars and light-duty trucks. Diesel highway vehicles and jet aircraft were

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

[8] Includes "other trucks" fueled by gasoline, diesel and LPG.

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

also significant contributors, respectively accounting for 19 and 12 percent of CO_2 emissions from the transportation end-use sector.[10] For information on transportation-related CO_2 emissions from agriculture and construction equipment, other off-road equipment, and recreational vehicles, please refer to Table A-112 in Annex 3.2.

Table 3-7: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg CO_2 Eq.)

Fuel/Vehicle Type	1990		1998	1999	2000	2001	2002	2003	2004
Gasoline	**964.9**		**1,083.7**	**1,111.1**	**1,117.1**	**1,122.1**	**1,149.1**	**1,152.9**	**1,174.3**
Automobiles	611.2		616.0	626.9	629.8	632.9	647.9	627.2	632.2
Light-Duty Trucks	304.0		420.0	436.3	438.4	441.5	453.1	482.7	497.9
Other Trucks	38.1		34.2	34.4	35.4	34.4	34.9	30.0	31.2
Buses	0.3		0.4	0.4	0.4	0.3	0.3	0.3	0.3
Motorcycles	1.7		1.8	1.8	1.8	1.7	1.6	1.6	1.7
Boats (Recreational)	9.5		11.3	11.3	11.3	11.3	11.2	11.1	11.1
Distillate Fuel Oil (Diesel)	**270.0**		**364.5**	**382.6**	**397.0**	**397.6**	**411.7**	**418.4**	**443.4**
Automobiles	7.7		5.5	4.3	3.6	3.6	3.7	4.1	4.2
Light-Duty Trucks	11.2		16.8	18.4	19.6	20.3	21.4	26.6	27.8
Other Trucks	186.4		271.7	287.5	302.1	302.1	315.6	316.7	333.6
Buses	7.8		9.2	10.3	10.0	9.1	8.6	9.4	9.3
Locomotives	34.8		39.9	41.4	41.2	41.4	41.8	42.8	45.1
Ships & Boats	10.6		9.8	12.5	14.3	15.8	15.6	12.7	16.3
Ships (Bunkers)	11.4		11.5	8.2	6.2	5.2	5.1	6.0	7.0
Jet Fuel	**220.4**		**235.6**	**242.9**	**251.2**	**240.4**	**234.4**	**229.1**	**237.4**
Commercial Aircraft	117.2		126.3	136.4	140.6	132.8	121.7	122.8	129.1
Military Aircraft	34.8		21.5	20.6	21.0	22.8	20.4	20.5	21.1
General Aviation Aircraft	6.3		7.7	9.2	9.2	9.0	9.3	9.3	9.6
Other Aircraft[b]	15.9		23.4	17.9	19.9	16.4	21.2	17.1	17.6
Aircraft (Bunkers)	46.2		56.7	58.8	60.5	59.3	61.8	59.4	59.9
Aviation Gasoline	**3.1**		**2.4**	**2.7**	**2.5**	**2.4**	**2.3**	**2.1**	**2.1**
General Aviation Aircraft	3.1		2.4	2.7	2.5	2.4	2.3	2.1	2.1
Residual Fuel Oil	**79.3**		**52.6**	**51.9**	**64.2**	**54.2**	**52.8**	**44.5**	**54.6**
Ships & Boats[c]	23.4		6.2	13.7	29.6	21.0	30.2	25.9	27.0
Ships (Bunkers)[c]	55.8		46.4	38.2	34.6	33.2	22.6	18.6	27.6
Natural Gas	**35.9**		**35.1**	**35.6**	**35.5**	**33.9**	**37.1**	**37.3**	**37.4**
Automobiles	+		+	+	+	+	+	+	+
Light Trucks	+		+	+	+	+	+	+	+
Buses	+		0.2	0.3	0.4	0.5	0.6	0.6	0.6
Pipeline	35.9		34.9	35.3	35.0	33.4	36.4	36.7	36.8
LPG	**1.4**		**1.0**	**0.8**	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**
Light Trucks	0.5		0.4	0.3	0.3	0.3	0.3	0.3	0.3
Other Trucks	0.8		0.6	0.5	0.4	0.5	0.5	0.5	0.5
Buses	+		+	+	+	+	+	+	+
Electricity	**3.0**		**3.1**	**3.2**	**3.4**	**3.5**	**3.4**	**4.3**	**4.7**
Rail	3.0		3.1	3.2	3.4	3.5	3.4	4.3	4.7
Total (Including Bunkers)[d]	**1,577.9**		**1,778.0**	**1,830.8**	**1,871.6**	**1,854.9**	**1,891.7**	**1,889.4**	**1,954.7**
Total (Excluding Bunkers)[d]	**1,464.4**		**1,663.4**	**1,725.6**	**1,770.3**	**1,757.0**	**1,802.2**	**1,805.4**	**1,860.2**

Note: Totals may not sum due to independent rounding.

[a] Emissions are no longer allocated to gasoline and diesel consumption from agriculture and construction, and electricity consumption from pipelines. This based on recognition that EIA statistics account for these activities in the industrial sector.

[b] This category represents all other jet fuel consumption, and may include some small commercial aircraft and jet fuel used for

[10] These percentages include emissions from bunker fuels.

heating oil.
[c] Fluctuations in emission estimates from the combustion of residual fuel oil are currently unexplained, but may be related to data collection problems.
[d] 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.
+ Less than 0.05 Tg CO_2 Eq.

Industrial End-Use Sector

The industrial end-use sector accounted for 28 percent of CO_2 emissions from fossil fuel combustion. On average, 54 percent of these emissions resulted from the direct consumption of fossil fuels for steam and process heat production. The remaining 46 percent was associated with their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.

The industrial end-use sector 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 2005a and 2005i).

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 is also affected by weather conditions.[11] 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 2003 to 2004, total industrial production and manufacturing output increased by 4.1 and 5.0 percent, respectively (FRB 2005). Over this period, output increased for all of the aforementioned industries that comprise the majority of manufacturing energy use—Petroleum Refineries, Chemicals, Primary Metals, Paper, Food, and Nonmetallic Mineral Products (see Figure 3-12).

Figure 3-12: Industrial Production Indexes (Index 1997=100)

Despite the growth in industrial output (51 percent) and the overall U.S. economy (51 percent) from 1990 to 2004, CO_2 emissions from the industrial end-use sector increased by only 4 percent. A number of factors are believed to have caused this disparity between rapid growth in industrial output and stagnant growth in industrial emissions are not entirely clear, including: 1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, 2) improvements in energy efficiency; and 3) a lowering of the carbon intensity of fossil fuel consumption as industry shifts from its historical reliance on coal and coke to heavier usage of natural gas. In 2004, CO_2 emissions from fossil fuel combustion and electricity use within the industrial end-use sectors were 1,595.0 Tg CO_2 Eq., or 1.4 percent above 2003 emissions.

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 21 and 17 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 68 and 77 percent of emissions from the residential and commercial end-use sectors, respectively. The

[11] 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.

remaining emissions 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 2004, CO_2 emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,166.8 Tg CO_2 Eq. and 983.1 Tg CO_2 Eq., respectively.

Emissions from the residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions (see Table 3-6). In the long-term, both end-use 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 70 percent of the direct (not including electricity) fossil fuel emissions from the residential and commercial sectors. In 2004, natural gas emissions decreased by 4 and 7 percent, respectively, in each of these sectors, due to warmer conditions in the United States (see Figure 3-13).

Figure 3-13: Heating Degree Days[12]

Electricity sales to the residential and commercial end-use sectors in 2004 increased by 1.6 and 2.4 percent, respectively. This trend can largely be attributed to the growing economy (4.2 percent), which led to increased demand for electricity. Increased consumption due to these factors was somewhat offset by decreases in air conditioning-related electricity consumption due to the cooler summer (see Figure 3-14). Electricity-related emissions in both the residential and commercial sectors rose due to increased consumption. Total emissions from the residential sector increased by less than 0.1 percent in 2004, with emissions from the commercial sector 0.5 percent higher than in 2003.

Figure 3-14: Cooling Degree Days[13]

Electricity Generation

The process of generating electricity is the single largest source of CO_2 emissions in the United States, representing 38 percent of total CO_2 emissions from all sources. 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 3-15). Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 40 percent in 2004.

Figure 3-15: Electricity Generation Retail Sales by End-Use Sector

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). The Department of Energy categorizes electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity,[14] while the other sectors consist of those

[12] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1971 through 2000.

[13] Degree days are relative measurements of outdoor air temperature. Cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1971 through 2000.

[14] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Nonutilities produce electricity for

producers that indicate their primary business is other than the production of electricity.

In 2004, the amount of electricity generated increased by 1.8 percent, largely due to the growing economy and expanding industrial production. However, CO_2 emissions increased by only 1.3 percent, as a larger share of electricity was generated by nuclear power and natural gas. While coal consumption for electricity generation increased by just 0.5 percent in 2004, natural gas consumption increased by 6.6 percent and nuclear power increased by 3.4 percent. As a result of this shift, carbon intensity from energy consumption for electricity generation decreased in 2004 (see Table 3-9). 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 2004. Electricity generation from renewables increased slightly (by 1 percent) in 2004.

[BEGIN BOX]

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, can be generated from many other sources that do not emit CO_2 in the energy conversion process. In the United States, useful energy is also produced from renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[15]

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 carbon intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of carbon emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized.[16] Fossil fuels vary in their average carbon 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.[17] In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. Other sources of energy, however, may be directly or indirectly carbon 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 carbon 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 carbon emitted is offset by the growth of new biomass.[18] The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-8 provides a time series of the carbon 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 carbon 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

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their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers).

[15] 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.

[16] Generally, more than 97 percent of the carbon in fossil fuel is oxidized to CO_2 with most carbon combustion technologies used in the United States.

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

[18] 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.

sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 Tg CO_2 Eq./EJ), which were the primary sources of energy. Lastly, the electricity generation sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg CO_2 Eq./QBtu)

Sector	1990		1998	1999	2000	2001	2002	2003	2004
Residential[a]	57.0		56.3	56.4	56.4	56.6	56.2	56.4	56.5
Commercial[a]	59.2		57.0	56.9	56.9	57.2	56.7	57.0	57.5
Industrial[a]	63.3		62.1	62.2	62.0	62.9	62.4	62.8	62.7
Transportation[a]	70.8		70.6	70.7	70.8	70.8	70.8	70.7	70.8
Electricity Generation[b]	86.0		85.6	85.3	85.1	84.7	84.7	85.4	85.2
U.S. Territories[c]	73.3		56.3	56.4	56.4	56.6	56.2	56.4	56.5
All Sectors[c]	**72.2**		**72.3**	**72.2**	**72.2**	**72.3**	**72.2**	**72.4**	**72.5**

[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 3-8, Table 3-9 presents carbon 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.[19] This table, therefore, provides a more complete picture of the actual carbon intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 3-9 emerges as the most carbon 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 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 carbon intensity. The carbon intensity of the electricity generation sector differs greatly from the scenario in Table 3-8, 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 3-9: Carbon Intensity from all Energy Consumption by Sector (Tg CO_2 Eq./QBtu)

Sector	1990		1998	1999	2000	2001	2002	2003	2004
Transportation[a]	70.5		70.2	70.3	70.4	70.3	70.3	70.1	69.9
Other End-Use Sectors[a, b]	57.2		57.4	56.8	57.5	58.1	57.3	57.8	57.7
Electricity Generation[c]	58.5		59.4	58.5	59.5	59.7	58.6	59.3	59.1
All Sectors[d]	**60.8**		**60.9**	**60.6**	**61.0**	**61.5**	**61.0**	**61.3**	**61.2**

[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.

[19] 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.

By comparing the values in Table 3-8 and Table 3-9, a few observations can be made. The use of renewable and nuclear energy sources has resulted in a significantly lower carbon intensity of the U.S. economy. Over the fourteen-year period of 1990 through 2004, however, the carbon intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies have not changed significantly.

The carbon intensity of total energy consumption in the United States has remained fairly constant. Per capita energy consumption has fluctuated, but is now roughly equivalent to levels in 1990 (see Figure 3-16). 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.

Figure 3-16: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2005a) and fossil fuel consumption data as discussed above and presented in Annex 2.1.

[END BOX]

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/UNEP/OECD/IEA 1997). 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 unpublished supplemental tables on petroleum product detail (EIA 2005b). The United States does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Grillot (2005).[20]

   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, and used in this inventory, are, instead, "bottom up" in nature. In other words, they are collected through surveys at the point of delivery or use and aggregated to determine national totals.[21]

   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 standard, which are to report energy statistics in terms of net calorific

[20] 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 2004.

[21] 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.

values (NCV) (i.e., lower heating values).[22]

2. *Subtract uses accounted for in the Industrial Processes chapter*. Portions of the fuel consumption data for six fuel categories—coking coal, 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 Gambogi (2005), EFMA (1995), U.S. Census Bureau (1991 through 1994), U.S. Census Bureau (1998 through 2003), USITC (2005), U.S. Census Bureau (2005), EIA (2005h), EIA (2001b), USAA (2005), USGS (1998 through 2002), USGS (1995), USGS (1995 through 2005), USGS (1991 through 2005), USGS (1991 through 2004), U.S. International Trade Commission (2004a), U.S. International Trade Commission (2004b), Onder and Bagdoyan (1993), and Johnson (2005).[23]

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.[24] 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 (2005b) and data for synthetic natural gas were collected from EIA (2005e), and data for CO_2 exports were collected from the Dakota Gasification Company (2004), Fitzpatrick (2002), Erickson (2003), EIA (2001a), EIA (2002 through 2003), EIA (2005e), and Kass (2005).

4. *Adjust Sectoral Allocation of Distillate Fuel Oil*. EPA had conducted a separate bottom-up analysis of transportation fuel consumption based on FHWA Vehicle Miles Traveled (VMT) that indicated that the amount of distillate consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel consumption was adjusted higher 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. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2005), Benson (2002 through 2004), DOE (1993 through 2004), EIA (2005a), EIA (1991 through 2005), EPA (2004b), and FHWA (1996 through 2005).

5. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. Depending on the end-use, this can result in storage of some or all of the carbon contained in the fuel for a period of time. As the emission pathways of carbon used for non-energy purposes are vastly different than fuel combustion, 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 (2005b).

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[22] 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.

[23] See sections on Iron and Steel Production, Ammonia Manufacture, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production in the Industrial Processes chapter.

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

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, determination of carbon content, and adjustment for the fraction of carbon not oxidized).[25] 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 2005) supplied data on military jet fuel use. Commercial jet fuel use was obtained from BEA (1991 through 2005) and DOT (1991 through 2005); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2005). Consumption of these fuels was subtracted from the corresponding fuels in the transportation end-use sector. Estimates of international bunker fuel emissions are discussed further in the section entitled International Bunker Fuels.

7. *Determine the total carbon content of fuels consumed*. Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to CO_2. The carbon content coefficients used by the United States were obtained from EIA's *Emissions of Greenhouse Gases in the United States 2004* (EIA 2005c) and EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail EIA (EIA 2005b). They are presented in Annexes 2.1 and 2.2.

8. *Adjust for carbon that does not oxidize during combustion*. Because most combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot and ash. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process was assumed to be 1 percent for petroleum[26] and coal and 0.5 percent for natural gas (see Annex 2.1). Unoxidized or partially oxidized organic (i.e., carbon containing) combustion products were assumed to have eventually oxidized to CO_2 in the atmosphere.[27] IPCC provided fraction oxidized values for petroleum and natural gas (IPCC/UNEP/OECD/IEA 1997). Bechtel (1993) provided the fraction oxidation value for coal.

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.[28] 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 jet fuel, CO_2 emissions were calculated directly based on reported consumption of fuel. For highway vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2005); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2004). For non-highway vehicles, activity data were obtained from AAR (2005), BEA (1991 through 2005), Benson (2002 through 2004), DOE (1993 through 2004), DESC (2005), DOC (1991 through 2005), DOT (1991 through 2005), EIA (2002a), EIA (2002b), EIA (2005a), EIA (2005d), EIA (2005g), EIA (1991 through 2005), EPA (2004), and FAA (2005). Heat contents and densities were obtained from EIA (2005a) and USAF (1998).[29] The difference between total U.S. jet fuel consumption

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

[26] Based on an analysis of carbon mass balances, it is assumed that 100 percent of carbon is oxidized during combustion in light-duty gasoline cars and trucks.

[27] See Indirect CO_2 from CH_4 Oxidation section in this chapter for a more detailed discussion.

[28] Electricity generation is not considered a final end-use sector, because energy is consumed primarily to provide electricity to the other sectors.

[29] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile

(as reported by EIA) and civilian air carrier consumption for both domestic and international flights (as reported by DOT and BEA) plus military jet fuel consumption is reported as "other" under the jet fuel category in Table 3-7, and includes such fuel uses as blending with heating oils and fuel used for chartered aircraft flights.

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 fuels used in these non-energy production processes were subtracted from the total fossil fuel consumption for 2004. 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. Additionally, inefficiencies in the combustion process, which can result in ash or soot remaining unoxidized for long periods, were also assumed. These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with Carbon 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.

Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.7.

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 inventory 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.[30] 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.[31]

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).[32] 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 3-10. Fossil fuel combustion CO_2 emissions in 2004 were estimated to be between 5,589.5 and 5,990.5 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 1 percent below to 6 percent above the 2004 emission estimate of 5,656.6 Tg CO_2 Eq.

Table 3-10: 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	2004 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]	**2,027.0**	**1,974.8**	**2,232.2**	**-3%**	**+10%**
Residential	1.0	1.0	1.2	-5%	+16%
Commercial	8.2	7.8	9.5	-4%	+16%
Industrial	117.1	113.3	137.2	-3%	+17%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,897.1	1,836.0	2,092.8	-3%	+10%
U.S. Territories	3.6	3.2	4.3	-12%	+20%
Natural Gas[b]	**1,191.2**	**1,204.8**	**1,274.9**	**1%**	**+7%**
Residential	265.5	258.9	285.1	-3%	+7%
Commercial	162.7	158.7	174.7	-2%	+7%

[30] 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.

[31] 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.

[32] 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.

Industrial	428.4	439.5	483.9	3%	+13%
Transportation	37.4	36.5	40.1	-2%	+7%
Electricity Generation	295.8	288.3	311.9	-3%	+5%
U.S. Territories	1.3	1.1	1.5	-12%	+17%
Petroleum[b]	**2,438.0**	**2,310.9**	**2,588.6**	**-5%**	**+6%**
Residential	103.0	98.2	108.7	-5%	+5%
Commercial	55.1	52.8	57.7	-4%	+5%
Industrial	318.0	271.3	377.0	-15%	+19%
Transportation	1,818.1	1,703.0	1,944.5	-6%	+7%
Electric Utilities	97.3	93.8	102.3	-4%	+5%
U.S. Territories	46.5	43.3	52.0	-7%	+12%
Total (excluding Geothermal)[b]	**5,656.2**	**5,589.1**	**5,990.1**	**-1%**	**+6%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Total (including Geothermal)[b,c]	**5,656.6**	**5,589.5**	**5,990.5**	**-1%**	**+6%**

NA (Not Applicable)
NE (Not Estimated)
[a] Range of emission estimates predicted by Monte Carlo 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.

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

The most significant change affecting fuel combustion estimates this year was to correct an error that resulted in emissions to be estimated from some fuels that were either exported or used in industrial processes. A portion of industrial sector fuels are exported as petrochemical feedstocks or used in industrial processes, and are subtracted from the estimated fuel consumed for non-energy use purposes, reported in Section 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels. However, these fuels had not been subtracted from fuels consumed for energy purposes, resulting in an overestimate of emissions from the industrial sector.

Energy consumption of coking coal and industrial other coal were adjusted due to revised consumption data for metallurgical coke used in the production of iron and steel, and new consumption data for metallurgical coal used the production of lead and zinc. The amount of coking coal used to manufacture the coke used in these processes is estimated based on the amount of coke produced. These coal consumption data are then subtracted from energy consumption estimates, as emissions from the production of iron and steel, lead, and zinc are estimated in the Industrial processes chapter.

The oxidation factor for motor gasoline used in light-duty vehicles has been changed to 1.00 from the IPCC default factor for petroleum of 0.99. An analysis of carbon mass balances for light-duty gasoline cars and trucks was conducted to assess the proper oxidation factor. The results suggested that the amount of unoxidized carbon is insignificant compared to the gaseous carbon fraction, and that 1.00 should be used to represent the oxidized carbon fraction in future inventories for gasoline fueled light-duty vehicles.

The Energy Information Administration (EIA 2005b) updated energy consumption data for all years. These revisions primarily impacted the emission estimates for 2003. EIA (2005b) now reports a small amount of consumption of other liquids is in the electricity generation sector. This fuel type is similar to the composition of jet fuel.

Overall, changes resulted in an average annual decrease of 42.9 Tg CO_2 Eq. (0.8 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2003.

Planned Improvements

Several items are being evaluated to improve the estimates of CO_2 emissions from fossil fuel combustion and to reduce uncertainty:

- The carbon oxidation factor for diesel fuel consumed in highway vehicles may be assessed to determine whether the IPCC default of 0.99 is appropriate, or whether a more representative factor can be determined.
- Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. territories data.

These improvements are not all-inclusive, but are part of an ongoing analysis and efforts to continually improve the CO_2 from fossil fuel combustion estimates.

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). These fuels are used in the industrial and transportation end-use sectors and are quite diverse, including natural gas, liquid 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 fuel uses are equally diverse, and include application as solvents, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, synthetic fibers and other materials.

CO_2 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 62 percent of the total carbon consumed for non-energy purposes is stored in products, and not released to the atmosphere; the remaining 38 percent is 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; 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. 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 carbon in non-energy applications.

As shown in Table 3-11, fossil fuel emissions in 2004 from the non-energy uses of fossil fuels were 153.5 Tg CO_2 Eq., which constituted approximately 3 percent of overall fossil fuel emissions, approximately the same proportion as in 1990. In 2004, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,684 TBtu, an increase of 27 percent since 1990 (see Table 3-12). About 68.2 Tg of the C (250.1 Tg CO_2 Eq.) in these fuels was stored, while the remaining 41.8 Tg C (153.5 Tg CO_2 Eq.) was emitted. The proportion of C emitted as CO_2 has remained about constant since 1990, at about 31 to 37 percent of total non-energy consumption (see Table 3-13).

Table 3-11: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (Tg CO_2 Eq.)

Year	1990	1998	1999	2000	2001	2002	2003	2004
Potential Emissions	312.9	390.5	415.1	385.5	364.8	371.6	361.2	403.6
Carbon Stored	195.7	237.7	254.6	244.8	233.8	235.1	227.7	250.0
Emissions	**117.2**	**152.8**	**160.6**	**140.7**	**131.0**	**136.5**	**133.5**	**153.4**

Methodology

The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values. Both the non-energy fuel consumption and carbon content data were supplied by the EIA (2004) (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 3-12 and Table 3-13, have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes chapter.[33]

For the remaining non-energy uses, the amount of C stored was estimated by multiplying the potential emissions by a storage factor. For several fuel types—petrochemical feedstocks (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 Municipal Solid Waste Combustion 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 the *Revised IPCC Guidelines for National Greenhouse Gas Inventories* (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 carbon in the respective NEU products.

Table 3-12: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	1998	1999	2000	2001	2002	2003	2004
Industry	**4,223.4**	**5,354.4**	**5,652.1**	**5,260.5**	**5,044.9**	**5,086.5**	**4,922.6**	**5,371.1**
Industrial Coking Coal	0.0	8.5	45.7	62.7	25.5	46.4	72.0	214.3
Industrial Other Coal	8.2	10.4	11.1	12.4	11.3	12.0	11.9	11.9
Natural Gas to Chemical Plants, Other Uses	278.0	407.9	419.4	421.5	410.6	405.9	389.6	380.1
Asphalt & Road Oil	1,170.2	1,262.6	1,324.4	1,275.7	1,256.9	1,240.0	1,219.5	1,303.9
LPG	1,117.7	1,678.9	1,755.1	1,603.3	1,537.1	1,564.5	1,439.0	1,437.5
Lubricants	186.3	190.8	192.8	189.9	174.0	171.9	159.0	161.0
Pentanes Plus	77.3	197.2	252.8	228.6	199.6	166.0	158.4	156.5
Naphtha (<401 ° F)	325.3	563.6	485.3	592.3	488.9	563.9	573.9	688.2
Other Oil (>401 ° F)	676.5	637.8	658.6	553.9	525.2	469.5	515.0	561.7
Still Gas	21.3	0.0	16.1	12.6	35.8	57.8	59.0	63.5
Petroleum Coke	83.6	119.8	189.0	49.4	129.4	111.2	80.8	189.4
Special Naphtha	100.8	103.9	141.0	94.3	77.8	99.4	75.8	47.2
Distillate Fuel Oil	7.0	11.7	11.7	11.7	11.7	11.7	11.7	11.7
Waxes	33.3	42.4	37.4	33.1	36.3	32.2	31.0	30.8

[33] 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, and Aluminum Production.

Miscellaneous Products	137.8	119.0	111.9	119.2	124.9	134.2	126.0	113.4
Transportation	**176.0**	**180.2**	**182.1**	**179.4**	**164.3**	**162.4**	**150.1**	**152.1**
Lubricants	176.0	180.2	182.1	179.4	164.3	162.4	150.1	152.1
U.S. Territories	**86.7**	**137.9**	**143.8**	**165.5**	**80.3**	**138.7**	**146.6**	**156.3**
Lubricants	0.7	1.3	1.4	16.4	+	1.5	1.6	1.7
Other Petroleum (Misc. Prod.)	86.0	136.6	142.4	149.1	80.3	137.2	145.0	154.6
Total	**4,486.1**	**5,672.5**	**5,977.9**	**5,605.3**	**5,289.5**	**5,387.6**	**5,219.3**	**5,679.5**

+ Does not exceed 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 carbon black production, which is also reported in the Industrial Processes chapter.

Note: Totals may not sum due to independent rounding.

Table 3-13: 2004 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Consumption (TBtu)	Carbon Content (Tg C)	Storage Factor	Carbon Stored (Tg C)	Carbon Emissions (Tg C)	Carbon Emissions (Tg CO_2 Eq.)
Industry	**5,371.1**	**103.8**	**-**	**67.5**	**36.2**	**132.8**
Industrial Coking Coal	214.3	6.6	0.10	0.7	6.0	21.9
Industrial Other Coal	11.9	0.3	0.62	0.2	0.1	0.4
Natural Gas to Chemical Plants	380.1	5.5	0.62	3.4	2.1	7.6
Asphalt & Road Oil	1,303.9	26.9	1.00	26.9	0.0	0.0
LPG	1,437.5	24.2	0.62	15.1	9.1	33.2
Lubricants	161.0	3.3	0.09	0.3	3.0	10.8
Pentanes Plus	156.5	2.9	0.62	1.8	1.1	3.9
Naphtha (<401° F)	688.2	12.5	0.62	7.8	4.7	17.2
Other Oil (>401° F)	561.7	11.2	0.62	7.0	4.2	15.4
Still Gas	63.5	1.1	0.62	0.7	0.4	1.5
Petroleum Coke	189.4	5.3	0.50	2.6	2.6	9.7
Special Naphtha	47.2	0.9	0.62	0.6	0.4	1.3
Distillate Fuel Oil	11.7	0.2	0.50	0.1	0.1	0.4
Waxes	30.8	0.6	0.58	0.4	0.3	0.9
Miscellaneous Products	113.4	2.3	0.00	0.0	2.3	8.5
Transportation	**152.1**	**3.1**	**-**	**0.3**	**2.8**	**10.2**
Lubricants	152.1	3.1	0.09	0.3	2.8	10.2
U.S. Territories	**156.3**	**3.1**	**-**	**0.3**	**2.8**	**10.3**
Lubricants	1.7	0.0	0.09	0.0	0.0	0.1
Other Petroleum (Misc. Prod.)	154.6	3.1	0.10	0.3	2.78	10.2
Total	**5,679.5**	**110.0**	**-**	**68.1**	**41.8**	**153.4**

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

[a] 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 carbon black production, which is also reported in the Industrial Processes chapter.

- Not applicable.

Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions (see Table 3-11). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including volatile organic compound, solvent, and non-combustion carbon monoxide 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's compilations of air emission factors (EPA 1995, 2001), *National Air Quality and Emissions Trends Report* data (EPA 2005), *Toxics Release Inventory, 1998* (2000a), *Biennial Reporting System* data (EPA 2004), pesticide sales and use estimates (EPA 1998, 1999, 2002) and hazardous waste data (EPA 2004); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001b, 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. Bureau of the Census (1999, 2003, 2004); the American Plastics Council (APC 2000, 2001, 2003, 2005; Eldredge-Roebuck 2000); the Society of the Plastics Industry (SPI 2000); the Rubber Manufacturers' Association (RMA 2002; STMC 2003); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001; FEB 2005); the *Material Safety Data Sheets* (Miller 1999); the Chemical Manufacturer's Association (CMA 1999); and the American Chemistry Council (ACC 2004.) 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 3-14 (emissions) and Table 3-15 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2004 was estimated to be between 112.8 and 153.7 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 20 percent below to 8 percent above the 2004 emission estimate of 141.7 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.

Table 3-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	80.6	65.3	96.7	-19%	+20%
Asphalt	CO_2	0.0	NA	NA	NA	NA
Lubricants	CO_2	21.2	17.6	24.4	-17%	+15%
Waxes	CO_2	0.9	0.7	1.5	-24%	+56%

Other	CO_2	50.7	22.3	56.8	-56%	+12%
Total	**CO_2**	**153.4**	**122.7**	**165.7**	**-20%**	**+8%**

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

Table 3-15: Tier 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2004 Storage Factor (%)	Uncertainty Range Relative to Inventory Factor[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	62%	60%	64%	-3%	+4%
Asphalt	CO_2	100%	99%	100%	-1%	+0%
Lubricants	CO_2	9%	4%	18%	-58%	+91%
Waxes	CO_2	58%	44%	69%	-24%	+19%
Other	CO_2	28%	21%	68%	-25%	+141%

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

In Table 3-15, 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. 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 carbon. Emission and storage totals for the different subcategories were compared, and trends across the time series were carefully 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.

Recalculations Discussion

This year's methodology reflects several refinements and improvements. The methodology for calculating emissions and storage for feedstocks has been revised in several ways. First, some disparities in data for production and consumption were reconciled. Production data relates only to production within the country; consumption data incorporates information on imports and exports as well as production. Because many commodities are emissive in their use, but not necessarily their production, consumption data is appropriately used in calculations for emissive fates. For purposes of developing an overall mass balance on U.S. non-energy uses of carbon, for those materials that are non-emissive (e.g., plastics), production data is most applicable. And for purposes of adjusting the mass balance to incorporate carbon flows associated with imports and exports, it was necessary to carefully review whether the mass balance already incorporated cross-boundary flows (through the use of consumption data) or not,

and to adjust the import/export balance accordingly. This year's effort included a more thorough review of the system boundaries on the mass balance, addressing the use of production and consumption data sets and making corresponding adjustments to the import / export calculations.

In an attempt to account for make the mass balance for petrochemical feedstocks more comprehensive, three additional NEU fates were incorporated into the calculations: antifreeze and deicers, food additives, and silicone rubber. Ethylene, diethylene, and propylene glycol are used in antifreeze and aircraft deicing solutions and generally have emissive fates; their consumption was tallied and added to the emissive side of the mass balance ledger. Many food additives such as acetic acid, maleic anhydride, adipic acid, cresylic acid, triethylene glycol, propylene glycol, dipropylene glycol, glycerin, propionic acid, and benzoic acid, are synthetic, i.e., derived from fossil sources. These are generally metabolized to CO_2, and thus were also counted as emissive uses. On the non-emissive side, silicone rubber is now reflected in the calculations. The results for petrochemicals reflect the additions of these new categories in the attempt to "close" the mass balance for fossil carbon. Compared to other fate categories, the mass of carbon in these three newly added components is small, comprising an average of 1.1 percent of annual carbon flows since 1990.

In another change, one of the emissive fates—refinery wastewaters—was dropped from the mass balance. This change was precipitated by better information on the boundaries for the EIA NEU data set used as the basis for the analysis. Although a small amount of carbon is emitted through refinery wastewater treatment, it is unlikely that this carbon ever enters the NEU system.

Finally, there have been several updates to the data used to calculate storage factors, not only by adding information for 2004 (where available) but also for updating data sets for earlier years. For example, the results reflect new data for energy recovery (through 2002), cleansers, and imports and exports. Overall, changes resulted in an average annual increase in CO_2 emissions from non-energy use of fuels of 15.2 Tg CO_2 Eq. (13 percent) for the period 1990 through 2003.

Planned Improvements

There are several improvements planned for the future:

- Collecting additional information on energy recovery from Manufacturing Energy Consumption Surveys. An effort is planned to carefully examine the "microdata" from these surveys to determine the nature and quantity of materials initially identified as being destined for "non-energy use" that are actually combusted for energy recovery.
- 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 carbon. Additional "fates" may be researched, including the fossil carbon 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 the remaining fuels (petroleum coke, 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. Stationary Combustion (excluding CO_2) (IPCC Source Category 1A)

Stationary combustion encompasses all fuel combustion activities from fixed sources (versus mobile combustion).

Other than CO_2, which was addressed in the previous section, gases from stationary combustion include the greenhouse gases CH_4 and N_2O and the indirect greenhouse gases NO_x, CO, and NMVOCs.[34] Emissions of these gases from stationary combustion sources depend upon fuel characteristics, size and vintage, along with combustion technology, pollution control equipment, and ambient environmental conditions. Emissions also vary with operation and maintenance practices.

N_2O and NO_x 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. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion; they are highest when less oxygen is present in the air-fuel mixture than is necessary for complete combustion. These conditions are most likely to occur during start-up, shutdown and during fuel switching (e.g., the switching of coal grades at a coal-burning electric utility plant). CH_4 and NMVOC emissions from stationary combustion are primarily a function of the CH_4 and NMVOC content of the fuel and combustion efficiency.

Emissions of CH_4 decreased 18 percent overall to 6.4 Tg CO_2 Eq. (307 Gg) in 2004. This decrease in CH_4 emissions was primarily due to lower wood consumption in the residential sector. Conversely, N_2O emissions rose 11 percent since 1990 to 13.7 Tg CO_2 Eq. (44 Gg) in 2004. The largest source of N_2O emissions was coal combustion by electricity generators, which alone accounted for 64 percent of total N_2O emissions from stationary combustion in 2004. Overall, however, stationary combustion is a small source of CH_4 and N_2O in the United States.

In contrast, stationary combustion is a significant source of NO_x emissions, though a smaller source of CO and N_2O NMVOCs. In 2004, emissions of NO_x from stationary combustion represented 39 percent of national NO_x emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 5 and 7 percent, respectively, to the national totals. From 1990 to 2004, emissions of NO_x and CO from stationary combustion decreased by 33 and 20 percent, respectively, and emissions of NMVOCs increased by 1 percent.

The decrease in NO_x emissions from 1990 to 2004 are mainly due to decreased emissions from electric power. The decrease in CO and increase in NMVOC emissions over this time period can largely be attributed to apparent changes in residential wood use, which is the most significant source of these pollutants from stationary combustion. Table 3-16 through Table 3-19 provide CH_4 and N_2O emission estimates from stationary combustion by sector and fuel type. Estimates of NO_x, CO, and NMVOC emissions in 2004 are given in Table 3-20.[35]

Table 3-16: CH_4 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1998	1999	2000	2001	2002	2003	2004
Electric Power	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Coal	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.1	0.1	0.1	0.1	0.1	+	0.1	0.1
Natural gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Industrial	**2.1**	**2.3**	**2.2**	**2.2**	**2.1**	**2.0**	**2.0**	**2.1**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural gas	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.8
Wood	0.9	1.0	1.0	1.0	0.9	0.8	0.8	0.9
Commercial	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2

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

[35] See Annex 3.1 for a complete time series of indirect greenhouse gas emission estimates for 1990 through 2004.

Natural gas	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Residential	**4.4**	**3.1**	**3.3**	**3.5**	**3.1**	**2.7**	**3.0**	**2.9**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wood	3.5	2.3	2.5	2.6	2.2	1.9	2.1	2.0
U.S. Territories	**+**	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	0.1	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**7.9**	**6.8**	**7.0**	**7.3**	**6.6**	**6.2**	**6.5**	**6.4**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-17: N_2O Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1998	1999	2000	2001	2002	2003	2004
Electric Power	**7.6**	**8.9**	**8.9**	**9.3**	**9.1**	**9.1**	**9.3**	**9.4**
Coal	7.1	8.4	8.4	8.8	8.6	8.6	8.8	8.8
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Wood	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2
Industrial	**3.2**	**3.2**	**3.2**	**3.3**	**3.1**	**2.9**	**2.9**	**3.0**
Coal	0.7	0.6	0.6	0.6	0.6	0.5	0.6	0.6
Fuel Oil	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Natural Gas	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Wood	1.7	1.9	1.9	1.9	1.7	1.6	1.6	1.7
Commercial	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	+	0.1	0.1	0.1	+	+	+	+
Residential	**1.1**	**0.8**	**0.9**	**0.9**	**0.9**	**0.8**	**0.9**	**0.8**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.1
Wood	0.7	0.5	0.5	0.5	0.4	0.4	0.4	0.4
U.S. Territories	**0.1**	**0.1**	**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	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**12.3**	**13.4**	**13.4**	**13.9**	**13.5**	**13.2**	**13.6**	**13.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-18: CH_4 Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1998	1999	2000	2001	2002	2003	2004
Electric Power	**27**	**31**	**31**	**32**	**32**	**32**	**33**	**33**
Coal	16	19	19	20	20	20	20	20
Fuel Oil	4	4	3	3	4	2	3	3
Natural Gas	3	4	5	5	5	5	5	5
Wood	4	4	4	4	4	4	5	5

Industrial	**101**	**107**	**106**	**107**	**99**	**97**	**95**	**98**
Coal	16	14	14	14	14	13	13	13
Fuel Oil	6	5	5	5	6	5	6	6
Natural Gas	37	43	41	42	38	39	37	39
Wood	41	46	46	47	41	40	39	41
Commercial	**35**	**36**	**37**	**38**	**34**	**34**	**35**	**35**
Coal	1	1	1	1	1	1	1	1
Fuel Oil	10	6	6	7	7	6	7	8
Natural Gas	13	15	15	15	15	15	16	15
Wood	11	14	15	15	12	11	11	12
Residential	**210**	**149**	**159**	**165**	**147**	**130**	**145**	**137**
Coal	9	4	4	3	3	3	3	3
Fuel Oil	14	12	14	15	15	14	15	15
Natural Gas	21	22	23	24	23	24	25	24
Wood	166	110	118	123	105	89	102	95
U.S. Territories	**2**	**2**	**2**	**2**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	2	2	2	2	3	3	3	3
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**374**	**325**	**335**	**346**	**316**	**295**	**311**	**307**

+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

Table 3-19: N_2O Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1998	1999	2000	2001	2002	2003	2004
Electricity Generation	**24**	**29**	**29**	**30**	**29**	**29**	**30**	**30**
Coal	23	27	27	28	28	28	28	28
Fuel Oil	1	1	1	1	1	+	1	1
Natural Gas	+	+	+	1	1	1	+	1
Wood	+	1	1	1	+	1	1	1
Industrial	**10**	**10**	**10**	**11**	**10**	**9**	**9**	**10**
Coal	2	2	2	2	2	2	2	2
Fuel Oil	2	1	1	2	2	2	2	2
Natural Gas	1	1	1	1	1	1	1	1
Wood	5	6	6	6	5	5	5	6
Commercial	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Residential	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	+	+
Wood	2	1	2	2	1	1	1	1
U.S. Territories	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**40**	**43**	**43**	**45**	**44**	**43**	**44**	**44**

+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

Table 3-20: NO_x, CO, and NMVOC Emissions from Stationary Combustion in 2004 (Gg)

Sector/Fuel Type	NO_x	CO	NMVOC
Electric Generation	**3,393**	**451**	**45**
Coal	2,886	226	21
Fuel Oil	113	28	4
Natural gas	252	95	10
Wood	NA	NA	NA
Other Fuels[a]	28	33	1
Internal Combustion	114	69	9
Industrial	**2,610**	**1,303**	**155**
Coal	541	143	10
Fuel Oil	160	52	8
Natural gas	955	419	53
Wood	NA	NA	NA
Other Fuels[a]	121	368	29
Internal Combustion	833	320	55
Commercial/Institutional	**243**	**124**	**16**
Coal	19	11	1
Fuel Oil	49	14	3
Natural gas	154	68	12
Wood	NA	NA	NA
Other Fuels[a]	21	31	9
Residential	**416**	**2,142**	**697**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	20	1,961	675
Other Fuels	396	181	23
Total	**6,662**	**4,020**	**922**

NA (Not Available)

[a] Includes LPG, waste oil, coke oven gas, and coke (EPA 2003, EPA 2005).

[b] Residential coal, fuel oil, and natural gas emissions are included in "Other Fuels" (EPA 2003, EPA 2005).

Note: Totals may not sum due to independent rounding. See Annex 3.1 for emissions in 1990 through 2004.

Methodology

CH_4 and N_2O emissions 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, electric power, and U.S. territories. For the CH_4 and N_2O estimates, fuel consumption data for the United States were obtained from EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail (EIA 2005). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by Grillot (2005).[36] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[37] Construction and agricultural fuel use was obtained from EPA (2004). Estimates

[36] 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.

[37] 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

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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). U.S. territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Emission estimates for NO_x, CO, and NMVOCs in this section were obtained from preliminary data (EPA 2005) 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. The major categories included in this section are those reported in EPA (2003) and EPA (2005): coal, fuel oil, natural gas, wood, other fuels (including LPG, coke, coke oven gas, and others), and stationary internal combustion. The EPA estimates emissions of NO_x, CO, and NMVOCs by sector and fuel source using a "bottom-up" estimating procedure. In other words, emissions were calculated either for individual sources (e.g., industrial boilers) or for multiple sources combined, using basic activity data as indicators of emissions. Depending on the source category, these basic activity data may include fuel consumption, fuel deliveries, tons of refuse burned, raw material processed, etc.

The overall emission control efficiency of a source category was derived from published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary combustion, as described above, is consistent with the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

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/EIA (2001) report.[38] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[39] However, the CH_4

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sources.

[38] 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.

[39] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels

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 *Good Practice Guidance*, 2000).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-21. Stationary combustion CH_4 emissions in 2004 (*including* biomass) were estimated to be between 4.7 and 12.5 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 26 percent below to 94 percent above the 2004 emission estimate of 6.4 Tg CO_2 Eq.[40] Stationary combustion N_2O emissions in 2004 (*including* biomass) were estimated to be between 10.4 and 39.4 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 24 percent below to 188 percent above the 2004 emissions estimate of 13.7 Tg CO_2 Eq.

Table 3-21: 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	2004 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	6.4	4.7	12.5	-26%	+94%
Stationary Combustion	N_2O	13.7	10.4	39.4	-24%	+188%

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

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

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 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 several changes. Slight changes to emission estimates for sectors are due to revised data from EIA (2005). This revision is explained in greater detail in the section on CO_2 Emissions from Fossil Fuel Combustion within this sector. The combination of the methodological and historical data changes resulted in an average annual decrease of 0.1 Tg CO_2 Eq. (0.8 percent) in CH_4 emissions from stationary combustion and an average annual decrease of 0.1 Tg CO_2 Eq. (0.4

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.

[40] 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.

percent) in N_2O emissions from stationary combustion for the period 1990 through 2003.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary source combustion and to reduce uncertainty. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated. Currently, the exclusion of biomass increases the uncertainty, although it was expected to reduce the uncertainty. These improvements are not all-inclusive, but are part of an ongoing analysis and efforts to continually improve these stationary estimates.

3.4. Mobile Combustion (excluding CO_2) (IPCC Source Category 1A)

Mobile combustion emits greenhouse gases other than CO_2, including CH_4, N_2O, and the indirect greenhouse gases NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, as well as usage of pollution control equipment. N_2O, 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. CH_4 and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

Emissions from mobile combustion were estimated by transport mode (e.g., highway, air, rail), fuel type (e.g. motor gasoline, diesel fuel, jet fuel), and vehicle type (e.g. passenger cars, light-duty trucks). Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile combustion emissions. Table 3-22 and Table 3-23 provide CH_4 and N_2O emission estimates, respectively, in Tg CO_2 Eq.; Table 3-24 and Table 3-25 present these estimates in Gg of each gas. Estimates of NO_x, CO, and NMVOC emissions in 2004 are given in Table 3-26.[41]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.5 percent) but was the second largest source of N_2O (11 percent) in the United States. From 1990 to 2004, CH_4 emissions declined by 38 percent, to 2.9 Tg CO_2 Eq. (140 Gg), due largely to control technologies employed on highway vehicles in the United States that reduce CO, NO_x, NMVOC, and CH_4 emissions. The same technologies, however, initially resulted in higher N_2O emissions, causing a 26 percent increase in N_2O emissions from mobile sources between 1990 and 1998. N_2O emissions have subsequently declined 22 percent as improvements in the emission control technologies installed on new vehicles have reduced emission rates of both NO_x and N_2O per vehicle mile traveled. As a result, N_2O emissions in 2004 were 1 percent lower than in 1990, at 42.8 Tg CO_2 Eq. (138 Gg) (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

Figure 3-17: Mobile Source CH_4 and N_2O Emissions

Table 3-22: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	1998	1999	2000	2001	2002	2003	2004
Gasoline Highway	**4.2**	**3.3**	**3.0**	**2.9**	**2.7**	**2.5**	**2.3**	**2.2**
Passenger Cars	2.6	1.8	1.7	1.6	1.5	1.4	1.3	1.3
Light-Duty Trucks	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9

[41] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2004.

Heavy-Duty Vehicles	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	+	+	+	+	+	+	+	+
Alternative Fuel Highway	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Highway	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.6**
Ships and Boats	0.1	+	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Farm Equipment	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1
Construction Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[b]	+	+	+	+	+	0.1	0.1	0.1
Total	**4.7**	**3.8**	**3.6**	**3.5**	**3.3**	**3.2**	**3.0**	**2.9**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] See Annex 3.2 for definitions of highway vehicle types.

[b] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

Table 3-23: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1998	1999	2000	2001	2002	2003	2004
Gasoline Highway	**40.1**	**51.2**	**50.3**	**49.1**	**46.0**	**43.5**	**40.8**	**38.6**
Passenger Cars	25.4	26.6	25.9	25.1	23.9	22.9	21.8	21.0
Light-Duty Trucks	14.1	23.6	23.5	23.1	21.2	19.7	18.1	16.7
Heavy-Duty Vehicles	0.6	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Alternative Fuel Highway	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Highway	**3.1**	**3.3**	**3.4**	**3.6**	**3.6**	**3.6**	**3.5**	**3.7**
Ships and Boats	0.4	0.2	0.3	0.4	0.4	0.5	0.4	0.4
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Farm Equipment	1.7	1.8	1.8	1.9	1.8	1.7	1.7	1.8
Construction Equipment	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Aircraft	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Other*	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Total	**43.5**	**54.8**	**54.1**	**53.1**	**50.0**	**47.5**	**44.8**	**42.8**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

*"Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

Table 3-24: CH_4 Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1998	1999	2000	2001	2002	2003	2004
Gasoline Highway	**201**	**155**	**145**	**137**	**127**	**120**	**112**	**106**
Passenger Cars	125	87	82	77	72	68	63	60
Light-Duty Trucks	65	60	56	54	50	47	44	41
Heavy-Duty Vehicles	10	7	6	5	5	5	4	4
Motorcycles	1	1	1	1	1	1	1	1
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**1**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
Non-Highway	**22**	**22**	**24**	**25**	**25**	**26**	**25**	**27**
Ships and Boats	3	2	3	4	4	4	4	4
Locomotives	3	3	3	3	3	3	3	4
Farm Equipment	7	7	7	7	7	7	6	7
Construction Equipment	4	5	5	5	6	6	6	6
Aircraft	2	3	3	3	3	3	3	3
Other*	2	2	2	2	2	2	2	3
Total	**224**	**181**	**173**	**167**	**159**	**152**	**144**	**140**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

Table 3-25: N_2O Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1998	1999	2000	2001	2002	2003	2004
Gasoline Highway	**129**	**165**	**162**	**158**	**148**	**140**	**132**	**125**
Passenger Cars	82	86	83	81	77	74	70	68
Light-Duty Trucks	45	76	76	74	68	63	58	54
Heavy-Duty Vehicles	2	3	3	3	3	3	3	3
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Highway	**10**	**11**	**11**	**12**	**12**	**12**	**11**	**12**
Ships and Boats	1	1	1	1	1	1	1	1
Locomotives	1	1	1	1	1	1	1	1
Farm Equipment	6	6	6	6	6	6	5	6
Construction Equipment	1	1	1	1	1	1	1	1
Aircraft	1	1	1	1	1	1	1	2
Other*	1	1	1	1	1	1	1	1
Total	**140**	**177**	**174**	**171**	**161**	**153**	**144**	**138**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

Mobile sources comprise the single largest source category of NO_x, CO, and NMVOC emissions in the United States. In 2004, mobile combustion contributed 55 percent of NO_x emissions, 90 percent of CO emissions, and 43 percent of NMVOC emissions. Since 1990, emissions of NO_x from mobile combustion decreased by 22 percent, CO emissions decreased 34 percent, and emissions of NMVOCs decreased by 46 percent.

Table 3-26: NO_x, CO, and NMVOC Emissions from Mobile Combustion in 2004 (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOC
Gasoline Highway	**3,206**	**55,541**	**3,525**
Passenger Cars	1,749	30,945	1,969
Light-Duty Trucks	1,109	22,107	1,369
Heavy-Duty Vehicles	336	2,361	170
Motorcycles	12	129	18

Diesel Highway	**2,881**	**851**	**171**
Passenger Cars	5	6	3
Light-Duty Trucks	5	5	3
Heavy-Duty Vehicles	2,871	840	165
Alternative Fuel Highway[a]	**IE**	**IE**	**IE**
Non-Highway	**3,377**	**22,181**	**2,186**
Ships and Boats	870	1,934	671
Locomotives	812	89	32
Farm Equipment	66	231	18
Construction Equipment	430	615	67
Aircraft[b]	618	1,032	115
Other[c]	582	18,280	1,284
Total	**9,465**	**78,574**	**5,882**

IE (Included Elsewhere)

Note: Totals may not sum due to independent rounding.

[a] NO_x emissions from alternative fuel highway vehicles are included under gasoline and diesel highway vehicles.

[b] Aircraft estimates include only emissions related to landing and take-off (LTO) cycles, and therefore do not include cruise altitude emissions.

[c] "Other" includes gasoline- and diesel-powered recreational, industrial, lawn and garden, light commercial, logging, airport service, and other equipment.

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). Depending upon the category, activity data included such information as fuel consumption, and vehicle miles traveled (VMT). The activity data and emission factors used are described in the subsections that follow. A complete discussion of the methodology used to estimate emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

EPA (2005c) and EPA (2003) provided emission estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[42] aircraft, and seven categories of non-highway vehicles.[43] These emission estimates reflect preliminary EPA data, which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. The methodology used to develop these estimates can be found on EPA's Air Pollutant Emission Trends website, at <http://www.epa.gov/ttn/chief/trends/index.html>.

Highway Vehicles

Emission estimates for gasoline and diesel highway vehicles were based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Emission estimates from alternative fuel vehicles (AFVs)[44] were based on VMT and emission factors by vehicle and fuel type.

Emission factors for gasoline and diesel highway vehicles were developed by ICF (2004). These factors were based

[42] These categories included: gasoline passenger cars, diesel passenger cars, light-duty gasoline trucks less than 6,000 pounds in weight, light-duty gasoline trucks between 6,000 and 8,500 pounds in weight, light-duty diesel trucks, heavy-duty gasoline trucks and buses, heavy-duty diesel trucks and buses, and motorcycles.

[43] These categories included: locomotives, marine vessels, farm equipment, construction equipment, other off-highway liquid fuel (e.g. recreational vehicles and lawn and garden equipment), and other off-highway gaseous fuel (e.g., other off-highway equipment running on compressed natural gas).

[44] 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 bifuel or dual fuel vehicles that may be partially powered by gasoline or diesel.

on EPA and California Air Resources Board (CARB) laboratory test results of different vehicle and control technology types. The EPA and CARB 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 was 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 to approximate average driving characteristics.

Emission factors for AFVs were developed after consulting a number of sources, including Argonne National Laboratory's GREET 1.5–Transportation Fuel Cycle Model (Wang 1999), Lipman and Delucchi (2002), the Auto/Oil Air Quality Improvement Research Program (CRC 1997), the California Air Resources Board (Brasil and McMahon 1999), and the University of California Riverside (Norbeck et al., 1998). The approach taken was to calculate CH_4 emissions from actual test data and determine N_2O emissions from NO_x emissions from the same tests. While the formation of N_2O is highly dependent on the type of catalyst used and the catalyst temperature, tailpipe N_2O is likely to increase as engine out NO_x emissions increase. Thus, as a first approximation, the NO_x to N_2O emission ratio will likely be constant for a given emission control group. 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 2004 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2005). VMT was then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using information on shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2004) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2005). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2005d) and EPA (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 highway vehicles were obtained from the EPA's Office of Transportation and Air Quality (EPA 2005a, 2005b, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1993), EPA (1994a), EPA (1994b), EPA (1998), EPA (1999), and IPCC/UNEP/OECD/IEA (1997).

Preliminary estimates for NO_x, CO, and NMVOCs were obtained from EPA (2005c) 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.

Non-Highway Vehicles

Fuel consumption data were employed as a measure of activity for non-highway vehicles, and fuel-specific emission factors were applied.[45] Activity data were obtained from AAR (2005), BEA (1991 through 2005), Benson (2002 through 2004), DOE (1993 through 2004), DESC (2005), DOC (1991 through 2005), DOT (1991 through 2005), EIA (2002a), EIA (2002b), EIA (2005a), EIA (2005b), EIA (2003 through 2004), EIA (1991 through 2005), EPA (2004), and FAA (2005). Emission factors for non-highway modes were taken from IPCC/UNEP/OECD/IEA (1997).

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

Uncertainty

This section discusses the uncertainty of the emission estimates for CH_4 and N_2O. Uncertainty was analyzed separately for highway vehicles and non-highway vehicles due to differences in their characteristics and their contributions to total mobile source emissions.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched since these gases are regulated emissions from motor vehicles in the United States, and the uncertainty of these emission estimates is believed to be relatively low. A much higher level of uncertainty is associated with CH_4 and N_2O emission factors, since emissions of these gases are not regulated in the United States, and unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are also highly complex.

Highway Vehicles

A quantitative uncertainty analysis was conducted for the highway 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 2004 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 mile traveled (VMT) data, by vehicle and fuel type and (2) emission factor data, by vehicle, fuel, and control technology type.

Mobile combustion emissions of CH_4 and N_2O per vehicle mile traveled vary significantly due to fuel type and composition, technology type, operating speeds and conditions, type of emission control equipment, equipment age, and operating and maintenance practices. The primary activity data, VMT, are collected and analyzed each year by government agencies.

To determine the uncertainty associated with the activity data used in the calculations of CH_4 and N_2O emissions, the agencies and the experts that supply the data were contacted. Because few of these sources were able to provide quantitative estimates of uncertainty, expert quantitative judgments were used to assess the uncertainty associated with the activity data.

The emission factors for highway vehicles used in the Inventory were obtained from ICF (2004). These factors were based on laboratory testing of vehicles. While the controlled testing environment simulates real driving conditions, emission results from such testing can only approximate real world conditions and emissions. For some vehicle and control technology types, the testing did not yield statistically significant results within the 95 percent confidence interval, requiring expert judgments to be used in developing the emission factors. In those cases, the emission factors were developed based on comparisons of fuel consumption between similar vehicle and control technology categories.

The estimates of VMT for highway vehicles by vehicle type in the United States were provided by FHWA (1996 through 2005), and were generated though the cooperation of FHWA and state and local governments. These estimates are subject to several possible sources of error, such as unregistered vehicles, and measurement and estimation errors. These VMT were apportioned by fuel type, based on data from DOE (2004), and then allocated to individual model years using temporal profiles of both the vehicle fleet by age and vehicle usage by model year in the United States provided by EPA (2005d) and EPA (2000). While the uncertainty associated with total U.S. VMT is believed to be low, the uncertainty within individual source categories was assumed to be higher given uncertainties associated with apportioning total VMT into individual vehicle categories, by fuel type, by technology type, and equipment age. The uncertainty of individual estimates was assumed to relate to the magnitude of estimated VMT (i.e., it was assumed smaller sources had greater percentage uncertainty). A further source of uncertainty occurs since FHWA and EPA use different definitions of vehicle type and estimates of VMT by vehicle type (provided by FHWA) are broken down by fuel type using EPA vehicle categories.

A total of 69 highway data input variables were simulated through Monte Carlo Simulation technique using @RISK software. Variables included VMT and emission factors for individual vehicle categories and technologies. In developing the uncertainty estimation model, a normal distribution was assumed for all activity-related input

variables (e.g., VMT) except in the case of buses, in which a triangular distribution was used. The dependencies and other correlations among the activity data were incorporated into the model to ensure consistency in the model specification and simulation. Emission factors were assigned uniform distributions, with upper and lower bounds assigned to input variables based on 97.5 percent confidence intervals of laboratory test data. In cases where data did not yield statistically significant results within the 95 percent confidence interval, estimates of upper and lower bounds were made using expert judgment. The bounds for the emission factor-related input variables were typically asymmetrical around their inventory estimates. Bias (or systematic uncertainties) associated with the emission factors was incorporated into the analysis when expert judgments were applied to the laboratory test results in determining the uncertainty characteristics and/or the bounds of the emission factors.[46] The results of this analysis are reported in the section below, titled *Quantitative Estimates of Uncertainty*.

Non-Highway Vehicles

Emissions from non-highway vehicles are a small portion of total emissions from mobiles sources, representing 22 percent of CH_4 emissions from mobile sources and 10 percent of N_2O emissions from mobile sources in 2004. Since they comprise a small share of mobile source emissions, even large uncertainties in these estimates would have a relatively small impact on the total emission estimate for mobile sources. As a result, a quantitative analysis of uncertainty of emissions from non-highway vehicles has not been performed. However, sources of uncertainty for non-highway vehicles are being investigated by examining the underlying uncertainty of emission factors and fuel consumption data.

Overall, a significant amount of uncertainty is associated with the emission estimates for non-road sources. A primary cause is a large degree of uncertainty surrounding emission factors. The IPCC *Good Practice Guidance* reports that CH_4 emissions from aviation and marine sources may be uncertain by a factor of two, while N_2O emissions may be uncertain by an order of magnitude for marine sources and several orders of magnitude for aviation. No information is provided on the uncertainty of emission factors for other non-highway sources.

Fuel consumption data have a lower uncertainty than emission factors, though large uncertainties do exist for individual sources. Fuel consumption for off-highway vehicles (i.e., equipment used for agriculture, construction, lawn and garden, railroad, airport ground support, etc., as well as recreational vehicles) was generated by EPA's NONROAD model (EPA 2004). This model estimates fuel consumption based on estimated equipment/vehicle use (in hours) and average fuel consumed per hour of use. Since the fuel estimates are not based upon documented fuel sales or consumption, a fair degree of uncertainty accompanies these estimates.

Estimates of distillate fuel sales for ships and boats were obtained from EIA's *Fuel Oil and Kerosene Sales* (EIA 1991 through 2004). These estimates have a moderate level of uncertainty since EIA's estimates are based on survey data and reflect sales to economic sectors, which may include use by both mobile and non-mobile sources within a sector. Domestic consumption of residual fuel by ships and boats is obtained from EIA (2005a). These estimates fluctuate widely from year to year, and are believed to be highly uncertain. In addition, estimates of distillate and residual fuel sales for ships and boats are adjusted for bunker fuel consumption, which introduces an additional (and much higher) level of uncertainty.

Jet fuel and aviation gasoline consumption data are obtained from EIA (2005a). Estimates of jet fuel consumption are also adjusted downward to account for international bunker fuels, introducing a significant amount of uncertainty. Additionally, all jet fuel consumption in the transportation sector is assumed to be consumed by aircraft. Some fuel purchased by airlines is not used in aircraft but instead used to power auxiliary power units, in ground equipment, and to test engines. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil.

[46] Random uncertainties are the main focus of statistical uncertainty analysis. Uncertainty estimates elicited from experts include both random and systematic uncertainty. Hence, both these types of uncertainty are represented in this uncertainty analysis.

In calculating CH_4 emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that CH_4 emissions occur only during the landing and take-off (LTO) cycles, with no CH_4 being emitted during the cruise cycle. However, a better approach would be to apply emission factors based on the number of LTO cycles.

Quantitative Estimates of Uncertainty

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-27. Mobile combustion CH_4 emissions in 2004 were estimated to be between 2.7 and 3.0 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 8 percent below to 4 percent above the 2004 emission estimate of 2.9 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions in 2004 were estimated to be between 36.1 and 55.3 Tg CO_2 Eq., indicating a range of 16 percent below to 29 percent above the 2004 emission estimate of 42.8 Tg CO_2 Eq.

Table 3-27: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Mobile Sources	CH_4	2.9	2.7	3.0	-8%	+4%
Mobile Sources	N_2O	42.8	36.1	55.3	-16%	+29%

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

This uncertainty analysis is a continuation of a multi-year process for developing credible quantitative uncertainty estimates for this source category using the IPCC Tier 2 approach to uncertainty analysis. In the upcoming years, the type and the characteristics of the actual probability density functions underlying the input variables will be identified and more credibly characterized. Accordingly, the quantitative uncertainty estimates reported in this section should be considered as preliminary and illustrative.

QA/QC and Verification

A source-specific QA/QC plan for mobile 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 focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between this year's and last year's Inventories was also conducted, and was qualitatively assessed to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

In order to ensure the highest quality estimates, the methodology is continuously revised based on comments from internal and external reviewers. This year, a number of adjustments were made to the historical data. Vehicle age distributions for 1999 forward were revised based on new data obtained from EPA's MOVES model (EPA 2005d). Diesel fractions for light trucks and medium-heavy trucks for 1998 through 2003 were updated based on data obtained from the *Vehicle Inventory and Use Survey* (Census 2000). The value for diesel consumption by boats was adjusted to remove all military bunker fuel consumption, which had not been properly removed from the estimates in previous version of the Inventory. Lastly, vehicle miles traveled and fuel consumption estimates for non-highway vehicles were revised for 2003 based on updated data from FHWA's *Highway Statistics* (FHWA 2005).

As a result of these changes, average estimates of CH_4 and N_2O emissions from mobile combustion decreased less than 0.1 Tg CO_2 Eq. (less than 1 percent) each year for the period 1990 through 2003.

Planned Improvements

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

1) *Update CH_4 and N_2O Emission Factors for Highway Vehicles*—A number of recent efforts have focused on improving the estimates of CH_4 and N_2O Emission Factors for alternative fuel highway vehicles. These studies are expected to be available next year, and will be reviewed to determine whether the current emission factors can be updated.

2) Continue the *Reconciliation of Fuel Consumption Estimates used for Calculating N_2O/CH_4 and CO_2*—Estimates of transportation fuel consumption by fuel type from EIA are used as the basis for estimating CO_2 emissions from the transportation sector. These estimates are then apportioned to mode and vehicle category based on "bottom up" estimates of fuel consumption from sources such as FHWA's *Highway Statistics* (FHWA 1996 through 2004) and DOE's *Transportation Energy Data Book* (DOE 1993 through 2004). These sources are also used to develop N_2O and CH_4 estimates. The EPA fuel consumption estimates, however, differ from the estimates derived using "bottom up" sources. For this Inventory, estimates of distillate fuel consumption have been reconciled. Potential improvements include reconciling additional fuel consumption estimates from EIA and other data sources, and revising the current process of allocating CO_2 emissions to particular vehicle types.

3) *Improve consideration of emissions from trucks used off-road*—Some light- and heavy-duty trucks travel for a portion of their mileage off-road. N_2O and CH_4 estimates for highway vehicles are developed based on vehicle mileage data from FHWA's *Highway Statistics*, which in turn, are drawn from the Highway Performance Monitoring System (HPMS). These emission estimates do not address travel by trucks off-road. Gasoline fuel consumed by trucks used off-road for construction, agriculture, and other industrial/commercial uses is reported in *Highway Statistics*, and is included as part of the non-road agriculture and construction categories. However, diesel fuel consumed by trucks used off-road is not addressed in the Inventory, and further work should be conducted to develop estimates of off-road truck use of diesel fuel. In addition, default emission factors from IPCC are applied to the off-highway modes. As a result, the emissions factors for agricultural equipment are applied both to equipment and trucks used in agriculture, and emissions factors for construction equipment are applied both to equipment and trucks used in construction.

4) *Improve estimation of VMT by vehicle/fuel type category*—The current Inventory process for estimating VMT by vehicle/fuel type category involves apportioning VMT by vehicle type to each fuel type on the basis of fuel consumption. While this is a reasonable simplification, this approach implicitly assumes the same average fuel economy for gasoline and diesel vehicles. A more accurate apportionment for VMT by fuel type for light-duty trucks and medium/heavy-duty trucks could potentially be developed using data on vehicle travel from the Vehicle Inventory and Use Survey (Census 2000) and other publications, or using VMT breakdowns by vehicle/fuel type combinations from the MOBILE6 or MOVES models.

3.5. 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. All 115 gassy underground coal mines 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, twenty-one 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 2004, eleven coal mines collected CH_4 from degasification systems and sold this gas to a pipeline, thus reducing emissions to the atmosphere. In addition, one coal mine used CH_4 from its degasification system to heat mine ventilation air on site. Two of the coal mines that sold gas to pipelines also used CH_4 to generate electricity or 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 2004 were estimated to be 56.3 Tg CO_2 Eq. (2,682 Gg), a decline of 31 percent since 1990 (see Table 3-28 and Table 3-29). Of this amount, underground mines accounted for 69 percent, surface mines accounted for 17 percent, and post-mining emissions accounted for 14 percent. In 1993, CH_4 generated from underground mining dropped, primarily due to labor strikes at many large underground mines. In 1994 and 1995, CH_4 emissions increased due to resumed production at high emitting mines after the labor strike. 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. CH_4 emissions increased slightly in 2003 due to additional gas drainage being vented to the atmosphere and a reduction in CH_4 recovery. Recovery continued to decrease in 2004 with reduced production from pre-drainage wells, increased use of horizontal gob wells that are vented to the atmosphere, and temporary closure of a major project due to a mine fire. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 2004.

Table 3-28: CH_4 Emissions from Coal Mining (Tg CO_2 Eq.)

Activity	1990		1997	1998	1999	2000	2001	2002	2003	2004
Underground Mining	62.1		44.3	44.5	41.7	39.4	38.0	35.9	38.6	38.9
Liberated	67.6		55.7	58.6	54.4	54.0	54.2	53.3	53.6	52.8
Recovered & Used	(5.6)		(11.4)	(14.1)	(12.7)	(14.6)	(16.1)	(17.4)	(15.0)	(13.9)
Surface Mining	10.4		9.3	9.4	9.0	8.8	9.2	8.8	8.4	9.3
Post-Mining (Underground)	7.7		7.4	7.4	6.8	6.7	6.8	6.4	6.4	6.6
Post-Mining (Surface)	1.7		1.5	1.5	1.5	1.4	1.5	1.4	1.4	1.5
Total	**81.9**		**62.6**	**62.8**	**58.9**	**56.3**	**55.5**	**52.5**	**54.8**	**56.3**

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

Table 3-29: CH_4 Emissions from Coal Mining (Gg)

Activity	1990		1997	1998	1999	2000	2001	2002	2003	2004
Underground Mining	2,956		2,111	2,118	1,985	1,878	1,811	1,708	1,839	1,851
Liberated	3,220		2,654	2,791	2,589	2,573	2,580	2,538	2,554	2,512
Recovered & Used	(265)		(543)	(673)	(605)	(695)	(769)	(830)	(716)	(661)
Surface Mining	497		445	448	428	417	438	420	402	444
Post-Mining (Underground)	367		354	352	325	317	323	304	305	315
Post-Mining (Surface)	81		72	73	69	68	71	68	65	72
Total	**3,900**		**2,983**	**2,990**	**2,807**	**2,679**	**2,644**	**2,500**	**2,611**	**2,682**

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

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[47] CH_4 concentrations. These mine-by-mine measurements are used to estimate CH_4 emissions from

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

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-one 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. This calculation was complicated by the fact that most CH_4 is not recovered and used during the same year in which the particular coal seam is mined. In 2004, eleven active coal mines sold recovered CH_4 into the local gas pipeline networks, while one coal mine used recovered CH_4 on site. 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 *Coal Industry Annual* (see Table 3-30) (EIA 2004), 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 (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 3-30: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,250	546,818	931,068
1991	368,635	532,656	901,291
1992	368,627	534,290	902,917
1993	318,478	539,214	857,692
1994	362,065	575,529	937,594
1995	359,477	577,638	937,115
1996	371,816	593,315	965,131
1997	381,620	607,163	988,783
1998	378,964	634,864	1,013,828
1999	355,433	642,877	998,310
2000	338,173	635,592	973,765
2001	345,305	676,142	1,021,446
2002	324,219	667,619	991,838
2003	320,047	651,251	971,297
2004	333,424	687,497	1,020,921

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

liberated and 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 increase if the drainage area is found to be larger 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 3-31. Coal mining CH_4 emissions in 2004 were estimated to be between 54.1 and 58.6 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 4 percent below to 4 percent above the 2004 emission estimate of 56.3 Tg CO_2 Eq.

Table 3-31: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Coal Mining	CH_4	56.3	54.1	58.6	-4%	+4%

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

Recalculations Discussion

Recalculations were performed on all years with negligible changes in 1994, 1996, and 1998-2002, as QA/QC of databases uncovered that emissions avoided had been miscalculated. Some recalculations were done in 2003 on Alabama mines but were not linked retroactively. These recalculations either led to no change in net emissions, or a change of 0.1 Tg CO_2 Eq. Emissions avoided for 2003 were adjusted downwardly as a major operator reported in 2004 that double-counting of some pre-drainage wells had previously occurred. Correction of this error led to a reduction in emissions avoided of 1.0 Tg CO_2 Eq. which changed total emissions for 2003 from 53.8 to 54.8 Tg CO_2 Eq.

Planned Improvements

To reduce the uncertainty associated with the radius of influence of each well, the appropriate drainage radius will be investigated for future inventories. Since the number of wells counted may increase if the drainage area is found to be larger than currently estimated, additional mines may be included in future estimates of recovery.

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

All underground and surface coal mining liberates CH_4 as part of the normal mining operations. The amount of CH_4 liberated depends on the amount that resides in the coal ("*in situ*") and surrounding strata when mining occurs. The in-situ CH_4 content depends upon the amount of CH_4 created during the coal formation (i.e., coalification) process, and the geologic characteristics of the coal seams. During coalification, more deeply buried deposits tend to generate more CH_4 and retain more of the gas after uplift to minable depths. Deep underground coal seams generally have higher CH_4 contents than shallow coal seams or surface deposits.

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 close and are 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 9.0 Tg CO_2 Eq. from 1990 through 2004, varying, in general, by approximately 1 to 18 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. Abandoned mine emissions peaked in 1996 (9.0 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 thirteen gassy mine closures during each of the years from 1998 through 2004, with only one closure in 2004. By 2004, abandoned mine emissions were reduced to 5.7 Tg CO_2 Eq. (see Table 3-32 and Table 3-33).

Table 3-32: CH_4 Emissions from Abandoned Coal Mines (Tg CO_2 Eq.)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
Abandoned Underground Mines	6.0	8.6	8.6	8.7	8.0	7.6	7.3	7.1
Recovered & Used	0.0	1.7	1.6	1.5	1.5	1.6	1.5	1.5
Total	**6.0**	**6.9**	**6.9**	**7.2**	**6.6**	**6.0**	**5.8**	**5.6**

Note: Totals may not sum due to independent rounding.

Table 3-33: CH_4 Emissions from Abandoned Coal Mines (Gg)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
Abandoned Underground Mines	287	407	407	415	383	362	349	339
Recovered & Used	0	79	77	72	70	74	72	70
Total	**287**	**328**	**330**	**343**	**313**	**288**	**277**	**269**

Note: Totals may not sum due to independent rounding.

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 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. 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, P_r, declines as described by the isotherm. The emission rate declines because the mine pressure (P_w) 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 mcf/d
- q_i = Initial gas rate at time zero (t_o) in million cubic feet per day (mcfd)
- b = The hyperbolic exponent, dimensionless
- D_i = Initial decline rate, 1/yr
- T = Elapsed time from to in 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 are also affected by both sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within 8 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).

$$q = q_ie^{(-Dt)}$$

where,

- q = Gas flow rate at time t in mcf/d
- q_i = Initial gas flow rate at time zero (t_o) in mcfd
- D = Decline rate, 1/yr
- t = Elapsed time from t_o in 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 438 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 263 of the 438 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 are helpful, but do 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, throughout the 20th century. The data was 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. 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. CH_4 degasification amounts were added to ventilation data for the total CH_4 liberation rate for fourteen mines that closed between 1992 and 2004. 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 2004, 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. Once the low, mid, and high values are selected, they are applied to a probability density function.

The emission estimates from underground ventilation systems were based on actual measurement data, which are believed to have relatively low uncertainty. A degree of imprecision was introduced because the measurements were not continuous, but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used may have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky and Wang 2000). Estimates of CH_4 liberated and recovered by degasification systems are also relatively certain because many coal mine operators provided information on individual well gas sales and mined through dates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-34. Abandoned coal mines CH_4 emissions in 2004 were estimated to be between 4.7 and 7.0 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 18 percent below to 23 percent above the 2004 emission estimate of 5.6 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 ±50 percent uncertainty.

Table 3-34: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	5.6	4.7	7.0	-18%	+23%

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

QA/QC and Verification

As part of a Tier 2 analysis, the United States undertook an effort to verify the model results used in the U.S. Inventory with field measurements. Field measurements were used to test the accuracy of the mathematical decline curves to be used for basin-specific emissions estimates. A series of field measurements were conducted at abandoned mine vent locations across the United States. Between November 1998 and February 2000, EPA recorded measurements at five mines that were not flooded. Measurements were recorded at two abandoned mines located in Ohio and Virginia continuously for 6 to 12 hours. As the methodology was finalized, EPA measured emissions from three additional mines located in Illinois and Colorado. These measurements were recorded hourly for 3 to 4 days and were normalized to average barometric pressures. Prior to these measurements, EPA's Office of Research and Development initiated a field research program in the early 1990s. Data for 21 abandoned mines located throughout the Northern and Central Appalachian, Black Warrior, and Illinois Basins were collected using similar techniques.

Measurements for all field data recorded were plotted against predicted emissions as part of the two studies from 1991 through 2000. Emission rates from nine of the ten mines that were measured fall very close to the predicted mid-case decline rate for their respective basins. For the exponential decline curve fit to the flooding mines, six of nine measurements fall within a 95 percent predictive confidence interval of the mean.

Of the abandoned mines in the database, only about 12 percent of the mines maintain vents to the atmosphere. Therefore, it is difficult to obtain field data. Additional field measurements, however, would be beneficial to further calibrate the equations defined above. Furthermore, it would be useful to extend measurements of diffuse emissions from sealed mines, since they comprise 44 percent of total mines.

Recalculations Discussion

In 2005, CH_4 emissions from abandoned mines were recalculated for 1990-2003. QA/QC of the database uncovered several mines that had been accounted for more than once. Changes in MSHA's database regarding date of abandonment for several mines led to adding them more than once—once for each time reported abandoned. Also, sale of mines and resultant renaming caused two mines to be added twice with different names.

Emissions for 2003 were recalculated, as additional recovery data for one mine was obtained, resulting in an increase of 0.1 Tg CO_2 Eq. in the amount of CH_4 recovered and used. Recalculation of the CH_4 emissions from flooded, abandoned mines yielded a decrease of 0.1 Tg CO_2 Eq. in CH_4 emitted for 2003. Additionally, a research project conducted on abandoned mine status yielded updates to the status of 19 mines, ten of which were previously designated "unknown." Recalculations led to a decrease in emissions each inventory year. The total emissions for 2003 decreased from 6.2 Tg CO_2 Eq. to 5.8 Tg CO_2 Eq. Data for other years from 1990-2002 saw similar changes, the most significant decrease occurring in total emissions for 2000 of 0.5 Tg CO_2 Eq.

3.7. 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 is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Total CH_4 emissions from

petroleum systems in 2004 were 25.65 Tg CO_2 Eq. (1,222 Gg). Since 1990, emissions declined due to a decline in domestic oil production and industry efforts to make emissions reductions (see Table 3-38 and Table 3-39). The various sources of emissions are detailed below.

Production Field Operations. Production field operations account for over 97 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 90 percent of the emissions from the production sector, fugitive emissions account for four percent, combustion emissions six percent, and process upset emissions just barely over one-tenth of a percent. The most dominant sources of vented emissions are offshore oil platforms (shallow and deep water platforms), field storage tanks and natural-gas-powered pneumatic devices (low bleed and high bleed). These five sources alone emit over 84 percent of the production field operations emissions. Offshore platform emissions are a combination of fugitive, vented, and combustion emissions from all equipment housed on the platform. 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 high and low-bleed pneumatics occur when pressurized gas that is used for control devices is bled to the atmosphere as they cycle up and down to modulate the system. Two additional large sources, chemical injection pumps and gas engines, together account for 10 percent of emissions from the production sector. The remaining eight percent of the emissions are distributed among 26 additional activities within the four categories: vented, fugitive, combustion and process upset emissions.

Crude Oil Transportation. Crude oil transportation activities account for less than one percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for 66 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 18 percent. The remaining 16 percent is distributed among four additional sources within these two categories.

Crude Oil Refining. Crude oil refining processes and systems account for only slightly over 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 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 from unburned CH_4 in engine exhausts and flares.

Table 3-35: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Production Field Operations	**33.8**		**29.0**	**27.8**	**27.1**	**26.7**	**26.1**	**25.3**	**25.0**
Pneumatic device venting	11.5		10.6	10.2	10.0	10.0	9.9	9.8	9.8
Tank Venting	3.8		3.4	3.2	3.2	3.2	3.2	3.1	3.0
Combustion & process upsets	1.8		1.7	1.6	1.6	1.6	1.6	1.5	1.5
Misc. venting & fugitives	16.2		12.8	12.3	11.8	11.4	10.9	10.3	10.2
Wellhead fugitives	0.5		0.5	0.5	0.5	0.5	0.5	0.5	0.5
Crude Oil Transportation	**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.5**		**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total	**34.4**		**29.7**	**28.5**	**27.8**	**27.4**	**26.8**	**25.9**	**25.7**

Table 3-36: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Production Field Operations	**1,609**		**1,381**	**1,326**	**1,292**	**1,271**	**1,242**	**1,203**	**1,188**
Pneumatic device venting	545		504	488	478	475	473	466	464
Tank Venting	179		162	154	154	154	151	150	143
Combustion & process upsets	88		80	76	76	75	75	73	73
Misc. venting & fugitives	771		610	584	562	545	520	492	486
Wellhead fugitives	26		25	24	22	22	23	22	23

Activity	1990	1998	1999	2000	2001	2002	2003	2004
Crude Oil Transportation	**7**	**6**	**6**	**5**	**5**	**5**	**5**	**5**
Refining	**25**	**27**	**27**	**28**	**27**	**27**	**27**	**28**
Total	**1,640**	**1,414**	**1,358**	**1,325**	**1,303**	**1,274**	**1,236**	**1,222**

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 1999, Radian 1996e). 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 EPA (1999) and Radian (1996e) studies. 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. For offshore oil production, two emission factors were calculated using data collected over a one-year period for all federal offshore platforms (MMS 2005c). 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 2004. 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 2005a,b,d).

Activity factors for years 1990 through 2004 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 Radian (1996e). For example, Radian (1996e) 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 Radian (1996e). In other cases, the activity factor was held constant from 1990 through 2004 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. See Annex 3.5 for additional detail.

Nearly all emission factors were taken from Radian (1996e) and EPA (1995, 1999). The remaining emission factors were taken from the following sources: EPA default values, MMS reports (MMS 2005c), the Exploration and Production (E&P) Tank model (DB Robinson Research Ltd. 1997), 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 1990-2004, 1995-2004, 1995-2005), the API *Basic Petroleum Data Book* (API 2004), *Methane Emissions from the Natural Gas Industry* by the Gas Research Institute and EPA (Radian 1996a-d,f), consensus of industry peer review panels, MMS reports (MMS 2001, 2005a,b,d), the *Oil & Gas Journal* (OGJ 2004a-b) and the United States Army Corps of Engineers (1995-2003).

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 with 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 five major sources, which account for 86 percent of the total emissions, the uncertainty surrounding these five 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 3-40. Petroleum systems CH_4 emissions in 2004 were estimated to be between 17.2 and 61.8 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 33 percent below to 141 percent above the 2004 emission estimate of 25.7 Tg CO_2 Eq.

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

Source	Gas	2004 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
Petroleum Systems	CH_4	25.7	17.2	61.8	-33%	+141%

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

Recalculations Discussion

Estimates of CH_4 from petroleum systems contain one major change with respect to previous inventories. In previous years, offshore production emissions were calculated as eight separate sources (2 categories of fugitives, 2 categories of venting, 2 categories of combustion, and 2 categories of process upsets) but new analysis of the 2000 GOADS report (MMS 2005c) yields comprehensive emissions factors for shallow water and deep water gas platforms. The shallow water and deep water sources from the GOADS analysis account for all offshore emissions and have replaced the eight sources from previous inventories.

The combination of these changes resulted in an average annual increase of 11.8 Tg CO_2 Eq. (63 percent) in CH_4 emissions from petroleum systems for the period 1990 through 2003. Emissions from offshore oil platforms account for the entire change in emissions.

Planned Improvements

Several improvements to the emission estimates are being evaluated that fine-tune and better track changes in emissions. These include, but are not limited to, some activity factors that are also accounted for in the Natural Gas STAR Program emission reductions, some emission factors for consistency between emission estimates from Petroleum Systems and Natural Gas Systems, and new data from recent studies that bear on both emission factors and activity factors. The growing body of data in the Natural Gas STAR Program, coupled with an increasing number of oil and gas companies doing internal greenhouse gas emissions inventories, provides an opportunity to reevaluate emission and activity factors, as well as the methodology currently used to project emissions from the base year.

Changes in state regulations, new facility construction, and activities of natural gas industry entities outside of the Natural Gas STAR program can lead to alterations in emissions profile that are not specifically accounted for in the current emissions inventory. Research of publicly available data sources will be conducted to develop a methodology for adjusting emissions factors over the inventory time series to account for these fluctuations.

3.8. 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 118.8 Tg CO_2 Eq. (5,658 Gg) of CH_4 in 2004, a slight decrease over 1990 emissions (see Table 3-38 and Table 3-39). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions.

CH_4 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 combusting engines and turbine 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 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 emissions. Emissions from field production accounted for approximately 33 percent of CH_4 emissions from natural gas systems in 2004.

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 emissions from compressors, including compressor seals, are the primary emission source from this stage. Processing plants account for about 12 percent of CH_4 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 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 exhaust are also sources of 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. CH_4 emissions from the transmission and storage sector account for approximately 32 percent of 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 1,135,000 miles of distribution mains in 2004, an increase from just over 944,000 miles in 1990 (OPS 2005b). Distribution system emissions, which account for approximately 23 percent of emissions from natural gas systems, result mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[48] An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage. Distribution system emissions in 2004 were 13 percent lower than 1990 levels.

Table 3-38: CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)*

[48] The percentages of total emissions from each stage may not sum to 100 percent due to independent rounding.

Stage	1990	1998	1999	2000	2001	2002	2003	2004
Field Production	34.0	38.2	35.3	39.2	42.3	43.5	42.1	39.3
Processing	14.8	14.8	14.7	14.9	15.0	14.5	14.5	14.0
Transmission and Storage	46.8	44.3	43.1	43.1	39.6	41.3	41.2	38.4
Distribution	31.0	28.2	28.7	29.6	28.7	26.0	26.9	27.1
Total	**126.7**	**125.4**	**121.7**	**126.7**	**125.6**	**125.4**	**124.7**	**118.8**

*Including CH_4 emission reductions achieved by the Natural Gas STAR program.
Note: Totals may not sum due to independent rounding.

Table 3-39: CH_4 Emissions from Natural Gas Systems (Gg)*

Stage	1990	1998	1999	2000	2001	2002	2003	2004
Field Production	1,621	1,819	1,679	1,865	2,014	2,073	2,007	1,873
Processing	706	704	698	708	716	691	688	667
Transmission and Storage	2,230	2,110	2,051	2,052	1,884	1,968	1,963	1,827
Distribution	1,477	1,341	1,369	1,407	1,367	1,239	1,281	1,291
Total	**6,034**	**5,973**	**5,797**	**6,033**	**5,981**	**5,971**	**5,939**	**5,658**

*Including CH_4 emission reductions achieved by the Natural Gas STAR program.
Note: Totals may not sum due to independent rounding.

Methodology

The primary basis for estimates of CH_4 emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 100 emission and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The 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. 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 emissions from natural gas systems.

Activity factor data were taken from the following sources: American Gas Association (AGA 1991-1998); American Petroleum Institute (API 2005); Minerals and Management Service (MMS 2005a-e); Monthly Energy Review (EIA 2005e); Natural Gas Liquids Reserves Report (EIA 2004b); Natural Gas Monthly (EIA 2005c,d,f); the Natural Gas STAR Program annual emissions savings (EPA 2005); Oil and Gas Journal (OGJ 1999–2005); Office of Pipeline Safety (OPS 2005a-b) and other Energy Information Administration publications (EIA 2004a, 2005a,b,g). Data from a program for estimating emissions from hydrocarbon production tanks is incorporated (DB Robinson Research Ltd. 1997). Coalbed CH_4 well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2005) and the Alabama State Oil and Gas Board (Alabama 2005). Other state well data was taken from: American Association of Petroleum Geologists (AAPG 2204); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2005); Montana Board of Oil and Gas Conservation (Montana 2005); Oklahoma Geological Survey (Oklahoma 2005); Morgan Stanley (Morgan Stanley 2005)Rocky Mountain Production Report (Lippman (2003); New Mexico Oil Conservation Division (New Mexico 2005a,b); Texas Railroad Commission (Texas 2005a-c); Utah Division of Oil, Gas and Mining (Utah 2005). Emissions factors were taken from EPA/GRI (1996).

Uncertainty

An quantitative uncertainty analysis was conducted to determine the level of uncertainty surrounding inventory 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 3-40. Natural gas systems CH_4 emissions in 2004 were estimated to be between 84.3 and 155.5 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 29 percent below to 31 percent above the 2004 emission estimate of 118.8 Tg CO_2 Eq.

Table 3-40: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Natural Gas Systems	CH_4	118.8	84.3	155.5	-29%	+31%

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

Recalculations Discussion

Significant changes were made to the emission calculations in the Production sector. The first change was a restructuring of sources to follow the EIA's National Energy Modeling System (NEMS) regions for oil and gas production in the United States. The EIA's NEMS groups oil and gas production into six distinct regions: North East, Mid-Central, Rocky Mountains, South West, West Coast, and Gulf Coast. The first step in the restructuring of the emissions from the production sector was to divide emissions from each source into NEMS regions using equivalent emissions factors but localized activity data. The net effect of this restructuring on the historical emission estimates is negligible, but did involve changes in the uncertainty estimate calculations. Several large sources from the previous year's inventory were broken down into smaller regional sources and a new set of top-ten sources that represent a major portion of the total emissions from the natural gas industry have been chosen to calculate the uncertainty of the estimate. A future step in the restructuring of the production sector emissions estimates will be to develop specific region emissions and activity factors.

Another change in this year's estimates is the methodology for calculating offshore natural gas production emissions. In previous years, offshore production emissions were calculated as five separate sources (2 categories of fugitives, venting, flaring, and emergency shut-downs), but analysis of new data in the 2000 Gulf-wide Offshore Air Data System (GOADS) report (MMS 2005c) yields comprehensive emissions factors for shallow water and deep water gas platforms. The shallow water and deep water sources from the GOADS analysis account for all offshore emissions and have replaced the five sources from previous inventories.

Finally, the emission factor for plastic pipelines (used in the distribution sector) was changed this year from the previous 11.40 scf/hr to 5.85scf/hr based on additional data points from the Southern California Gas Company (1991). The new emission factor reflects plastic pipeline produced before 1982; a lower emission factor of 0.99 scf/hr is estimated for plastic pipeline produced after 1982. Because activity data can not be appropriately disaggregated into these two time frames, the pre-1982 value is used for all years. If activity data become available to distinguish pre- and post-1982 plastic pipeline the emission estimates will be subsequently revised.

The combination of these methodological and historical data changes resulted in an average annual decrease of 4.5 Tg CO_2 Eq. (3 percent) in CH_4 emissions from natural gas systems for the period 1990 through 2003.

Planned Improvements

Several improvements to the emission estimates are being evaluated that fine-tune and better track changes in emissions. These include, but are not limited to, some activity factors that are also accounted for in the Natural Gas STAR Program emission reductions, some emission factors for consistency between emission estimates from the Petroleum Systems and Natural Gas Systems source categories, and new data from recent studies that bear on both emission factors and activity factors. The growing body of data in the Natural Gas STAR Program, coupled with an increasing number of oil and gas companies doing internal greenhouse gas emissions inventories, provides an opportunity to reevaluate emission and activity factors, as well as the methodology currently used to project emissions from the base year.

Changes in state regulations, new facility construction, and activities of natural gas industry entities outside of the Natural Gas STAR program can lead to fluctuations in emissions that are not specifically accounted for in the current emissions inventory. Research of publicly available data sources will be conducted to develop a methodology for adjusting emissions factors over the inventory time series to account for these fluctuations.

Improvements to emissions and activity factors in the NEMS production regions will be a major focus in upcoming inventories. This second step in the restructuring of the production sector estimates requires the development of unique regional factors to reflect the differences in the natural gas industries' operations throughout the United States.

3.9. Municipal Solid Waste Combustion (IPCC Source Category 1A5)

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) 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 2000c, Goldstein and Matdes 2001, Kaufman et al. 2004). Almost all combustion of municipal solid wastes in the United States occurs at waste-to-energy facilities where energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Combustion of municipal solid wastes results in conversion of the organic inputs to CO_2. According to the 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 combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon 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 carbon 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. Tires (which contain rubber and carbon black) are also considered a "non-hazardous" waste and are included in the municipal solid waste combustion estimate, though waste disposal practices for tires differ from the rest of municipal solid waste.

Approximately 30 million metric tons of municipal solid wastes were combusted in the United States in 2003 (see Table 3-46). CO_2 emissions from combustion of municipal solid wastes rose 78 percent since 1990, to an estimated 19.4 Tg CO_2 Eq. (19,360 Gg) in 2004, as the volume of plastics and other fossil carbon-containing materials in MSW increased (see Table 3-41 and Table 3-42). Waste combustion is also a source of N_2O emissions (De Soete 1993). N_2O emissions from municipal solid waste combustion were estimated to be 0.5 Tg CO_2 Eq. (1 Gg) in 2004, and have not changed significantly since 1990.

Table 3-41: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Tg CO_2 Eq.)

Gas/Waste Product	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	**10.9**		**17.1**	**17.6**	**17.9**	**18.6**	**18.9**	**19.4**	**19.4**
Plastics	8.0		11.4	12.0	12.1	12.6	12.6	12.9	12.9
Synthetic Rubber in Tires	0.2		0.9	0.9	0.9	0.9	1.0	1.0	1.0

Carbon Black in Tires	0.2		1.2	1.2	1.2	1.2	1.2	1.3	1.3
Synthetic Rubber in MSW	1.3		1.6	1.6	1.7	1.8	1.8	1.8	1.8
Synthetic Fibers	1.2		2.0	2.0	2.1	2.2	2.2	2.3	2.3
N_2O	**0.5**		**0.4**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**
Total	**11.4**		**17.5**	**18.0**	**18.3**	**19.1**	**19.4**	**19.9**	**19.9**

Table 3-42: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	**10,919**		**17,094**	**17,632**	**17,921**	**18,634**	**18,862**	**19,360**	**19,360**
Plastics	7,953		11,427	11,950	12,095	12,599	12,630	12,885	12,885
Synthetic Rubber in Tires	191		887	890	893	895	952	1,010	1,010
Carbon Black in Tires	249		1,160	1,164	1,167	1,170	1,245	1,320	1,320
Synthetic Rubber in MSW	1,330		1,627	1,612	1,682	1,793	1,804	1,848	1,848
Synthetic Fibers	1,196		1,992	2,016	2,085	2,177	2,231	2,298	2,298
N_2O	**2**		**1**	**1**	**1**	**1**	**2**	**2**	**2**

Indirect greenhouse gases are also emitted during waste incineration and open burning, as shown in Table 3-43. These emissions are a relatively small portion of the overall indirect greenhouse gas emissions, comprising less than 5 percent for each gas over the entire time series.

Table 3-43: NO_x, CO, and NMVOC Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
NO_x	**82**		**145**	**143**	**114**	**114**	**134**	**134**	**134**
Waste Incineration	44		49	48	38	38	45	45	45
Open Burning	38		96	95	76	76	89	89	89
CO	**978**		**2,826**	**2,725**	**1,670**	**1,672**	**1,672**	**1,672**	**1,672**
Waste Incineration	337		69	66	40	41	41	41	41
Open Burning	641		2,757	2,659	1,630	1,631	1,631	1,631	1,631
NMVOCs	**222**		**326**	**302**	**257**	**258**	**281**	**282**	**282**
Waste Incineration	44		23	19	15	16	18	18	18
Open Burning	178		303	284	242	242	264	264	264

Note: Totals may not sum due to independent rounding.

Methodology

Emissions of CO_2 from MSW combustion include CO_2 generated by the combustion of plastics, synthetic fibers, and synthetic rubber, as well as the combustion of synthetic rubber and carbon black in tires. These emissions were calculated by multiplying the amount of each material combusted by the carbon content of the material and the fraction oxidized (98 percent). Plastics combusted in municipal solid wastes were categorized into seven plastic resin types, each material having a discrete carbon content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete carbon content. Scrap tires contain several types of synthetic rubber, as well as carbon black. Each type of synthetic rubber has a discrete carbon content, and carbon black is 100 percent carbon. 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 combustion sources is provided in Annex 3.6.

For each of the methods used to calculate CO_2 emissions from municipal solid waste combustion, data on the quantity of product combusted and the carbon content of the product are needed. For plastics, synthetic rubber, and synthetic fibers, the amount of material in municipal solid wastes and its portion combusted were taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c, 2002a, 2003, 2005a). For synthetic rubber and carbon black in scrap tires, this information was provided by the *U.S. Scrap Tire Markets 2003* (RMA 2004) and *Scrap Tires, Facts and Figures* (STMC 2000, 2001, 2002, 2003, 2004). Data were not available for

2004, so the values were assumed to equal the value for 2003.

Average carbon 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. For synthetic rubber in scrap tires information about scrap tire composition was taken from the Scrap Tire Management Council's internet site (STMC 2003).

The assumption that 98 percent of organic carbon is oxidized (which applies to all municipal solid waste combustion categories for CO_2 emissions) was reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2002b).

Combustion of municipal solid waste also results in emissions of N_2O. These emissions were calculated as a function of the total estimated mass of municipal solid waste combusted and an emission factor. The N_2O emission estimates are based on different data sources. As noted above, N_2O emissions are a function of total waste combusted in each year; for 1990 through 2003, these data were derived from the information published in *BioCycle* (Kaufman et al 2004). As for the activity data for CO_2 emissions, data on total waste combusted was not available for 2004, so the value for this year was assumed to equal the most recent value available (2003). Table 3-44 provides data on municipal solid waste generation and percentage combustion 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).

Table 3-44: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Combusted (%)
1990	266,365,714	11.5
1991	254,628,360	10.0
1992	264,668,342	11.0
1993	278,388,835	10.0
1994	292,915,829	10.0
1995	296,390,405	10.0
1996	297,071,712	10.0
1997	308,870,755	9.0
1998	339,865,243	7.5
1999	347,089,277	7.0
2000	371,071,109	7.0
2001	404,002,786[a]	7.4[a]
2002	436,934,464	7.7
2003	436,934,464[b]	7.7[b]
2004	436,934,464[b]	7.7[b]

[a] Interpolated between 2000 and 2002 values.
[b] Assumed equal to 2002 value.

EPA (2005b) provided emission estimates for NO_x, CO, and NMVOCs from waste incineration and open burning, which were determined using industry published production data and applying average emission factors.

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 municipal solid waste combustion. 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 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, carbon content of carbon black).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-45. Municipal solid waste combustion CO_2 emissions in 2004 were estimated to be between 16.36 and 21.11 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 15 percent below to 9 percent above the 2004 emission estimate of 19.36 Tg CO_2 Eq. Also at a 95 percent confidence level, municipal solid waste combustion N_2O emissions in 2004 were estimated to be between 0.14 and 1.34 Tg CO_2 Eq. This indicates a range of 73 percent below to 157 percent above the 2004 emission estimate of 0.52 Tg CO_2 Eq.

Table 3-45: Tier 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from Municipal Solid Waste Combustion (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Municipal Solid Waste Combustion	CO_2	19.4	16.4	21.1	-15%	+10%
Municipal Solid Waste Combustion	N_2O	0.5	0.1	1.3	-73%	+157%

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

The uncertainties in the waste combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data.

- *MSW Combustion Rate.* A source of uncertainty affecting both fossil CO_2 and N_2O emissions is the estimate of the MSW combustion rate. The EPA (2000c, 2002a, 2003) estimates of materials generated, discarded, and combusted carry considerable uncertainty associated with the material flows methodology used to generate them. Similarly, the *BioCycle* (Glenn 1999, Goldstein and Matdes 2000, Goldstein and Matdes 2001, Kaufman et al. 2004) estimate of total waste combustion— used for the N_2O emissions estimate—is based on a survey of state officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. The survey methodology changed significantly and thus the results reported for 2002 are not directly comparable to the earlier results (Kaufman et al. 2004), introducing further uncertainty. Despite the differences in methodology and data sources, the two references— the EPA's Office of Solid Waste (EPA 2000a, 2002b, 2003) and the *BioCycle* series—provide estimates of total solid waste combusted that are relatively consistent (see Table 3-46).

Table 3-46: U.S. Municipal Solid Waste Combusted, as Reported by EPA and BioCycle (Metric Tons)

Year	EPA	BioCycle
1990	28,855,809	30,632,057
1991	27,773,783	25,462,836
1992	29,568,442	29,113,518
1993	28,696,188	27,838,884
1994	29,532,844	29,291,583
1995	32,182,194	29,639,040
1996	32,831,450	29,707,171
1997	33,597,844	27,798,368
1998	31,205,358	25,489,893
1999	30,859,134	24,296,249
2000	30,571,624	25,974,978
2001	30,416,919	29,694,205[a]
2002	30,340,252	33,643,954
2003	29,995,479	NA
2004	NA	NA

NA (Not Available)
[a] Interpolated between 2000 and 2002 values.

- *Fraction Oxidized.* Another source of uncertainty for the CO_2 emissions estimate is fraction oxidized. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. Despite this variability in oxidation rates, a value of 98 percent was assumed for this analysis.
- *Missing Data on Municipal Solid Waste Composition.* Disposal rates have been interpolated when there is an incomplete interval within a time series. Where data are not available for years at the end of a time series (1990, 2004), they are set equal to the most recent years for which estimates are available.
- *Average Carbon Contents.* Average carbon contents were applied to the mass of "Other" plastics combusted, synthetic rubber in tires and municipal solid waste, and synthetic fibers. These average values were estimated from the average carbon content of the known products recently produced. The true carbon content of the combusted waste may differ from this estimate depending on differences in the chemical formulation between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty is probably small since the major elastomers' carbon contents range from 77 to 91 percent; for plastics, where carbon contents range from 29 to 92 percent, it may be more significant. Overall, this is a small source of uncertainty.
- *Synthetic/Biogenic Assumptions.* A portion of the fiber and rubber in municipal solid waste is biogenic in origin. Assumptions have been made concerning the allocation between synthetic and biogenic materials based primarily on expert judgment.
- *Combustion Conditions Affecting N_2O Emissions.* Because insufficient data exist to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented exhibit high uncertainty. The emission factor for N_2O from municipal solid waste combustion facilities used in the analysis is an average of default values used to estimate N_2O emissions from facilities worldwide (Johnke 1999, UK: Environment Agency 1999, Yasuda 1993). These factors span an order of magnitude, reflecting considerable variability in the processes from site to site. Due to a lack of information on the control of N_2O emissions from MSW combustion facilities in the United States, the estimate of zero percent for N_2O emissions control removal efficiency also exhibits uncertainty.

Recalculations Discussion

Historical waste combustion activity data were modified according to the updated *Characterization of Municipal Solid Waste in the United States* (EPA 2005a) report, which affected estimates for CO_2 emissions in previous inventory years. Additionally, historical estimates for N_2O emissions from waste combustion increased slightly due to an updated emissions factor. Overall, changes resulted in an average annual increase in CO_2 emissions from

waste combustion of less than 0.05 Tg CO_2 Eq. (0.2 percent) for the period 1990 through 2003, and an average annual increase in N_2O emissions of 0.1 Tg CO_2 Eq. (14 percent) over the same period.

3.10. Natural Gas Flaring and Indirect Greenhouse Gas Emissions from Oil and Gas Activities (IPCC Source Category 1B2)

The flaring of natural gas from on- and off-shore oil wells is a small source of CO_2. In addition, oil and gas activities also release small amounts of NO_x, CO, and NMVOCs. This source accounts for only a small proportion of overall emissions of each of these gases. Emissions of NO_x, and CO from petroleum and natural gas production activities were both less than 1 percent of national totals, while NMVOC and SO_2 emissions were roughly 2 percent of national totals.

The flaring (i.e., combustion) and venting of natural gas during petroleum production result in the release of CO_2 and CH_4 emissions, respectively. Barns and Edmonds (1990) noted that of total reported U.S. venting and flaring, approximately 20 percent may be vented, with the remaining 80 percent flared, but it is now believed that flaring accounts for an even greater proportion. Studies indicate that the percentage of natural gas that is flared from off-shore U.S. production is considerably lower (approximately 30 percent in 2003), due in part to differences in the legislation governing on- and off-shore natural gas production. CH_4 emissions from venting are accounted for in the Petroleum Systems source category. For 2004, total CO_2 emissions from flaring activities were estimated to be 6.0 Tg CO_2 Eq. (6,034 Gg), an increase of 4 percent from 1990 levels. On-shore flaring activities accounted for 5.9 Tg CO_2 Eq. (5,872 Gg), or 97 percent, of the total flaring emissions, while off-shore flaring constituted 0.2 Tg CO_2 Eq. (162 Gg), or 3 percent, of the total (see Table 3-47).

Table 3-47: CO_2 Emissions from On-Shore and Off-Shore Natural Gas Flaring (Tg CO_2 Eq.)

Location	1990		1998	1999	2000	2001	2002	2003	2004
On-Shore Flaring	5.5		6.3	6.7	5.5	5.9	6.0	5.9	5.9
Off-Shore Flaring	0.3		0.3	0.3	0.2	0.2	0.2	0.2	0.2
Total Flaring	**5.8**		**6.6**	**6.9**	**5.8**	**6.1**	**6.2**	**6.1**	**6.0**

Note: Totals may not sum due to independent rounding.

Table 3-48: CO_2 Emissions from On-Shore and Off-Shore Natural Gas Flaring (Gg)

Location	1990		1998	1999	2000	2001	2002	2003	2004
On-Shore Flaring	5,509		6,250	6,679	5,525	5,858	6,001	5,936	5,872
Off-Shore Flaring	296		316	264	244	236	203	155	162
Total Flaring	**5,805**		**6,566**	**6,943**	**5,769**	**6,094**	**6,204**	**6,091**	**6,034**

Note: Totals may not sum due to independent rounding.

In addition, oil and gas activities, including production, transportation, and storage, result in the release of small amounts of NO_x, CO, and NMVOCs. Indirect greenhouse gas emissions from this source from 1990 to 2004 are presented below (see Table 3-49).

Table 3-49: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	NO_x	CO	NMVOCs
1990	139	302	555
1998	130	332	440
1999	109	145	414
2000	111	146	389
2001	113	147	400
2002	135	116	340
2003	135	116	341
2004	135	116	341

Methodology

Estimates of CO_2 emissions from on- and off-shore natural gas flaring were prepared using an emission factor of 54.71 Tg CO_2 Eq./QBtu of flared gas, and an assumed flaring efficiency of 100 percent. Indirect greenhouse gas emission estimates for NO_x, CO, and NMVOCs were determined using industry-published production data and applying average emission factors.

Total on-shore natural gas vented and flared was taken from EIA's *Natural Gas Annual* (EIA 2004); however, there is a discrepancy in the time series. One facility in Wyoming had been incorrectly reporting CO_2 vented as CH_4. EIA noted and corrected these data in the *Natural Gas Annual 2000* (EIA 2001) for the years 1998 and 1999 only. Data for 1990 through 1997 were adjusted by assuming a proportionate share of CO_2 in the flare gas for those years as for 1998 and 1999. The adjusted values are provided in Table 3-50. It was assumed that all reported vented and flared gas was flared. This assumption is consistent with that used by EIA in preparing their emission estimates, under the assumption that many states require flaring of natural gas (EIA 2000b). The emission and thermal conversion factors were also provided by EIA (2001) and are included in Table 3-50.

The total off-shore natural gas vented and flared was obtained from the Minerals Management Service's OGOR-B reports (MMS 2004). The percentage of natural gas flared was estimated using data from a 1993 air quality study and emissions inventory of the Gulf of Mexico (MOADS) and a 2000 emissions inventory conducted for the Breton National Wilderness Area Management Plan (BOADS). See Table 3-51.

Emission estimates for NO_x, CO, and NMVOCs from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations were obtained from preliminary data (EPA 2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gasoline service stations operations.

Table 3-50: Total Natural Gas Reported Vented and Flared (Million Ft^3) and Thermal Conversion Factor (Btu/Ft^3)

Year	Vented and Flared (original)	Vented and Flared (revised)*	Thermal Conversion Factor
1990	150,415	91,130	1,105
1991	169,909	92,207	1,108
1992	167,519	83,363	1,110
1993	226,743	108,238	1,106
1994	228,336	109,493	1,105
1995	283,739	144,265	1,106
1996	272,117	135,709	1,109
1997	256,351	124,918	1,107
1998	103,019	103,019	1,109
1999	110,285	110,285	1,107
2000	91,232	91,232	1,107
2001	96,913	96,913	1,105
2002	99,178	99,178	1,106
2003	98,113	98,113	1,106
2004	97,047	97,047	1,106

* Wyoming venting and flaring estimates were revised. See text for further explanation.

Table 3-51: Volume Flared Offshore (MMcf) and Fraction Vented and Flared (Percent)

Natural Gas Flaring	1990	1998	1999	2000	2001	2002	2003	2004
Total Gulf of Mexico (GOM) Vented & Flared (MMcf)	13,610	16,280	14,057	12,971	12,990	12,412	10,646	10,296
Estimated Flaring Fraction of GOM Vented & Flared	36%	32%	31%	31%	30%	27%	24%	26%

Total	**4,900**	**5,210**	**4,358**	**4,021**	**3,897**	**3,351**	**2,555**	**2,677**

Uncertainty

No quantitative uncertainty analysis was conducted to determine the level of uncertainty associated with emissions from natural gas flaring.

Uncertainties in CO_2 emission estimates primarily arise from assumptions concerning the flaring efficiency and the correction factor applied to 1990 through 1997 venting and flaring data. Uncertainties in indirect greenhouse gas emission estimates are partly due to the accuracy of the emission factors used and projections of growth.

Recalculations Discussion

The historical data for natural gas flaring was adjusted slightly, which resulted in an average annual decrease in CO_2 emissions from flaring of less than 0.05 Tg (0.1 percent) for the period 1990 through 2003.

3.11. 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.[49] These decisions are reflected in the *Revised 1996 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).[50]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4, N_2O, CO, NO_x, NMVOCs, particulate matter, and SO_2.[51] Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[52] 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

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[49] 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).

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

[51] Sulfur dioxide emissions from jet aircraft and marine vessels, although not estimated here, are mainly determined by the sulfur content of the fuel. In the United States, jet fuel, distillate diesel fuel, and residual fuel oil average sulfur contents of 0.05, 0.3, and 2.3 percent, respectively. These percentages are generally lower than global averages.

[52] 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).

fuel, while the typical fuel used for general aviation is aviation gasoline.[53]

Emissions of CO_2 from aircraft are essentially a function of fuel use. CH_4, N_2O, CO, NO_x, and NMVOC emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). CH_4, CO, and NMVOCs are the product of incomplete combustion and occur mainly during the landing and take-off phases. In jet engines, N_2O and NO_x are primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. The impact of NO_x on atmospheric chemistry depends on the altitude of the actual emission. The cruising altitude of supersonic aircraft, near or in the ozone layer, is higher than that of subsonic aircraft. At this higher altitude, NO_x emissions contribute to stratospheric ozone depletion.[54] At the cruising altitudes of subsonic aircraft, however, NO_x emissions contribute to the formation of tropospheric ozone. At these lower altitudes, the positive radiative forcing effect of ozone has enhanced the anthropogenic greenhouse gas forcing.[55] The vast majority of aircraft NO_x emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[56]

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, 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. CO_2 is the primary greenhouse gas emitted from marine shipping. In comparison to aviation, the atmospheric impacts of NO_x from shipping are relatively minor, as the emissions occur at ground level.

Overall, aggregate greenhouse gas emissions in 2004 from the combustion of international bunker fuels from both aviation and marine activities were 95.5 Tg CO_2 Eq., or 17 percent below emissions in 1990 (see Table 3-52). Although emissions from international flights departing from the United States have increased significantly (30 percent), emissions from international shipping voyages departing the United States have decreased by 49 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. Emissions of NO_x by aircraft during idle, take-off, landing and at cruising altitudes are of primary concern because of their effects on ground-level ozone formation (see Table 3-53).

Table 3-52: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**113.5**	**114.6**	**105.2**	**101.4**	**97.8**	**89.5**	**84.1**	**94.5**
Aviation	46.2	56.7	58.8	60.5	59.3	61.8	59.4	59.9
Marine	67.3	57.9	46.4	40.9	38.5	27.7	24.6	34.6
CH_4	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	+	+	+	+	+	+	+	+
Marine	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.0**	**1.0**	**0.9**	**0.9**	**0.9**	**0.8**	**0.8**	**0.9**
Aviation	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Marine	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.3
Total	**114.6**	**115.7**	**106.3**	**102.4**	**98.8**	**90.4**	**84.9**	**95.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

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

[54] Currently, only military supersonic aircraft fly at these altitudes.

[55] However, at this lower altitude, ozone does little to shield the earth from ultraviolet radiation.

[56] Cruise altitudes for civilian subsonic aircraft generally range from 8.2 to 12.5 km (27,000 to 41,000 feet).

Table 3-53: CO_2, CH_4, N_2O, and Indirect Greenhouse Gas Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**113,503**	**114,557**	**105,228**	**101,366**	**97,815**	**89,489**	**84,083**	**94,499**
Aviation	46,230	56,657	58,799	60,507	59,337	61,787	59,448	59,912
Marine	67,272	57,900	46,429	40,859	38,477	27,701	24,635	34,587
CH_4	**8**	**7**	**6**	**6**	**5**	**4**	**4**	**5**
Aviation	1	2	2	2	2	2	2	2
Marine	7	6	5	4	4	3	2	3
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**2**	**3**
Aviation	1	2	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1	1
CO	**115**	**127**	**124**	**124**	**120**	**118**	**112**	**119**
Aviation	76	93	97	100	98	102	98	99
Marine	39	34	27	24	23	16	15	20
NO_x	**1,985**	**1,778**	**1,478**	**1,334**	**1,266**	**988**	**900**	**1,167**
Aviation	182	224	233	240	235	245	236	237
Marine	1,803	1,554	1,245	1,095	1,031	743	664	930
NMVOCs	**59**	**55**	**48**	**44**	**42**	**35**	**32**	**40**
Aviation	11	14	15	15	15	15	15	15
Marine	48	41	33	29	27	20	18	25

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

Methodology

Emissions of CO_2 were estimated by applying of carbon 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 the EIA and are presented in Annex 2.1, Annex 2.2, and Annex 3.7 of this Inventory. Heat content and density conversions were taken from EIA (2005) and USAF (1998). 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.

Emission estimates for CH_4, N_2O, CO, NO_x, and NMVOCs 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, N_2O, CO, NO_x, and NMVOC 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, 0.1 for N_2O, 5.2 for CO, 12.5 for NO_x, and 0.78 for NMVOCs. For marine vessels consuming either distillate diesel or residual fuel oil the following values, in the same units, except where noted, were employed: 0.32 for CH_4, 0.08 for N_2O, 1.9 for CO, 87 for NO_x, and 0.052 g/MJ for NMVOCs. 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 collected from three government agencies. Jet fuel consumed by U.S. flag air carriers for international flight segments was supplied by the Bureau of Transportation Statistics (DOT 1991 through 2005). It was assumed that 50 percent of the fuel used by U.S. flagged carriers for international flights—both departing and arriving in the United States—was purchased domestically for flights departing from the United States. In other words, only one-half of the total annual fuel consumption estimate was used in the calculations. Data on jet fuel expenditures by foreign flagged carriers departing U.S. airports was taken from unpublished data collected by the Bureau of Economic Analysis (BEA) under the U.S. Department of Commerce (BEA 1991 through 2005). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT (1991 through 2005) and used to convert the BEA expenditure data to gallons of fuel consumed. 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 Services' 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 2004). 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 3-54. 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 2005). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DESC (2004). 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 3-55.

Table 3-54: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990		1998	1999	2000	2001	2002	2003	2004
U.S. Carriers	1,954		2,462	2,625	2,737	2,619	2,495	2,418	2,465
Foreign Carriers	2,051		3,009	3,086	3,162	3,113	3,537	3,377	3,353
U.S. Military	862		502	488	480	524	482	473	498
Total	**4,867**		**5,973**	**6,199**	**6,380**	**6,255**	**6,515**	**6,268**	**6,316**

Note: Totals may not sum due to independent rounding.

Table 3-55: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990		1998	1999	2000	2001	2002	2003	2004
Residual Fuel Oil	4,781		3,974	3,272	2,967	2,846	1,937	1,597	2,363
Distillate Diesel Fuel & Other	617		627	308	290	204	158	137	167
U.S. Military Naval Fuels	522		518	511	329	318	348	459	530
Total	**5,920**		**5,119**	**4,091**	**3,586**	**3,368**	**2,443**	**2,193**	**3,059**

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.[57] 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.

Particularly for aviation, the DOT (1991 through 2005) international flight segment fuel data used for U.S. flagged carriers does not include smaller air carriers and unfortunately defines flights departing to Canada and some flights to Mexico as domestic instead of international. As for the BEA (1991 through 2005) data on foreign flagged carriers, there is some uncertainty as to the average fuel price, and to the completeness of the data. It was also not

[57] See uncertainty discussions under Carbon Dioxide Emissions from Fossil Fuel Combustion.

possible to determine what portion of fuel purchased by foreign carriers at U.S. airports was actually used on domestic flight segments; this error, however, is believed to be small.[58]

Uncertainties exist with regard to the total fuel used by military aircraft and ships, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. These data may slightly over or under estimate actual total fuel use in aircraft and ships because each Service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. There are uncertainties in aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2001. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel-type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, Department and military Service data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated, but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through additional data collection.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than 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.[59]

There is also concern as to the reliability of the existing DOC (1991 through 2005) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

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

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[58] Although foreign flagged air carriers are prevented from providing domestic flight services in the United States, passengers may be collected from multiple airports before an aircraft actually departs on its international flight segment. Emissions from these earlier domestic flight segments should be classified as domestic, not international, according to the IPCC.

[59] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes. The estimates in Mobile Combustion are also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

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 slightly revised for both U.S. and foreign carriers. These changes were due to revisions to international fuel cost for foreign carriers and international jet fuel consumption for U.S. carriers, provided by DOT (2005). These historical data changes resulted in minimal changes to the emission estimates for 1999 through 2003, which averaged to an annual increase in emissions from international bunker fuels of less than 0.1 Tg CO_2 Eq. (0.2 percent) in CO_2 emissions, annual increase of less than 0.1 Tg CO_2 Eq. (less than 0.2 percent) in CH_4 emissions, and annual increase of less than 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions.

3.12. 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 the biogenic carbon emitted is offset by the uptake of CO_2 resulting 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 carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

In 2004, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 191.7 Tg CO_2 Eq. (191,737 Gg) (see Table 3-56 and Table 3-57). As the largest consumer of woody biomass, the industrial sector was responsible for 71 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 18 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Table 3-56: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990		1998	1999	2000	2001	2002	2003	2004
Industrial	135.3		150.5	152	153.6	135.4	131.1	128	135.9
Residential	59.9		39.9	42.7	44.7	38.2	32.3	37.0	34.3
Commercial	4.0		5.0	5.4	5.5	4.2	4.0	4.1	4.2
Electricity Generation	13.3		14.1	14.2	13.9	13.0	15.5	17.3	17.3
Total	**212.5**		**209.5**	**214.3**	**217.6**	**190.8**	**182.9**	**186.3**	**191.7**

Note: Totals may not sum due to independent rounding.

Table 3-57: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990		1998	1999	2000	2001	2002	2003	2004
Industrial	135,347		150,510	152,019	153,559	135,413	131,079	127,970	135,943
Residential	59,911		39,920	42,677	44,685	38,153	32,267	37,019	34,270
Commercial	4,037		4,963	5,394	5,481	4,175	4,037	4,100	4,246
Electricity Generation	13,252		14,097	14,233	13,851	13,034	15,487	17,250	17,278
Total	**212,547**		**209,490**	**214,323**	**217,577**	**190,776**	**182,878**	**186,339**	**191,737**

Note: Totals may not sum due to independent rounding.

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 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 2004, the United States consumed an estimated 2.96 trillion Btu of ethanol, and as a result, produced approximately 19.5 Tg CO_2 Eq. (19,493 Gg) (see Table 3-58) 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.

Table 3-58: CO_2 Emissions from Ethanol Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.2	4,155
1998	7.7	7,711
1999	8.0	8,017
2000	9.2	9,188
2001	9.7	9,701
2002	11.5	11,473
2003	15.8	15,771
2004	19.5	19,493

Methodology

Woody biomass emissions were estimated by taking U.S. consumption data (EIA 2005) (see Table 3-59), provided in energy units for the industrial, residential, commercial, and electric generation sectors, and applying two EIA gross heat contents (Lindstrom 2003). One heat content (16.953114 MMBtu/MT Wood & Wood Waste) was applied to the industrial sector's consumption, while the other heat content (15.432359 MMBtu/MT Wood & Wood Waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT Wood (Lindstrom 2003) was then applied to the resulting quantities of woody biomass to obtain CO_2 emissions 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 2003) to U.S. ethanol consumption data that were provided in energy units (EIA 2005) (see Table 3-60).

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

Year	Industrial	Residential	Commercial	Electricity Generation
1990	1,442	581	39	129
1998	1,603	387	48	137
1999	1,620	414	52	138
2000	1,636	433	53	134
2001	1,443	370	40	126
2002	1,396	313	39	150
2003	1,363	359	40	167
2004	1,448	332	41	168

Table 3-60: Ethanol Consumption (Trillion Btu)

Year	Trillion Btu
1990	63
1998	117
1999	122
2000	139
2001	147
2002	174
2003	239
2004	296

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 increase 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

The historical data for wood biomass consumption was adjusted slightly, which resulted in an average annual decrease in emissions from wood biomass and ethanol consumption of 2.0 Tg CO_2 Eq. (0.9 percent) from 1990 through 2003.

[BEGIN BOX]

Box 3-3: Formation of CO_2 through Atmospheric CH_4 Oxidation

CH_4 emitted to the atmosphere will eventually oxidize into CO_2, which remains in the atmosphere for up to 200 years. The global warming potential (GWP) of CH_4, however, does not account for the radiative forcing effects of the CO_2 formation that results from this CH_4 oxidation. The IPCC *Guidelines for Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) do not explicitly recommend a procedure for accounting for oxidized CH_4, but some of the resulting CO_2 is, in practice, included in the inventory estimates because of the intentional "double-counting" structure for estimating CO_2 emissions from the combustion of fossil fuels. According to the IPCC Guidelines, countries should estimate emissions of CH_4, CO, and NMVOCs from fossil fuel combustion, but also assume that these compounds eventually oxidize to CO_2 in the atmosphere. This is accomplished by using CO_2 emission factors that do not factor out carbon in the fuel that is released as in the form of CH_4, CO, and NMVOC molecules. Therefore, the carbon in fossil fuel is intentionally double counted, as an atom in a CH_4 molecule and as an atom in a CO_2 molecule.[60] While this approach does account for the full radiative forcing effect of fossil fuel-related greenhouse gas emissions, the timing is not accurate because it may take up to 12 years for the CH_4 to oxidize and form CO_2.

There is no similar IPCC approach to account for the oxidation of CH_4 emitted from sources other than fossil fuel combustion (e.g., landfills, livestock, and coal mining). CH_4 from biological systems contains carbon that is part of a rapidly cycling biological system, and therefore any carbon created from oxidized CH_4 from these sources is matched with carbon removed from the atmosphere by biological systems—likely during the same or subsequent year. Thus, there are no additional radiative forcing effects from the oxidation of CH_4 from biological systems. For example, the carbon content of CH_4 from enteric fermentation is derived from plant matter, which itself was created through the conversion of atmospheric CO_2 to organic compounds.

The remaining anthropogenic sources of CH_4 (e.g., fugitive emissions from coal mining and natural gas systems, industrial process emissions) do increase the long-term CO_2 burden in the atmosphere, and this effect is not captured in the inventory. The following tables provide estimates of the equivalent CO_2 production that results from the atmospheric oxidation of CH_4 from these remaining sources. The estimates for CH_4 emissions are gathered from the

[60] It is assumed that 100 percent of the CH_4 emissions from combustion sources are accounted for in the overall carbon emissions calculated as CO_2 for sources using emission factors and carbon mass balances. However, it may be the case for some types of combustion sources that the oxidation factors used for calculating CO_2 emissions do not accurately account for the full mass of carbon emitted in gaseous form (i.e., partially oxidized or still in hydrocarbon form).

respective sections of this report, and are presented in Table 3-61. The CO_2 estimates are summarized in Table 3-62.

Table 3-61: CH_4 Emissions from Non-Combustion Fossil Sources (Gg)

Source	1990	1998	1999	2000	2001	2002	2003	2004
Coal Mining	3,900	2,990	2,807	2,679	2,644	2,500	2,611	2,682
Abandoned Coal Mines	286	328	330	343	313	288	277	269
Natural Gas Systems	6,034	5,973	5,797	6,033	5,981	5,971	5,939	5,658
Petroleum Systems	1,640	1,414	1,358	1,325	1,303	1,274	1,236	1,222
Petrochemical Production	56	80	81	80	68	72	72	77
Silicon Carbide Production	1	1	1	1	+	+	+	+
Iron and Steel Production	63	57	56	57	51	48	49	50
Total	**11,980**	**10,842**	**10,430**	**10,518**	**10,360**	**10,153**	**10,184**	**9,957**

Note: These emissions are accounted for under their respective source categories. Totals may not sum due to independent rounding.

Table 3-62: Formation of CO_2 through Atmospheric CH_4 Oxidation (Tg CO_2 Eq.)

Source	1990	1998	1999	2000	2001	2002	2003	2004
Coal Mining	10.7	8.2	7.7	7.4	7.3	6.9	7.2	7.4
Abandoned Coal Mines	0.8	0.9	0.9	0.9	0.9	0.8	0.8	0.7
Natural Gas Systems	16.6	16.4	15.9	16.6	16.4	16.4	16.3	15.6
Petroleum Systems	4.5	3.9	3.7	3.6	3.6	3.5	3.4	3.4
Petrochemical Production	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+
Iron and Steel Production	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Total	**32.9**	**29.8**	**28.7**	**28.9**	**28.5**	**27.9**	**28.0**	**27.4**

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

The estimates of CO_2 formation are calculated by applying a factor of 44/16, which is the ratio of molecular weight of CO_2 to the molecular weight of CH_4. For the purposes of the calculation, it is assumed that CH_4 is oxidized to CO_2 in the same year that it is emitted. As discussed above, this is a simplification, because the average atmospheric lifetime of CH_4 is approximately 12 years.

CO_2 formation can also result from the oxidation of CO and NMVOCs. However, the resulting increase of CO_2 in the atmosphere is explicitly included in the mass balance used in calculating the storage and emissions from non-energy uses of fossil fuels, with the carbon components of CO and NMVOC counted as CO_2 emissions in the mass balance.[61]

[END BOX]

[61] See Annex 2.3 for a more detailed discussion on accounting for indirect emissions from CO and NMVOCs.

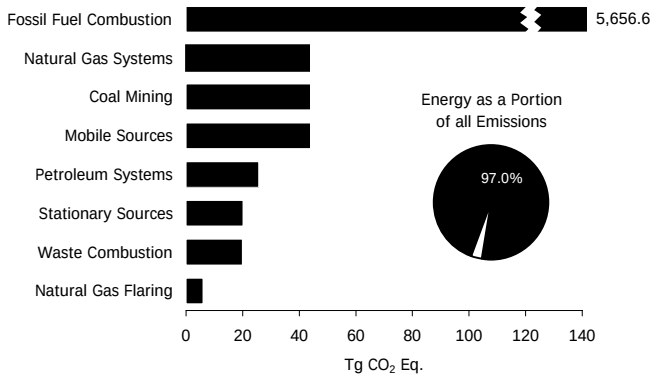
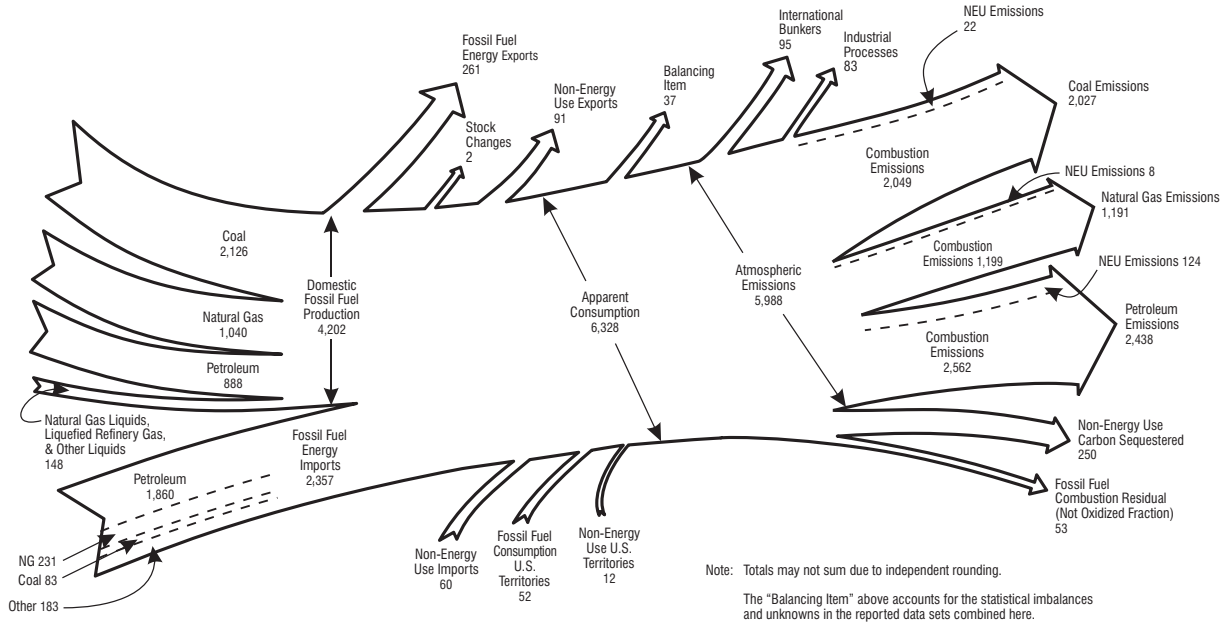


Figure 3-1: 2004 Energy Sector Greenhouse Gas Sources

Figure 3-2

2004 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

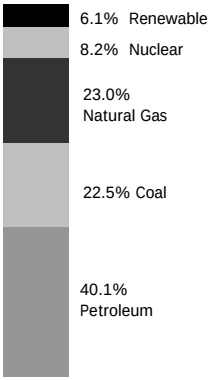


Figure 3-3: 2004 U.S. Energy Consumption by Energy Source

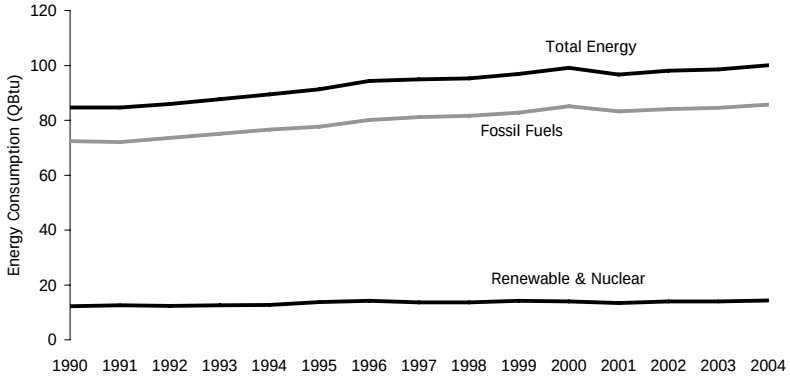


Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)
Note: Expressed as gross calorific values

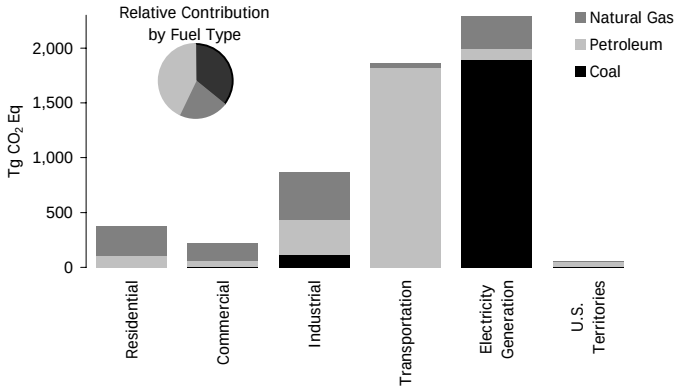


Figure 3-5: 2004 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: The electricity generation sector also includes emissions of less than 0.01 Tg CO_2 Eq. from geothermal-based electricity generation

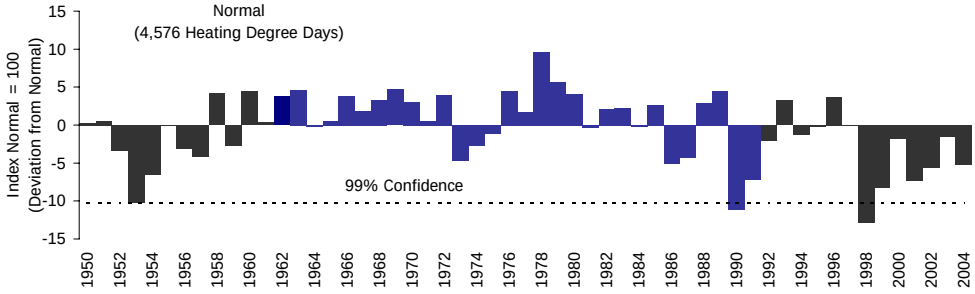


Figure 3-6. Annual Deviations from Normal Heating Degree Days for the United States (1950-2004)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

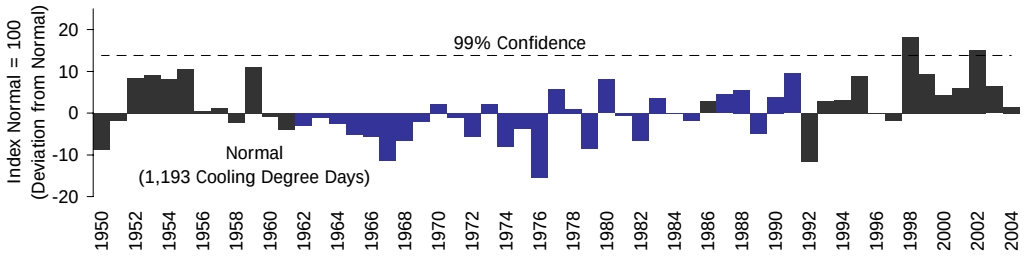


Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950-2004)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

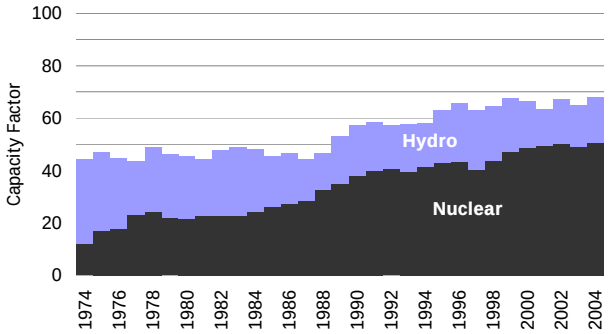


Figure 3-8: Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1974-2004)

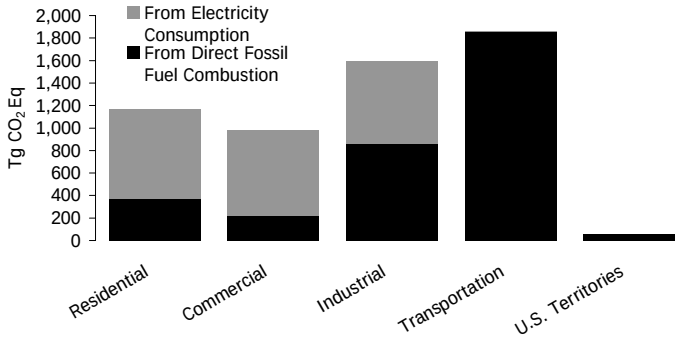


Figure 3-9: 2004 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

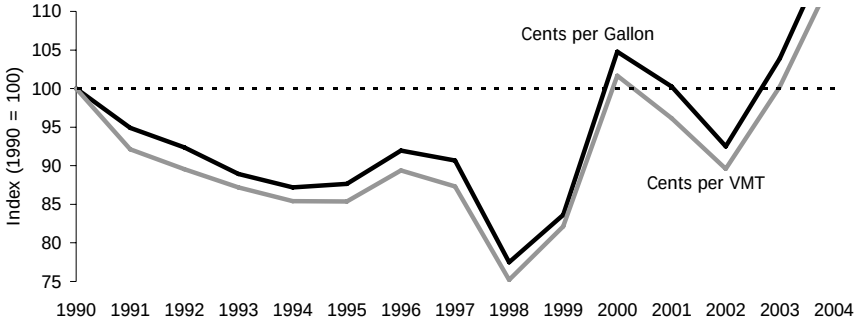


Figure 3-10: Motor Gasoline Retail Prices (Real)



Figure 3-11: Personal Vehicle Fuel Economy

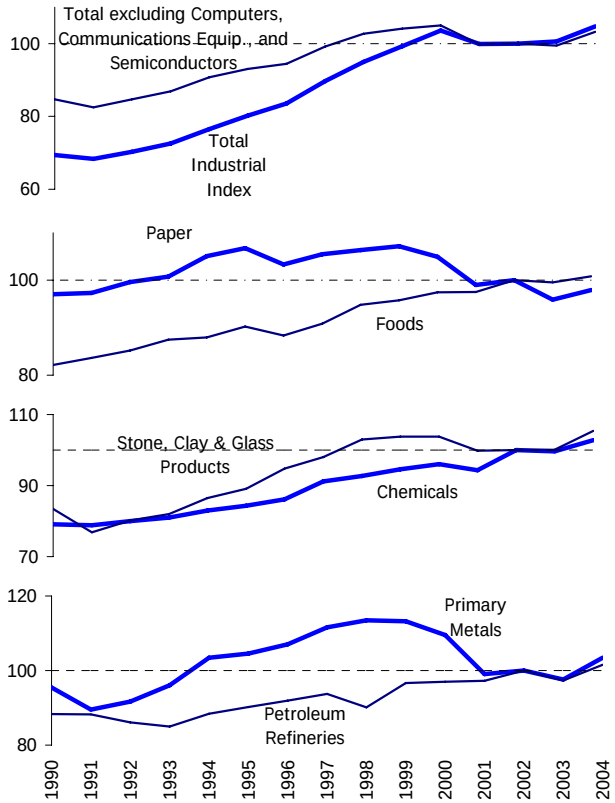


Figure 3-12: Industrial Production Indexes (Index 1997=100)

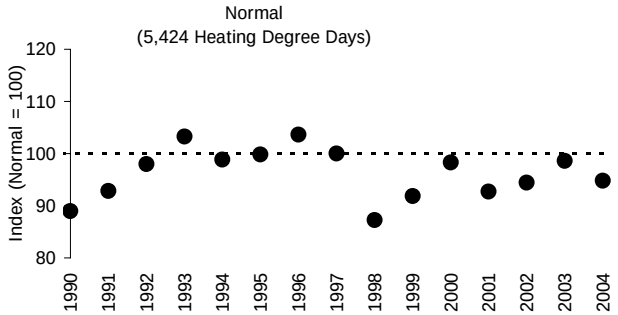


Figure 3-13: Heating Degree Days
Note: Excludes Alaska and Hawaii

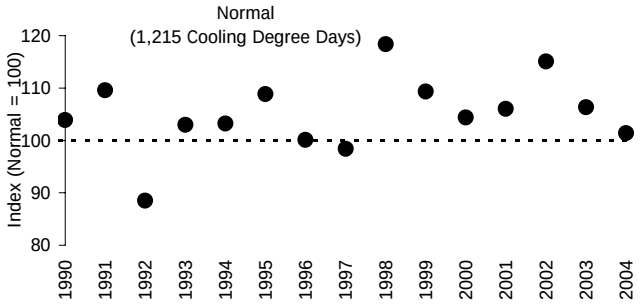


Figure 3-14: Cooling Degree Days
Note: Excludes Alaska and Hawaii

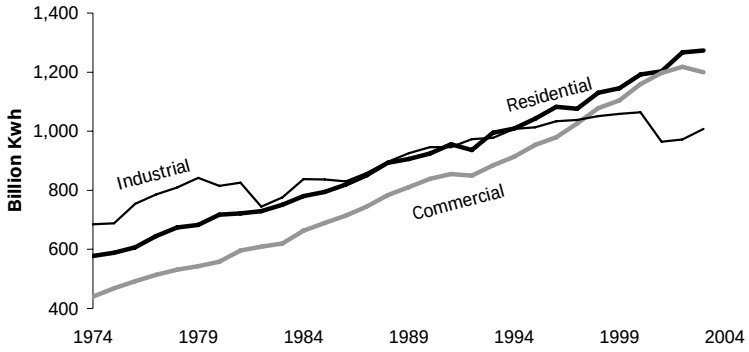


Figure 3-15: Electric Generation Retail Sales by End-Use Sector
Note: The transportation end-use sector consumes minor quanties of electricity.

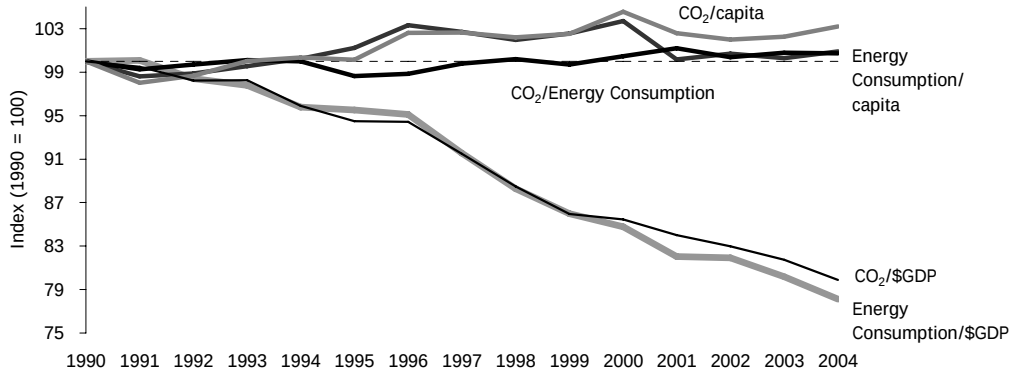


Figure 3-16: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

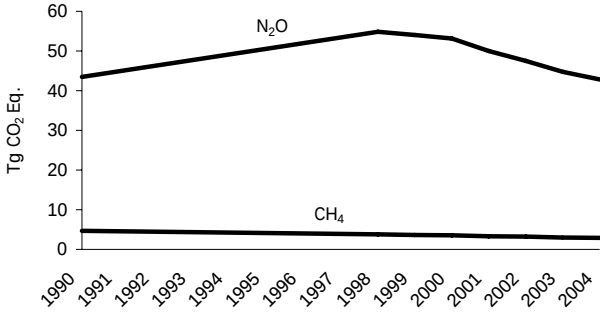


Figure 3-17: Mobile Source CH_4 and N_2O Emissions

Descriptions of Figures: Energy

Figure 3-1 illustrates the CO_2, CH_4 and N_2O emissions from Energy (Tg CO_2 Eq) as presented in Table 3-1. Fossil fuel is the greatest source, responsible for 5,656.6 Tg CO_2 Eq. In addition, there is a pie chart that indicates that energy accounted for 97 % of U.S. greenhouse gas emissions in 2004.

Figure 3-2 illustrates U.S. fossil carbon flows in 2004.

Figure 3-3 illustrates U.S. energy consumption sorted by energy source. Petroleum accounted for 40.1%; coal accounted for 22.5%, natural gas accounted for 23.0%, nuclear accounted for 8.2%, and renewable accounted for 6.1% of U.S. energy consumption in 2004.

Figure 3-4 is a line graph showing trends in U.S. energy consumption. The total energy increased from about 84.7 quadrillion Btu in 1990 to 100 quadrillion Btu in 2004, decreasing slightly in 2001. Fossil fuel energy consumption increased from 72.5 quadrillion Btu in 1990, to 85.7 quadrillion Btu in 2004. Renewable and nuclear energy increased as a slower rate, from 12.2 quadrillion Btu in 1990 to 14.4 quadrillion Btu in 2004.

Figure 3-5 depicts 2004 CO_2 emissions from fossil fuel combustion by sector and fuel type using the data presented in Table 3-3. In addition, there is a pie chart that indicates that petroleum accounted for 43% of emissions from fossil fuel combustion.

Figure 3-6 is a graph depicting the annual deviations from normal heating degree days for the U.S. from 1950 to 2004 with the index normal equal to 100. In 1950, the deviation from normal was 0.3. By 1953, the deviation was at -10. It increased to -3 before decreasing again to -4 in 1957. In 1958, it was 4. In 1961, it was almost normal, followed with increasing years, and returning to normal in 1964. 1970 saw a 3 point increase from normal, while 1978 saw a 6 point increase from normal. 1986 and 1987 were 5 and 4, respectively, below normal. 1998 was approximately -13 below normal while 2004 deviated approximately 5 below the normal index.

Figure 3-7 is a graph depicting the annual deviations from normal cooling degree days for the U.S. from 1950 to 2004 with the index normal equal to 100. In 1950, the deviation from normal was -9 while 1953 saw an 9 point increase. 1960 through 1976 were mostly below normal, with 1976 at a -15 deviation. The rest of the series are positive, but 1989, 1992, 1995, and 1997 were all negative deviations. 1998 and 2002 were approximately 18 and 15 above normal, respectively. 2004 saw another increase at approximately 1 above the normal index.

Figure 3-8 is a graph depicting nuclear and hydroelectric power plant capacity factors in the United States from 1974 to 2004. The capacity factor for hydroelectric power plants was between 40 and 50 from 1973 to 1988. In 1990 it exceeded 50 and gradually increased until it reached a peak of almost 70 in 1999. It declined in 2001 and 2003. In 2004, hydroelectric power plant capacity factor was 68 The capacity factor for nuclear plants increased steadily from 12 in 1974 to 50 in 2002, and has remained fairly constant in 2004.

Figure 3-9 illustrates the data presented in Table 3-6, CO_2 emissions from fossil fuel combustion by end use sector.

Figure 3-10 is a line graph depicting real motor gasoline retail prices from 1990 to 2004. Gasoline prices in cents per gallon started at the 1990 index of 100. Prices declined to their lowest value in 1998 at 77. In 2000, they peaked at approximately 105, the first year above the 100 index. Following the 2000 high, prices dropped to 92 in 2002. In 2003, they rose above the 100 index once more, and in 2004 they cost 119. Gasoline prices in cents per vehicle miles traveled started at the 1990 index of 100. In 1998, they reached their minimum at approximately 75. In 2000, they reached their peak of 102, before dropping to 92 in 2002, and then back to 119 in 2004.

Figure 3-11 is a line graph depicting personal vehicle fuel efficiency from 1990 to 2004. All passenger vehicles' fuel efficiency steadily increased, from approximately 19 miles per gallon in 1990, to nearly 20 miles per gallon in 2004. All motor vehicles fuel efficiency increased slightly, from approximately 20 miles per gallon in 1990, to over 22 miles per gallon in 2004.

Figure 3-12 includes four different line graphs depicting industrial production indexes, with the 1997 index equal to 100. The first graph shows that the total industrial index increased steadily since 1990, peaked in 2000 at 105, decreased to 100 in 2001, and increased to 103 in 2004. The total index excluding computers, communications equipment and semiconductors increased steadily, peaked in 2000 at 105, and decreased to 103 in 2004. The second graph shows that the pulp and paper index increased gradually from 1990, before decreasing to 105 in 2000. The foods index increased gradually from an index of 90 to an index of 101 in 2004. The third graph shows the stone, clay and glass products started at 83 in 1990, and peaked in 2000 at 104 before decreasing to the baseline index in 2001 then increasing in 2004 to 105. The chemicals and products index increased steadily from 88 in 1990 to 105 in 2004. The fourth graph shows the primary metals index begin at approximately 95 in 1990, peaks in 1998 at 113, and increases slightly in 2004 to an index of 103. The petroleum products index increased steadily from 88 in 1990 to 100 in 2004.

Figure 3-13 is a dotted line graph depicting heating degree days from 1990 to 2004, excluding Alaska and Hawaii. Heating degree days are compared to a normal index of 5,424. In 1990, the heating degree days had an index of 89, increasing steadily to 103 in 1993. The index dipped in the mid-nineties, then declined to a low of 87 in 1998. Since then, the index has generally increased, with some fluctuation. In 2004, the index of heating degree days was at an index of 95.

Figure 3-14 is a dotted line graph depicting heating degree days from 1990 to 2004, excluding Alaska and Hawaii. Heating degree days are compared to a normal index of 1,215. In 1990, there was an index of 104. Since that time, the index has fluctuated a great deal, peaking four times. However, the index has remained above the normal of 100, excepting 1992 and 1998. In 2004, the index of cooling days was 100.

Figure 3-15 shows three lines depicting electric generation retail sales in kilowatt-hours by end user, industrial, residential, and commercial, from 1974 to 2004. All three lines slope upward, with commercial and residential increasing more dramatically than industrial. In 1974, industrial sales were 685 kW-h, in 2004 sales were 1008 kW-h. In 1974, residential sales were 588 kW-h, rising to 1273 in 2004. In 1974, commercial sales were 440 kW-h, increasing to 2000 kW-h in 2004.

Figure 3-16 displays energy consumption and energy-related CO_2 emissions per capita and per dollar GDP from 1990 to 2004. They are indexed where 1990 levels equal 100. CO2 per dollar GDP and Energy consumption per GDP have both decreased steadily from 100 in 1990 to 80 and 78, respectively. CO_2 per capita, energy consumption per capita, and CO_2 per energy consumption have all remained relatively stable over the time series; in 2004 CO_2 per capita had an index of 103.2, while energy consumption per capita and CO_2 per energy consumption both an index of 101.

Figure 3-17 depicts the CH_4 and N_2O emissions from mobile combustion in Tg CO_2 eq. from 1990 to 2004. N_2O steadily increased from 43 Tg CO_2 eq. in 1990 until it peaked in 1998 and has since declined. In 2004, mobile N_2O emissions were 43 Tg CO_2 eq. CH_4 emissions have steadily decreased since the 1990 levels of 4.7 Tg CO_2 eq. In 2004, the CH_4 emissions from mobile sources were 3 Tg CO_2 eq.

4. Industrial Processes

Greenhouse gas emissions are produced as a by-product 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 manufacture, ammonia manufacture 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, aluminum production, petrochemical production, silicon carbide production and consumption, lead production, zinc production, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1: 2004 Industrial Processes Chapter Greenhouse Gas 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 2004, industrial processes generated emissions of 320.7 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 5 percent of total U.S. greenhouse gas emissions. CO_2 emissions from all industrial processes were 152.6 Tg CO_2 Eq. (152,650 Gg) in 2004. This amount accounted for only 3 percent of national CO_2 emissions. CH_4 emissions from petrochemical, silicon carbide, and iron and steel production resulted in emissions of approximately 2.7 Tg CO_2 Eq. (127 Gg) in 2004, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from adipic acid and nitric acid production were 22.4 Tg CO_2 Eq. (72 Gg) in 2004, or 6 percent of total U.S. N_2O emissions. In 2004, combined emissions of HFCs, PFCs and SF_6 totaled 143.0 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 6.5 percent from 1990 to 2004 despite decreases in emissions from several industrial processes, such as iron and steel, aluminum production, ammonia manufacture and urea application, 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.

Table 4-1 summarizes emissions for the Industrial Processes chapter in units of Tg CO_2 Eq., while unweighted native gas emissions in gigagrams (Gg) are provided in Table 1-2.

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

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	**174.8**		**171.9**	**167.5**	**166.4**	**152.5**	**152.6**	**147.6**	**152.6**
Iron and Steel Production	85.0		67.7	63.8	65.3	57.8	54.6	53.3	51.3
Cement Manufacture	33.3		39.2	40.0	41.2	41.4	42.9	43.1	45.6
Ammonia Manufacture & Urea Application	19.3		21.9	20.6	19.6	16.7	18.5	15.3	16.9
Lime Manufacture	11.2		13.9	13.5	13.3	12.8	12.3	13.0	13.7
Limestone and Dolomite Use	5.5		7.4	8.1	6.0	5.7	5.9	4.7	6.7
Aluminum Production	7.0		6.4	6.5	6.2	4.5	4.6	4.6	4.3

Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.2	4.1	4.1	4.1	4.2
Petrochemical Production	2.2	3.0	3.1	3.0	2.8	2.9	2.8	2.9
Titanium Dioxide Production	1.3	1.8	1.9	1.9	1.9	2.0	2.0	2.3
Phosphoric Acid Production	1.5	1.6	1.5	1.4	1.3	1.3	1.4	1.4
Ferroalloy Production	2.0	2.0	2.0	1.7	1.3	1.2	1.2	1.3
CO_2 Consumption	0.9	0.9	0.8	1.0	0.8	1.0	1.3	1.2
Zinc Production	0.9	1.1	1.1	1.1	1.0	0.9	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Consumption	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	**2.5**	**2.9**	**2.9**	**2.9**	**2.5**	**2.5**	**2.5**	**2.7**
Petrochemical Production	1.2	1.7	1.7	1.7	1.4	1.5	1.5	1.6
Iron and Steel Production	1.3	1.2	1.2	1.2	1.1	1.0	1.0	1.0
Silicon Carbide Production	+	+	+	+	+	+	+	+
N_2O	**33.0**	**26.9**	**25.6**	**25.6**	**20.8**	**23.1**	**22.9**	**22.4**
Nitric Acid Production	17.8	20.9	20.1	19.6	15.9	17.2	16.7	16.6
Adipic Acid Production	15.2	6.0	5.5	6.0	4.9	5.9	6.2	5.7
HFCs, PFCs, and SF_6	**90.8**	**133.4**	**131.5**	**134.7**	**124.9**	**132.7**	**131.0**	**143.0**
Substitution of Ozone Depleting Substances	0.4	54.5	62.8	71.2	78.6	86.2	93.5	103.3
HCFC-22 Production	35.0	40.1	30.4	29.8	19.8	19.8	12.3	15.6
Electrical Transmission and Distribution	28.6	16.7	16.1	15.3	15.3	14.5	14.0	13.8
Semiconductor Manufacture	2.9	7.1	7.2	6.3	4.5	4.4	4.3	4.7
Aluminum Production	18.4	9.1	9.0	9.0	4.0	5.3	3.8	2.8
Magnesium Production and Processing	5.4	5.8	6.0	3.2	2.6	2.6	3.0	2.7
Total	**301.1**	**335.1**	**327.5**	**329.6**	**300.7**	**310.9**	**304.1**	**320.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

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

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	**174,791**	**171,897**	**167,450**	**166,379**	**152,529**	**152,605**	**147,649**	**152,650**
Iron and Steel Production	85,023	67,689	63,821	65,316	57,822	54,550	53,335	51,334
Cement Manufacture	33,278	39,218	39,991	41,190	41,357	42,898	43,082	45,559
Ammonia Manufacture & Urea Application	19,306	21,934	20,615	19,616	16,719	18,510	15,278	16,894
Lime Manufacture	11,242	13,919	13,473	13,322	12,828	12,309	12,987	13,698
Limestone and Dolomite Use	5,533	7,449	8,057	5,960	5,733	5,885	4,720	6,702
Aluminum Production	7,045	6,359	6,458	6,244	4,505	4,596	4,608	4,346
Soda Ash Manufacture and Consumption	4,141	4,325	4,217	4,181	4,147	4,139	4,111	4,205
Petrochemical Production	2,221	3,015	3,054	3,004	2,787	2,857	2,777	2,895
Titanium Dioxide Production	1,308	1,819	1,853	1,918	1,857	1,997	2,013	2,259
Phosphoric Acid Production	1,529	1,593	1,539	1,382	1,264	1,338	1,382	1,395
Ferroalloy Production	1,980	2,027	1,996	1,719	1,329	1,237	1,159	1,287
CO_2 Consumption	860	912	849	957	818	968	1,293	1,183
Zinc Production	939	1,140	1,080	1,129	976	927	502	502
Lead Production	285	308	310	311	293	290	289	259
Silicon Carbide Consumption	100	190	137	130	94	105	111	133
CH_4	**120**	**138**	**138**	**138**	**119**	**120**	**121**	**127**
Petrochemical Production	56	80	81	80	68	72	72	77
Iron and Steel Production	63	57	56	57	51	48	49	50
Silicon Carbide Production	1	1	1	1	+	+	+	+
N_2O	**107**	**87**	**83**	**83**	**67**	**75**	**74**	**72**
Nitric Acid Production	58	67	65	63	51	56	54	54
Adipic Acid Production	49	19	18	19	16	19	20	19
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**

Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production[a]	3	3	3	3	2	2	1	1
Electrical Transmission and Distribution[b]	1	1	1	1	1	1	1	1
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
Magnesium Production and Processing[b]	+	+	+	+	+	+	+	+
NO_x	**591**	**637**	**595**	**626**	**656**	**630**	**631**	**632**
CO	**4,124**	**3,163**	**2,156**	**2,217**	**2,339**	**2,286**	**2,286**	**2,286**
NMVOCs	**2,426**	**2,047**	**1,183**	**1,773**	**1,769**	**1,723**	**1,725**	**1,727**

+ Does not exceed 0.5 Gg
M (Mixture of gases)
[a] HFC-23 emitted
[b] SF_6 emitted
Note: Totals may not sum due to independent rounding.

In order to ensure the quality of the emission estimates from industrial processes, Tier 1 quality assurance and quality control (QA/QC) procedures and checks have been performed on all industrial process sources. Where performed, Tier 2 procedures focused on the emission factor and activity data sources and methodology used for estimating emissions, and will be described within the QA/QC and Verification Discussion of that source description. In addition to the national QA/QC plan, a more detailed plan was developed specifically for the CO_2 and CH_4 industrial processes sources. This plan was based on the U.S. strategy, but was tailored to include specific procedures recommended for these sources.

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 of 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 2004 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 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.

4.1. Iron and Steel Production (IPCC Source Category 2C1)

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of CO_2 and CH_4. Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron containing about 3 to 5 percent carbon by weight). Metallurgical coke is manufactured in a coke plant using coking coal as a raw material. Iron may be introduced into the blast furnace in the form of raw iron ore, pellets, briquettes, or sinter. Pig iron (containing about 0.4 percent carbon by weight) is used as a raw material in the production of steel. 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.

The production of metallurgical coke from coking coal and the consumption of the metallurgical coke used as a reducing agent in the blast furnace are considered in the inventory to be non-energy (industrial) processes, not energy (combustion) processes. Coal 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. Coke oven gas and coal tar are carbon containing by-products of the coke manufacturing process. Coke oven gas is generally burned as a fuel within the steel mill. Coal tar is used as a raw material to produce anodes used for primary aluminum production and other electrolytic processes, and also used in the production of other coal tar products. The coke production process produces CO_2 emissions and fugitive CH_4 emissions.

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 prior to being charged into the blast furnace. The sintering process produces CO_2 emissions and fugitive CH_4 emissions.

The metallurgical coke is a reducing agent in the blast furnace. CO_2 is produced as the metallurgical coke used in the blast furnace process is oxidized and the iron is reduced. Steel (containing less than 2 percent carbon by weight) is produced from pig iron in a variety of specialized steel making furnaces. The majority of CO_2 emissions from the iron and steel process come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel. Some carbon is also stored in the finished iron and steel products.

Emissions of CO_2 and CH_4 from iron and steel production in 2004 were 51.3 Tg CO_2 Eq. (51,334 Gg) and 1.0 Tg CO_2 Eq. (50 Gg), respectively (see Table 4-3 and Table 4-4). Emissions have fluctuated significantly from 1990 to 2004 due to changes in domestic economic conditions and changes in product imports and exports. In 2004, domestic production of pig iron increased by 4.5 percent and coal coke production decreased by 1.5 percent. Overall, domestic pig iron and coke production have declined since the 1990s. Pig iron production in 2004 was 11 percent lower than in 2000 and 14 percent below 1990 levels. Coke production in 2004 was 19 percent lower than in 2000 and 39 percent below 1990 levels.

Table 4-3: CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	85.0		67.7	63.8	65.3	57.8	54.6	53.3	51.3
CH_4	1.3		1.2	1.2	1.2	1.1	1.0	1.0	1.0
Total	**86.3**		**68.9**	**65.0**	**66.5**	**58.9**	**55.6**	**54.3**	**52.4**

Table 4-4: CO_2 and CH_4 Emissions from Iron and Steel Production (Gg)

Year	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	85,023		67,689	63,821	65,316	57,823	54,550	53,335	51,334
CH_4	63		57	56	57	51	48	49	50

Methodology

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). The total coking coal consumed at coke plants and the total amount of coking coal produced were identified. These data were used to estimate the emissions associated with producing coke from coking coal and attributed to the production of iron and steel. Additionally, the amount of coke consumed to produce pig iron and the emissions associated with this production were estimated. The carbon content of the coking coal and coke consumed in these processes were estimated by multiplying the energy consumption by material specific carbon-content coefficients. The carbon content coefficients used are presented in Annex 2.1.

Emissions from the re-use of scrap steel were also estimated by assuming that all the associated carbon-content of the scrap steel, which has an associated carbon-content of approximately 0.4 percent, are released during the scrap re-use process.

Lastly, emissions from carbon anodes, used during the production of steel in electric arc furnaces (EAF), were also estimated. Emissions of CO_2 were calculated by multiplying the annual production of steel in electric arc furnaces by an emission factor (4.4 kg CO_2/ton $steel_{EAF}$). It was assumed that the carbon anodes used in the production of steel in electric arc furnaces are composed of 80 percent petroleum coke and 20 percent coal tar pitch (DOE 1997). Since coal tar pitch is a by-product of the coke production process and its carbon-related emissions have already been accounted for earlier in the iron and steel emissions calculation as part of the process, the emissions were reduced by the amount of carbon in the coal tar pitch used in the anodes to avoid double counting.

Emissions associated with the production of coke from coking coal, pig iron production, the re-use of scrap steel, and the consumption of carbon anodes during the production of steel were summed.

Additionally, the coal tar pitch component of carbon anodes consumed during the production of aluminum are accounted for in the aluminum production section of this chapter. The emissions were reduced by the amount of coal tar pitch used in aluminum production to avoid double counting. The amount of coal tar pitch consumed for processes other than the aluminum production and as EAF anodes and net imports of coal tar were also estimated. A storage factor was applied to estimate emissions associated with other coal tar pitch consumption and net imports.

Carbon storage was accounted for by assuming that all domestically manufactured steel had a carbon content of 0.4 percent. Furthermore, any pig iron that was not consumed during steel production, but fabricated into finished iron products, was assumed to have a carbon content of 4 percent.

The potential CO_2 emissions associated with carbon contained in pig iron used for purposes other than iron and steel production, stored in the steel product, stored as coal tar, and attributed to carbon anode consumption during aluminum production were summed and subtracted from the total emissions estimated above.

The production processes for coal coke, 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 emission factors taken from the 1995 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1995) (see Table 4-5) to annual domestic production data for coal coke, sinter, and pig iron.

Table 4-5: CH_4 Emission Factors for Coal Coke, Sinter, and Pig Iron Production (g/kg)

Material Produced	g CH_4/kg produced
Coal Coke	0.5
Pig Iron	0.9
Sinter	0.5

Source: IPCC/UNEP/OECD/IEA 1997

Data relating to the amount of coal consumed at coke plants, and for the production of coke for domestic consumption in blast furnaces, were taken from the Energy Information Administration (EIA), *Monthly Energy Review* September 2005 (EIA 2005a); Quarterly Coal Report October through December (EIA 1998, 1999, 2000, 2001, 2002, 2003, 2004a, 2005b). Data on total coke consumed for pig iron production were taken from the

American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2001, 2002, 2003, 2004, 2005) and provided by the AISI Annual Statistical Report (Larmoyeux 2005). Scrap steel consumption data for 1990 through 2004 were obtained from *Annual Statistical Reports* (AISI 1995, 2001, 2002, 2003, 2004, 2005) (see Table 4-6). Crude steel production, as well as pig iron use for purposes other than steel production, was also obtained from *Annual Statistical Reports* (AISI 1996, 2001, 2002, 2004, 2005). Carbon content percentages for pig iron and crude steel and the CO_2 emission factor for carbon anode emissions from steel production were obtained from IPCC *Good Practice Guidance* (IPCC 2000). Data on the non-energy use of coking coal are obtained from EIA's *Emissions of U.S. Greenhouse Gases in the United States* (EIA 2004b). Information on coal tar net imports were determined using data from the U.S. Bureau of the Census' U.S. International Trade Commission's Trade Dataweb (U.S. Bureau of the Census 2005). Coal tar consumption for aluminum production data were estimated based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program and data from USAA Primary Aluminum Statistics (USAA 2004, 2005) (see Aluminum Production in this chapter). Annual consumption of iron ore used in sinter production for 1990 through 2004 were obtained from the USGS *Iron Ore Yearbook* (USGS 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005). The CO_2 emission factor for carbon anode emissions from aluminum production was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates for the composition of carbon anodes used during EAF steel and aluminum production were obtained from *Energy and Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

Table 4-6: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Gas/Activity Data	1990	1998	1999	2000	2001	2002	2003	2004
CO_2								
Coal Consumption at Coke Plants	35,269	25,573	25,499	26,254	23,655	21,461	21,998	21,473
Coke Consumption for Pig Iron	25,043	19,966	18,817	19,307	17,236	15,959	15,482	15,068
Basic Oxygen Furnace Steel Production	56,216	45,147	52,365	53,965	47,359	45,463	45,874	47,714
Electric Arc Furnace Steel Production	33,510	44,514	45,064	47,860	42,774	46,125	47,804	51,969
CH_4								
Coke Production	25,054	18,181	18,240	18,877	17,191	15,221	15,579	15,540
Iron Ore Consumption for Sinter	12,239	10,791	11,072	10,784	9,234	9,018	8,984	8,984
Domestic Pig Iron Production for Steel	49,062	47,471	45,678	47,400	41,741	39,601	40,487	42,292

Uncertainty

The time series data sources for production of coal coke, sinter, pig iron, steel, and aluminum upon which the calculations are based are assumed to be consistent for the entire time series. The estimates of CO_2 emissions from the production and utilization of coke are based on consumption data, average carbon contents, and the fraction of carbon oxidized. Uncertainty is associated with the total U.S. coke consumption and coke consumed for pig iron production data. These data are provided by different data sources (EIA and AISI) and comparisons between the two datasets for net imports, production, and consumption identified discrepancies; however, the data chosen are considered the best available. These data and factors produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each of these factors. For example, carbon oxidation factors may vary depending on inefficiencies in the combustion process, where varying degrees of ash or soot can remain unoxidized.

Simplifying assumptions were made concerning the composition of carbon anodes (80 percent petroleum coke and 20 percent coal tar). For example, within the aluminum industry, the coal tar pitch content of anodes can vary from 15 percent in prebaked anodes to 24 to 28 percent in Soderberg anode pastes (DOE 1997). An average value was assumed and applied to all carbon anodes utilized during aluminum and steel production. The assumption is also made that all coal tar used during anode production originates as a by-product of the domestic coking process. Similarly, it was assumed that all pig iron and crude steel have carbon contents of 4 percent and 0.4 percent, respectively. The carbon content of pig iron can vary between 3 and 5 percent, while crude steel can have a carbon content of up to 2 percent, although it is typically less than 1 percent (IPCC 2000). There is also uncertainty associated with the total amount of coal tar products produced and with the storage factor for coal tar.

Uncertainty surrounding the CO_2 emission factor for carbon anode consumption in aluminum production was also estimated. Emissions vary depending on the specific technology used by each plant (Prebake or Soderberg). Emissions were estimated according to process and plant specific methodology outlined in the aluminum production section of this chapter. Based on expert elicitation, carbon anodes were assumed to be 20 percent coal tar pitch for the whole time series (Kantamaneni 2005). Similarly, the carbon anode emission factor for steel production can vary between 3.7 and 5.5 kg CO_2/ton steel (IPCC 2000). For this analysis, the upper bound value was used.

For the purposes of the CH_4 calculation it is assumed that none of the CH_4 is captured in stacks or vents and that all of the CH_4 escapes as fugitive emissions. Additionally, the CO_2 emissions calculation is not corrected by subtracting the carbon content of the CH_4, which means there may be a slight double counting of carbon as both CO_2 and CH_4.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-7. Iron and Steel CO_2 emissions were estimated to be between 45.8 and 74.5 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 11 percent below and 45 percent above the emission estimate of 51.3 Tg CO_2 Eq. Iron and Steel CH_4 emissions were estimated to be between 1.0 Tg CO_2 Eq. and 1.1 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 8 percent below and 8 percent above the emission estimate of 1.0 Tg CO_2 Eq.

Table 4-7: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production (Tg. CO_2 Eq. and Percent)

Source	Gas	2004 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
Iron and Steel Production	CO_2	51.3	45.8	74.5	-11%	+45%
Iron and Steel Production	CH_4	1.0	1.0	1.1	-7%	+9%

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

Recalculations Discussion

Elements of the methodology to estimate CO_2 emissions from iron and steel production were revised for the entire time series to include a more accurate dataset. Previously, emissions associated with the carbon content of imported pig iron were estimated and added to the total emissions associated with iron and steel production. Imported pig iron production was estimated as the difference between U.S. pig iron production and U.S. pig iron consumption. These estimates proved unreliable for 2004 warranting pursuit of new methodology.

New methods utilize data on total coke consumed for pig iron production as well as total coking coal used for coke production. EIA reports minor inconsistencies in the early years of the total U.S. coking coal datasets (EIA 1998); however, overall the datasets, which offset the need to estimate imported pig iron and coke, are believed to provide more accurate emission estimates. These changes resulted in an average annual decrease of 1.2 Tg CO_2 Eq. (2 percent) in CO_2 emissions from iron and steel production for 1990 through 2003.

4.2. Cement Manufacture (IPCC Source Category 2A1)

Cement manufacture 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 production has accounted for about 2.4 percent of total global industrial and energy-related CO_2 emissions (IPCC 1996, USGS 2003). Cement is manufactured in nearly 40 states. CO_2 emitted from the chemical process of cement production represents one of the largest sources 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 1,300°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and CO_2. This process is known as calcination or calcining. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier by-product CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and used to make Portland cement. The production of masonry cement from Portland cement requires additional lime and, thus, results in additional CO_2 emissions. However, this additional lime is already accounted for in the Lime Manufacture source category in this chapter; therefore, the additional emissions from making masonry cement from clinker are not counted in this source category's total. They are presented here for informational purposes only.

In 2004, U.S. clinker production—including Puerto Rico—totaled 88,104 thousand metric tons (Van Oss 2005). The resulting emissions of CO_2 from 2004 cement production were estimated to be 45.6 Tg CO_2 Eq. (45,559 Gg) (see Table 4-8). Emissions from masonry production from clinker raw material are accounted for under Lime Manufacture.

Table 4-8: CO_2 Emissions from Cement Production (Tg CO_2 Eq. and Gg)*

Year	Tg CO_2 Eq.	Gg
1990	33.3	33,278
1998	39.2	39,218
1999	40.0	39,991
2000	41.2	41,190
2001	41.4	41,357
2002	42.9	42,898
2003	43.1	43,082
2004	45.6	45,559

* Totals exclude CO_2 emissions from making masonry cement from clinker, which are accounted for under Lime Manufacture.

After falling in 1991 by two percent from 1990 levels, cement production emissions have grown every year since. Overall, from 1990 to 2004, emissions increased by 37 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

CO_2 emissions from cement manufacture are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone). While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of the 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:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

[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.

CO_2 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 64.6 percent (IPCC 2000) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.507 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{\text{Clinker}} = 0.646 \text{ CaO} \times \left[\frac{44.01 \text{ g/mole CO}_2}{56.08 \text{ g/mole CaO}} \right] = 0.507 \text{ tons CO}_2\text{/ton clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as two percent of the CO_2 emissions calculated from clinker production. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2000).

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by approximately five percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since:

$$0.6 \times 0.05/(1 + 0.05) = 2.86\%$$

An emission factor for this added lime can then be calculated by multiplying this 2.86 percent by the molecular weight ratio of CO_2 to CaO (0.785) to yield 0.0224 metric tons of additional CO_2 emitted for every metric ton of masonry cement produced.

As previously mentioned, the CO_2 emissions from the additional lime added during masonry cement production are accounted for in the section on CO_2 emissions from Lime Manufacture. Thus, the activity data for masonry cement production are shown in this chapter for informational purposes only, and are not included in the cement emission totals.

The 1990 through 2004 activity data for clinker and masonry cement production (see Table 4-9) were obtained through a personal communication with Hendrick Van Oss (Van Oss 2005) of the USGS and through the USGS *Mineral Yearbook: Cement* (USGS 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004). Data for 2004 clinker production were obtained from the USGS *Mineral Industry Summary: Cement* (USGS 2005). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

Table 4-9: Cement Production (Gg)

Year	Clinker	Masonry
1990	64,355	3,209
1991	62,918	2,856
1992	63,415	3,093
1993	66,957	2,975
1994	69,787	3,283
1995	71,257	3,603
1996	71,706	3,469
1997	74,112	3,634
1998	75,842	3,989
1999	77,337	4,375
2000	79,656	4,332
2001	79,979	4,450

2002	82,959	4,449
2003	83,315	4,737
2004	88,104	5,300

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 clinker kiln. Uncertainty is also associated with the amount of lime added to masonry cement, but it is accounted for under the Lime Manufacture source category. The lime content of clinker varies from 64 to 66 percent. CKD loss can range from 1.5 to eight percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction 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 4-10. Cement Manufacture CO_2 emissions were estimated to be between 39.7 and 51.8 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 13 percent below and 14 percent above the emission estimate of 45.6 Tg CO_2 Eq.

Table 4-10: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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 Manufacture	CO_2	45.6	39.7	51.8	-13%	+14%

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

Recalculations Discussion

Activity data for 2003 were revised to reflect data released after the publication of the 1990 through 2003 report. The revisions resulted in a less than one percent increase in 2003 emissions.

4.3. Ammonia Manufacture and Urea Application (IPCC Source Category 2B1)

Emissions of CO_2 occur during the production of synthetic ammonia, primarily through the use of natural gas as a feedstock. One nitrogen production plant located in Kansas is producing ammonia from petroleum coke 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. 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 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 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. CO_2 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:

$$0.88\ CH_4 + 1.26\ Air + 1.24\ H_2O \xrightarrow{\text{(catalyst)}} 0.88\ CO_2 + N_2 + 3\ H_2$$

$$N2 + 3\ H2 \rightarrow 2\ NH3$$

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 carbon as well as nitrogen. The chemical reaction that produces urea is:

$$2\ NH_3 + CO_2 \rightarrow\ NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

The carbon in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2; therefore, the CO_2 produced by ammonia production and subsequently used in the production of urea does not change overall CO_2 emissions. However, the CO_2 emissions are allocated to the ammonia and urea production processes in accordance to the amount of ammonia and urea produced.

Net emissions of CO_2 from ammonia manufacture in 2004 were 9.6 Tg CO_2 Eq. (9,571 Gg), and are summarized in Table 4-11 and Table 4-12. Emissions of CO_2 from urea application in 2004 totaled 7.3 Tg CO_2 Eq. (7,323Gg), and are summarized in Table 4-11 and Table 4-11.

Table 4-11: CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq.)

Source	1990		1998	1999	2000	2001	2002	2003	2004
Ammonia Manufacture	12.6		14.2	12.9	12.1	9.3	10.5	8.8	9.6
Urea Application	6.8		7.7	7.7	7.5	7.4	8.0	6.5	7.3
Total	**19.3**		**21.9**	**20.6**	**19.6**	**16.7**	**18.5**	**15.3**	**16.9**

Table 4-12: CO_2 Emissions from Ammonia Manufacture and Urea Application (Gg)

Source	1990		1998	1999	2000	2001	2002	2003	2004
Ammonia Manufacture	12,553		14,215	12,948	12,128	9,321	10,501	8,815	9,571
Urea Application	6,753		7,719	7,667	7,488	7,398	8,010	6,463	7,323
Total	**19,306**		**21,934**	**20,615**	**19,616**	**16,719**	**18,511**	**15,278**	**16,894**

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 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 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. The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production, and that amount of CO_2 emissions is allocated to urea fertilizer application. 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 application.

The calculation of the total non-combustion CO_2 emissions from nitrogenous fertilizers accounts for CO_2 emissions from the application of imported and domestically produced urea. For each ton of imported urea applied, 0.73 tons of CO_2 are emitted to the atmosphere. The amount of imported urea applied is calculated based on the net of urea imports and exports.

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 carbon 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 European Fertilizer Manufacturers Association Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The 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. 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). Ammonia and urea production data (see Table 4-13) were obtained from Coffeyville Resources (Coffeyville 2005) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 2005) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Import and export data for urea were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual reports (U.S. Census Bureau) for 1997 through 2004, 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 4-13).

Table 4-13: Ammonia Production, Urea Production, and Urea Net Imports (Gg)

Year	Ammonia Production	Urea Production	Urea Net Imports
1990	15,425	8,124	1,086
1991	15,576	7,373	648
1992	16,261	8,142	656
1993	15,599	7,557	2,305
1994	16,211	7,584	2,249
1995	15,788	7,363	2,055
1996	16,260	7,755	1,051
1997	16,231	7,430	1,600
1998	16,761	8,042	2,483
1999	15,728	8,080	2,374
2000	14,342	6,969	3,241
2001	11,092	6,080	4,008
2002	12,577	7,038	3,884
2003	10,279	5,783	3,030
2004	10,939	5,755	4,231

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. The EFMA reported an emission factor range of 1.15 to 1.30 ton CO_2/ton NH_3, with 1.2 ton CO_2/ton NH_3 reported as a typical value. The actual emission factor depends upon the amount of air used in the ammonia production process, with 1.15 ton CO_2/ton NH_3 being the approximate stoichiometric minimum that is achievable for the conventional reforming process. By using natural

gas consumption data for each ammonia plant, more accurate estimates of CO_2 emissions from ammonia production could be calculated. However, these consumption data are often considered confidential. Also, natural gas is consumed at ammonia plants both as a feedstock to the reforming process and for generating process heat and steam. Natural gas consumption data, if available, would need to be divided into feedstock use (non-energy) and process heat and steam (fuel) use, as CO_2 emissions from fuel use and non-energy use are calculated separately.[2]

Natural gas feedstock consumption data for the U.S. ammonia industry as a whole is available from the Energy Information Administration (EIA) *Manufacturers Energy Consumption Survey* (MECS) for the years 1985, 1988, 1991, 1994 and 1998 (EIA 1994, 1998). These feedstock consumption data collectively correspond to an effective average emission factor of 1.0 ton CO_2/ton NH_3, which appears to be below the stoichiometric minimum that is achievable for the conventional steam reforming process. The EIA data for natural gas consumption for the years 1994 and 1998 correspond more closely to the CO_2 emissions calculated using the EFMA emission factor than do data for previous years. The 1994 and 1998 data alone yield an effective emission factor of 1.1 ton CO_2/ton NH_3, corresponding to CO_2 emissions estimates that are approximately 1.5 Tg CO_2 Eq. below the estimates calculated using the EFMA emission factor of 1.2 ton CO_2/ton NH_3. Natural gas feedstock consumption data are not available from EIA for other years, and data for 1991 and previous years may underestimate feedstock natural gas consumption, and therefore the EFMA emission factor was used to estimate CO_2 emissions from ammonia production, rather than EIA data.

All ammonia production and subsequent urea production was assumed to be 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. Research indicates that there is only one U.S. plant that manufactures ammonia from petroleum coke. CO_2 emissions from this plant are explicitly accounted for in the Inventory estimates. No data for ammonia plants using naphtha or other feedstocks other than natural gas have been identified. Therefore, all other CO_2 emissions from ammonia plants are calculated using the emission factor for natural gas feedstock. However, actual emissions may differ because processes other than catalytic steam reformation and feedstocks other than natural gas may have been used for ammonia production. Urea is also used for other purposes than as a nitrogenous fertilizer. It was assumed that 100 percent of the urea production and net imports are used as fertilizer or in otherwise emissive uses. 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. For example, research has identified one ammonia production plant that is recovering byproduct CO_2 for use in EOR. Such CO_2 is currently assumed to remain sequestered (see the section of this chapter on CO_2 Consumption) however, time series data for the amount of CO_2 recovered from this plant is not available and therefore all of the CO_2 produced by this plant is assumed to be emitted to the atmosphere and allocated to Ammonia Manufacture. 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.

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[2] It appears that the IPCC emission factor for ammonia production of 1.5 ton CO_2 per ton ammonia may include both CO_2 emissions from the natural gas feedstock to the process and some CO_2 emissions from the natural gas used to generate process heat and steam for the process. Table 2-5, Ammonia Production Emission Factors, in Volume 3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual* (IPCC 1997) includes two emission factors, one reported for Norway and one reported for Canada. The footnotes to the table indicate that the factor for Norway does not include natural gas used as fuel but that it is unclear whether the factor for Canada includes natural gas used as fuel. However, the factors for Norway and Canada are nearly identical (1.5 and 1.6 tons CO_2 per ton ammonia, respectively) and it is likely that if one value does not include fuel use, the other value also does not. For the conventional steam reforming process, however, the EFMA reports an emission factor range for feedstock CO_2 of 1.15 to 1.30 ton per ton (with a typical value of 1.2 ton per ton) and an emission factor for fuel CO_2 of 0.5 tons per ton. This corresponds to a total CO_2 emission factor for the ammonia production process, including both feedstock CO_2 and process heat CO_2, of 1.7 ton per ton, which is closer to the emission factors reported in the *IPCC 1996 Reference Guidelines* than to the feedstock-only CO_2 emission factor of 1.2 ton CO_2 per ton ammonia reported by the EFMA. Because it appears that the emission factors cited in the *IPCC Guidelines* may actually include natural gas used as fuel, we use the 1.2 tons/ton emission factor developed by the EFMA.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-14. Ammonia Manufacture and Urea Application CO_2 emissions were estimated to be between 15.5 and 18.3 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 8 percent below and 8 percent above the emission estimate of 16.9 Tg CO_2 Eq.

Table 4-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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 Manufacture and Urea Application	CO_2	16.9	15.5	18.3	-8%	+8%

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

Recalculations Discussion

Estimates of CO_2 emissions from ammonia manufacture and urea application for the years 2002 and 2003 were revised to reflect updated data from the U.S. Census Bureau and new data sources from the Coffeyville Nitrogen Plant. These changes resulted in a decrease in CO_2 emissions from ammonia manufacture of 0.1 Tg CO_2 Eq. (1 percent) for 2002 and 0.3 Tg CO_2 Eq. (3 percent) for 2003.

Planned Improvements

The United States recognizes that the Tier 2 methodology is preferred for estimating CO_2 emissions from ammonia manufacture. Historically, efforts have been made to acquire feedstock data for this source category however the relevant data were not available. In addition to some of the future work noted in the Uncertainty section, additional planned improvements for this source category include developing a plan to determine the feasibility of acquiring the relevant data for the Tier 2 assessment. If successful, the results will be included in future inventory submissions.

4.4. Lime Manufacture (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. Lime has historically ranked fifth in total production of all chemicals in the United States. 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. CO_2 is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce 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)[3] production. It is also important to note that, for certain applications, lime reabsorbs CO_2 during use (see Uncertainty, below).

Lime production in the United States—including Puerto Rico—was reported to be 20,027 thousand metric tons in

[3] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

2004 (USGS 2005). This resulted in estimated CO_2 emissions of 13.7 Tg CO_2 Eq. (or 13,698 Gg) (see Table 4-15 and Table 4-16).

Table 4-15: Net CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	11.2
1998	13.9
1999	13.5
2000	13.3
2001	12.8
2002	12.3
2003	13.0
2004	13.7

Table 4-16: CO_2 Emissions from Lime Manufacture (Gg)

Year	Potential	Recovered*	Net Emissions
1990	11,735	(493)	11,242
1998	14,980	(1,061)	13,919
1999	14,651	(1,188)	13,473
2000	14,554	(1,233)	13,322
2001	13,946	(1,118)	12,828
2002	13,360	(1,051)	12,309
2003	14,136	(1,149)	12,987
2004	14,823	(1,125)	13,698

* For sugar refining and precipitated calcium carbonate production.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

At the turn of the 20th century, over 80 percent of lime consumed in the United States went for construction uses. The contemporary lime market is distributed across four end-use categories as follows: metallurgical uses, 37 percent; environmental uses, 28 percent; chemical and industrial uses, 21 percent; construction uses, 13 percent; and refractory dolomite, one percent. In the construction sector, hydrated lime is still used to improve durability in plaster, stucco, and mortars. In 2004, the amount of hydrated lime used for traditional building remained unchanged from 2003 (USGS 2005).

Lime production in 2004 increased over four percent from 2003, the second annual increase in production after four years of decline. Overall, from 1990 to 2004, lime production has increased by 26 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization technologies. In 1993, EPA completed regulations under the Clean Air Act capping sulfur dioxide (SO_2) emissions from electric utilities. Lime scrubbers' high efficiencies and increasing affordability have allowed the flue gas desulfurization end-use to expand significantly over the years. Phase II of the Clean Air Act Amendments, which went into effect on January 1, 2000, remains the driving force behind the growth in the flue gas desulfurization market (USGS 2003).

Methodology

During the calcination stage of lime manufacture, 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). 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 is adjusted to remove the mass of chemically combined water found in hydrated lime, using the midpoint of default ranges provided by the IPCC *Good Practice Guidance* (IPCC 2000). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 24 percent for dolomitic hydrated lime.

Lime production in the United States was 20,027 thousand metric tons in 2004 (USGS 2005), resulting in potential CO_2 emissions of 14.8 Tg CO_2 Eq. Some of the CO_2 generated during the production process, however, was recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. Combined lime manufacture by these producers was 1,887 thousand metric tons in 2004. It was assumed that approximately 80 percent of the CO_2 involved in sugar refining and PCC was recovered, resulting in actual CO_2 emissions of 13.7 Tg CO_2 Eq.

The activity data for lime manufacture and lime consumption by sugar refining and PCC production for 1990 through 2004 (see Table 4-17) were obtained from USGS (1992 through 2004). Hydrated lime production is reported separately in Table 4-18. The CaO and CaO•MgO contents of lime were obtained from the IPCC *Good Practice Guidance* (IPCC 2000). 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. For sugar refining and PCC, it was assumed that 100 percent of lime manufacture and consumption was high-calcium, based on communication with the National Lime Association (Males 2003).

Table 4-17: Lime Production and Lime Use for Sugar Refining and PCC (Gg)

Year	High-Calcium Production[a]	Dolomitic Production[a,b]	Use for Sugar Refining and PCC
1990	12,947	2,895	826
1991	12,840	2,838	964
1992	13,307	2,925	1,023
1993	13,741	3,024	1,279
1994	14,274	3,116	1,374
1995	15,193	3,305	1,503
1996	15,856	3,434	1,429
1997	16,120	3,552	1,616
1998	16,750	3,423	1,779
1999	16,110	3,598	1,992
2000	15,850	3,621	2,067
2001	15,630	3,227	1,874
2002	14,900	3,051	1,762
2003	16,040	3,124	1,926
2004	16,500	3,527	1,887

[a] Includes hydrated lime.
[b] Includes dead-burned dolomite.

Table 4-18: Hydrated Lime Production (Gg)

Year	High-Calcium Hydrate	Dolomitic Hydrate
1990	1,781	319
1991	1,841	329
1992	1,892	338
1993	1,908	342
1994	1,942	348
1995	2,027	363

1996	1,858	332
1997	1,820	352
1998	1,950	383
1999	2,010	298
2000	1,550	421
2001	2,030	447
2002	1,500	431
2003	2,140	464
2004	2,300	337

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of these products. 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 manufacture lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime manufacture 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). CO_2 reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2; whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. 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.[4]

In some cases, lime is generated from calcium carbonate by-products at pulp mills and water treatment plants.[5] 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 carbon 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.[6]

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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-19. Lime CO_2 emissions were estimated to be between 12.6 and 14.8 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte

[4] 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).

[5] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, 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 [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$] and no CO_2 is released.

[6] Based on comments submitted by and personal communication with Dr. Sergio F. Galeano, Georgia-Pacific Corporation.

Carlo Stochastic Simulations). This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 13.7 Tg CO_2 Eq.

Table 4-19: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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 Manufacture	CO_2	13.7	12.6	14.8	-8%	+8%

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

Recalculations Discussion

An inconsistency with the appropriate number of significant digits established by the IPCC for the water contents of hydrated lime was identified and corrected for the entire time series. The adjustment increased annual emission estimates throughout the time series by less than one percent relative to the previous Inventory report. The 2003 data used to estimate CO_2 recovery from PCC and sugar refining were updated to reflect revisions to USGS data, but the revision did not result in a net change in CO_2 recovery, thus net lime emissions were unchanged for 2003.

4.5. Limestone and Dolomite Use (IPCC Source Category 2A3)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[7] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass manufacture, 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 to generate CO_2 as a by-product. 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 2004, approximately 10,487 thousand metric tons of limestone and 4,373 thousand metric tons of dolomite were consumed for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 6.7 Tg CO_2 Eq. (6,702 Gg) (see

Table 4-20 and Table 4-21). Emissions in 2004 increased 42 percent from the previous year and have increased 21 percent overall from 1990 through 2004.

Table 4-20: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Flux Stone	3.0		5.1	6.0	2.8	2.5	2.4	2.1	4.1
Glass Making	0.2		0.2	0	0.4	0.1	0.2	0.3	0.4
FGD	1.4		1.2	1.2	1.8	2.6	2.8	1.9	1.9
Magnesium Production	0.1		0.1	0.1	0.1	0.1	0.0	0.0	0.0
Other Miscellaneous Uses	0.8		0.9	0.7	0.9	0.5	0.7	0.4	0.4
Total	**5.5**		**7.4**	**8.1**	**6.0**	**5.7**	**5.9**	**4.7**	**6.7**

Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid

[7] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

water treatment, acid neutralization, and sugar refining.

Table 4-21: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Flux Stone	2,999		5,132	6,030	2,830	2,514	2,405	2,072	4,112
Limestone	2,554		4,297	4,265	1,810	1,640	1,330	904	2,023
Dolomite	446		835	1,765	1,020	874	1,075	1,168	2,088
Glass Making	217		157	0	368	113	61	337	350
Limestone	189		65	0	368	113	61	337	350
Dolomite	28		91	0	0	0	0	0	0
FGD	1,433		1,230	1,240	1,774	2,551	2,766	1,932	1,871
Magnesium Production	64		73	73	73	53	0	0	0
Other Miscellaneous Uses	819		858	713	916	501	652	380	369
Total	**5,533**		**7,449**	**8,057**	**5,960**	**5,733**	**5,885**	**4,720**	**6,702**

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.

Methodology

CO_2 emissions were calculated by multiplying the quantity of limestone or dolomite consumed by the average carbon content, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). This assumes that all carbon is oxidized and released. 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.

Traditionally, the production of magnesium metal was the only other 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 2004 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 4-22) were obtained from personal communication with Valentine Tepordei of the USGS (Tepordei 2005) and in the USGS *Minerals Yearbook: Crushed Stone Annual Report* (USGS 1993, 1995a, 1995b, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a, 2002a, 2003a, 2004a). The production capacity data for 1990 through 2003 of dolomitic magnesium metal (see Table 4-23) also came from the USGS (1995c, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b, 2002b, 2003b, 2004b, 2005). 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 2004 *Minerals Yearbook: Magnesium*; therefore, it is assumed that this process continues to be non-existent in the United States (USGS 2005). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

Finally, 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 uses fraction of total consumption in that year.[8]

Table 4-22: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Flux Stone	6,738		11,514	13,390	6,249	5,558	5,275	4,501	8,971
Limestone	5,804		9,767	9,694	4,114	3,727	3,023	2,055	4,599
Dolomite	933		1,748	3,696	2,135	1,831	2,252	2,466	4,373
Glass Making	489		340	0	836	258	139	765	796
Limestone	430		149	0	836	258	139	765	796
Dolomite	59		191	0	0	0	0	0	0
FGD	3,258		2,795	2,819	4,031	5,798	6,286	4,390	4,253
Other Miscellaneous Uses	1,835		1,933	1,620	2,081	1,138	1,483	863	840
Total	**12,319**		**16,582**	**17,830**	**13,197**	**12,751**	**13,183**	**10,520**	**14,859**

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 4-23: Dolomitic Magnesium Metal Production Capacity (Metric Tons)

Year	Production Capacity
1990	35,000
1991	35,000
1992	14,909
1993	12,964
1994	21,111
1995	22,222
1996	40,000
1997	40,000
1998	40,000
1999	40,000
2000	40,000
2001	29,167
2002	0
2003	0
2004	0

Note: Production capacity for 2002, 2003, and 2004 amount to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002).

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. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. 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. Much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this

[8] This approach was recommended by USGS.

unspecified quantity to the correct end-uses. Also, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher carbon content. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, the uncertainty of the estimates for limestone used in glass making is especially high. 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. However, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-24. Limestone and Dolomite Use CO_2 emissions were estimated to be between 6.2 and 7.2 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 7 percent below and 8 percent above the emission estimate of 6.7 Tg CO_2 Eq.

Table 4-24: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	6.7	6.2	7.2	-7%	+8%

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

4.6. Soda Ash Manufacture 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 three states produce natural soda ash: Wyoming, California, and Colorado. Of these three states, only net emissions of CO_2 from Wyoming were calculated. This difference is a result of the production processes employed in each state.[9] During the production process used in Wyoming, trona ore is treated to produce soda ash. CO_2 is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 2004, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.6 Tg CO_2 Eq. (1,607 Gg). Soda ash consumption in the United States generated 2.6 Tg CO_2 Eq. (2,598 Gg) in 2004. Total emissions from soda ash manufacture in 2004 were 4.2 Tg CO_2 Eq. (4,205 Gg) (see Table 4-25 and Table 4-26). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2004 increased by approximately 2 percent from the previous year, and have increased overall by approximately 2 percent since 1990.

[9] 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 by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted.

Table 4-25: CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq.)

Year	Manufacture	Consumption	Total
1990	1.4	2.7	4.1
1998	1.6	2.7	4.3
1999	1.5	2.7	4.2
2000	1.5	2.7	4.2
2001	1.5	2.6	4.1
2002	1.5	2.7	4.1
2003	1.5	2.6	4.1
2004	1.6	2.6	4.2

Note: Totals may not sum due to independent rounding.

Table 4-26: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,431	2,710	4,141
1998	1,607	2,718	4,324
1999	1,548	2,668	4,217
2000	1,529	2,652	4,181
2001	1,500	2,648	4,147
2002	1,470	2,668	4,139
2003	1,509	2,602	4,111
2004	1,607	2,598	4,205

Note: Totals may not sum due to independent rounding.

The United States represents about one-fourth of total world soda ash output. The distribution of soda ash by end-use in 2004 was glass making, 50 percent; chemical production, 26 percent; soap and detergent manufacturing, 11 percent; distributors, five percent; flue gas desulfurization, one percent; water treatment, pulp and paper production, two percent each; and miscellaneous, four percent (USGS 2005).

Although the United States continues to be a major supplier of world soda ash, China's soda ash production surpassed the United States in 2003, and continued to be higher than the United States in 2004. The trend is expected to continue, as will the strict competition in Asian markets. The world market for soda ash is expected to grow 2.0 to 2.5 percent annually (USGS 2005).

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. CO_2 and water are generated as by-products of the calcination process. CO_2 emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3H(CO_3)_2 \cdot 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 16.5 million metric tons of trona mined in 2004 for soda ash production (USGS 2005) resulted in CO_2 emissions of approximately 1.6 Tg CO_2 Eq. (1,607 Gg).

Once manufactured, 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 carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are

released for every metric ton of soda ash consumed.

The activity data for trona production and soda ash consumption (see Table 4-27) were taken from USGS (1994 through 2004). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-27: Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture*	Consumption
1990	14,700	6,530
1991	14,700	6,280
1992	14,900	6,320
1993	14,500	6,280
1994	14,600	6,260
1995	16,500	6,500
1996	16,300	6,390
1997	17,100	6,480
1998	16,500	6,550
1999	15,900	6,430
2000	15,700	6,390
2001	15,400	6,380
2002	15,100	6,430
2003	15,500	6,270
2004	16,500	6,260

* Soda ash manufactured from trona ore only.

Uncertainty

Emission estimates from soda ash manufacture 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 4-28. Soda Ash Manufacture and Consumption CO_2 emissions were estimated to be between 3.9 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 7 percent below and 7 percent above the emission estimate of 4.2 Tg CO_2 Eq.

Table 4-28: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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 Manufacture and Consumption	CO_2	4.2	3.9	4.5	-7%	+7%

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

Planned Improvements

Emissions from soda ash production in Colorado, which is produced using the nahcolite production process, will be investigated for inclusion in future inventories.

4.7. 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 TiO_2 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. CO_2 is emitted from the chloride process, which 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 carbon as a raw material and does not emit CO_2.

The chloride process is based on the following chemical reactions:

$$2\ FeTiO_3 + 7\ Cl_2 + 3\ C \rightarrow 2\ TiCl_4 + 2\ FeCl_3 + 3\ CO_2$$

$$2\ TiCl_4 + 2\ O_2 \rightarrow 2\ TiO_2 + 4\ Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (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 petroleum coke is manufactured specifically for this purpose. Emissions of CO_2 from titanium dioxide production in 2004 were 2.3 Tg CO_2 Eq. (2,259 Gg), an increase of 11 percent from the previous year and 73 percent from 1990, due to increasing production within the industry (see Table 4-29).

Table 4-29: CO_2 Emissions from Titanium Dioxide (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.3	1,308
1998	1.8	1,819
1999	1.9	1,853
2000	1.9	1,918
2001	1.9	1,857
2002	2.0	1,997
2003	2.0	2,013
2004	2.3	2,259

Methodology

Emissions of CO_2 from titanium dioxide production were calculated by multiplying annual titanium dioxide production by chlorine process-specific emission factors.

Data were obtained for the total amount of TiO_2 produced each year, and it was assumed that 97 percent of the total production in 2004 was produced using the chloride process. 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. 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 carbon inputs. The amount of petroleum coke consumed annually in TiO_2 production was calculated based on the assumption that petroleum coke used in the process is 90 percent carbon and 10 percent inert materials.

The emission factor for the TiO_2 chloride process was taken from the report, *Everything You've Always Wanted to Know about Petroleum Coke* (Onder and Bagdoyan 1993). Titanium dioxide production data for 1990 through 2004 (see Table 4-30) were obtained from personal communication with Joseph Gambogi, USGS Commodity Specialist, of the USGS (Gambogi 2005) and through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2003). Data for the percentage of the total TiO_2 production capacity that is chloride process for 1994 through 2002 were also taken from the USGS *Minerals Yearbook* and from Joseph Gambogi for 2004. 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. The composition data for petroleum coke were obtained from Onder and Bagdoyan (1993).

Table 4-30: Titanium Dioxide Production (Gg)

Year	Gg
1990	979
1991	992
1992	1,140
1993	1,160
1994	1,250
1995	1,250
1996	1,230
1997	1,340
1998	1,330
1999	1,350
2000	1,400
2001	1,330
2002	1,410
2003	1,420
2004	1,540

Uncertainty

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated 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. 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 4-31. Titanium dioxide consumption CO_2 emissions were estimated to be between 1.9 and 2.6 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 16 percent below and 16 percent above the emission estimate of 2.3 Tg CO_2 Eq.

Table 4-31: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	2.3	1.9	2.6	-16%	+16%

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

4.8. Phosphoric Acid Production (IPCC Source Category 2A7)

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 ($CaSO_4$-$2H_2O$), 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 carbon in the form of calcium carbonate (limestone) and also may contain organic carbon. 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 carbon 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 carbon (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 1997). The primary chemical reactions for the production of phosphoric acid from phosphate rock are:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow 3CaSO_4\ 6H_2O + 6H_3PO_4$$

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:

$$CaCO_3 + H_2SO_4\ + H_2O\ \rightarrow CaSO_4\ 2H_2O + CO_2$$

Total marketable phosphate rock production in 2004 was 39.0 million metric tons. Approximately 81 percent of domestic phosphate rock production was mined in Florida and North Carolina, while approximately 13 percent of production was mined in Idaho and Utah. In addition, 2.5 million metric tons of crude phosphate rock was imported for consumption in 2004. Marketable phosphate rock production, including domestic production and imports for consumption, increased by approximately 4.2 percent between 2003 and 2004. However, over the 1990 to 2004 period, production decreased by 11 percent. The 35.3 million metric tons produced in 2001 was the lowest production level recorded since 1965 and was driven by a worldwide decrease in demand for phosphate fertilizers. Total CO_2 emissions from phosphoric acid production were 1.4 Tg CO_2 Eq. (1,395 Gg) in 2004 (see Table 4-32).

Table 4-32: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
1998	1.6	1,593
1999	1.5	1,539

2000	1.4	1,382
2001	1.3	1,264
2002	1.3	1,338
2003	1.4	1,382
2004	1.4	1,395

Methodology

CO_2 emissions from production of phosphoric acid from phosphate rock is 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 USGS reports in the Minerals Yearbook, Phosphate Rock, the aggregate amount of phosphate rock mined annually in Florida and North Carolina and the aggregate amount of phosphate rock mined annually in Idaho and Utah, and reports the annual amounts of phosphate rock exported and imported for consumption (see Table 4-33). Data for domestic production of phosphate rock, exports of phosphate rock, and imports of phosphate rock for consumption for 1990 through 2004 were obtained from *USGS Mineral Yearbook, Phosphate Rock* (USGS 1994 through 2005). In 2004, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005).

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 3.5 percent inorganic carbon (as CO_2), and phosphate rock imported from Morocco contains approximately 5 percent inorganic carbon (as CO_2). Calcined phosphate rock mined in North Carolina and Idaho contains approximately 1.5 percent and 1.0 percent inorganic carbon (as CO_2), respectively (see Table 4-34).

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 (81 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. The USGS reported that one phosphate rock producer in Idaho is producing calcined phosphate rock; however, no production data were available for this single producer (USGS 2003). 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.

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic carbon (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 carbon content of the phosphate rock is converted to CO_2 and that all of the organic carbon content remains in the phosphoric acid product.

Table 4-33: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location/Year	1990	1998	1999	2000	2001	2002	2003	2004
U.S. Production	49,800	43,640	41,440	37,370	32,830	34,720	36,410	36,530
FL & NC	42,494	38,000	35,900	31,900	28,100	29,800	31,300	31,600
ID & UT	7,306	5,640	5,540	5,470	4,730	4,920	5,110	4,930
Exports—FL & NC	6,240	378	272	299	9	62	64	-
Imports—Morocco	451	1,760	2,170	1,930	2,500	2,700	2,400	2,500
Total U.S. Consumption	**44,011**	**45,022**	**43,338**	**39,001**	**35,321**	**37,358**	**38,746**	**39,030**

Source: USGS 2005, 2004, 2003, 2002, 2001, 2000, 1999, 1998, 1997, 1996, 1995.
- Assumed equal to zero.

Table 4-34: Chemical Composition of Phosphate Rock (percent by weight)

Composition	Central	North Florida	North Carolina	Idaho	Morocco

	Florida		(calcined)	(calcined)	
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

Source: FIPR 2003
- Assumed equal to zero.

Uncertainty

Phosphate rock production data used in the emission calculations are developed by the USGS through monthly and semiannual voluntary surveys of the eleven companies that owned phosphate rock mines during 2004. The phosphate rock production data are not considered to be a significant source of uncertainty because all eleven of the domestic phosphate rock producers report their annual production to the USGS. Data for imports for consumption and exports of phosphate rock used in the emission calculation 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.

One source of potentially significant uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the data for 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. Only one set of data from the Florida Institute of Phosphate Research was available for the composition of phosphate rock mined domestically and imported, and data for uncalcined phosphate rock mined in North Carolina and Idaho were unavailable. Inorganic carbon content (as CO_2) of phosphate rock could vary ±1 percent from the data included in Table 4-34, resulting in a variation in CO_2 emissions of ±20 percent. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of the FIPR indicated that in the phosphoric acid production process the organic carbon 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 carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production. However, if, for example, 50 percent of the organic carbon content of the phosphate rock were to be emitted as CO_2 in the phosphoric acid production process, the CO_2 emission estimate would increase by on the order of 50 percent.

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 carbon in the phosphate rock into CO_2. However, according to the USGS, only one producer in Idaho is currently calcining phosphate rock, and no data were available concerning the annual production of this single producer (USGS 2005). Total production of phosphate rock in Utah and Idaho combined amounts to approximately 15 percent of total domestic production in 2004 (USGS 2005). If it is assumed that 100 percent of the reported domestic production of phosphate rock for Idaho and Utah was first calcined, and it is assumed that 50 percent of the organic carbon content of the total production for Idaho and Utah was converted to CO_2 in the calcination process, the CO_2 emission estimate would increase on the order of 10 percent.

Finally, USGS indicated that 10 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2004). 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 carbon content in phosphate rock, but none from the organic carbon content. This phosphate rock, consumed for other purposes, constitutes approximately 10 percent of total phosphate rock consumption. If it were assumed that there are zero emissions from other uses of phosphate rock, CO_2 emissions would fall 10 percent.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-35. Phosphoric acid

production CO_2 emissions were estimated to be between 1.1 and 1.7 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 18 percent below and 19 percent above the emission estimate of 1.4 Tg CO_2 Eq.

Table 4-35: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	1.4	1.1	1.7	-18%	+19%

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

Planned Improvements

The estimate of CO_2 emissions from phosphoric acid production could be improved through collection of additional data. Additional data is being collected concerning the carbonate content of uncalcined phosphate rock mined in various locations in the United States. Additional research will also be conducted concerning the disposition of the organic carbon content of the phosphate rock in the phosphoric acid production process. Only a single producer of phosphate rock is calcining the product, and only a single producer is manufacturing elemental phosphorus. Annual production data for these single producers will probably remain unavailable.

4.9. Ferroalloy Production (IPCC Source Category 2C2)

CO_2 is 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. Subsequently, 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:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

Emissions of CO_2 from ferroalloy production in 2004 were 1.3 Tg CO_2 Eq. (1,287 Gg) (see Table 4-36), an 11 percent increase from the previous year and a 35 percent reduction since 1990.

Table 4-36: CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	2.0	1,980
1998	2.0	2,027
1999	2.0	1,996
2000	1.7	1,719
2001	1.3	1,329
2002	1.2	1,237
2003	1.2	1,159
2004	1.3	1,287

Methodology

Emissions of CO_2 from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) 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 50 percent silicon ferrosilicon (2.35 tons CO_2/ton of alloy produced) was applied. Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon (3.9 tons CO_2 per ton alloy produced) was applied. The emission factor for silicon metal was assumed to be 4.3 tons CO_2/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/UNEP/OECD/IEA 1997), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon and 10 percent inert material.

Ferroalloy production data for 1990 through 2004 (see Table 4-37) were obtained from the USGS through personal communications with the USGS Silicon Commodity Specialist (Corathers 2005) and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004). 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 4-37). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Table 4-37: 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
1998	162,000	147,000	195,000	99,800
1999	252,000	145,000	195,000	NA
2000	229,000	100,000	184,000	NA
2001	167,000	89,000	137,000	NA
2002	156,000	98,000	113,000	NA
2003	113,000	75,800	139,000	NA
2004	120,000	92,300	150,000	NA

NA (Not Available)

Uncertainty

Although some ferroalloys may be produced using wood or other biomass as a carbon 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 carbon is of biogenic origin.[10] 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.

Also, annual ferroalloy production is now reported by the USGS in three broad categories: ferroalloys containing 25

[10] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change, and Forestry chapter.

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 4-38. Ferroalloy production CO_2 emissions were estimated to be between 1.3 and 1.3 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 3 percent below and 3 percent above the emission estimate of 1.3 Tg CO_2 Eq.

Table 4-38: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	1.3	1.3	1.3	-3%	+3%

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

Recalculations Discussion

Estimates of CO_2 emissions from ferroalloy production for 2003 were revised to reflect updated data from the USGS. This change resulted in a decrease in CO_2 emissions from ferroalloy production of 0.2 Tg CO_2 Eq. (16 percent) for 2003.

4.10. Carbon Dioxide Consumption (IPCC Source Category 2B5)

CO_2 is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected 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. CO_2 used in EOR applications is considered for the purposes of this analysis to remain sequestered in the underground formations into which the CO_2 is injected.

It is unclear to what extent the CO_2 used for EOR will be re-released to the atmosphere. CO_2 used in EOR applications is compressed at the CO_2 production source, transported by pipeline to the EOR field, and injected into wellheads. Potential CO_2 leakage pathways from CO_2 production, transportation, and injection include fugitive emissions from the compressors, pipeline equipment, and wellheads. Also, the CO_2 used for EOR may migrate to the wellhead after a few years of injection (Hangebrauk et al. 1992) or may be partially recovered as a component of crude oil produced from the wells (Denbury Resources 2003a). This CO_2 may be recovered and re-injected into the wellhead or separated from the petroleum produced and vented to the atmosphere. More research is required to determine the amount of CO_2 that may escape from EOR operations through leakage from equipment, as a component of the crude oil produced, or as leakage directly from the reservoir through geologic faults and fractures or through improperly plugged or improperly completed wells. For the purposes of this analysis, it is assumed that all of the CO_2 produced for use in EOR applications is injected into reservoirs (i.e., there is no loss of CO_2 to the atmosphere during CO_2 production, transportation, or injection for EOR applications) and that all of the injected CO_2 remains sequestered within the reservoirs.

CO_2 is produced from naturally occurring CO_2 reservoirs, as a by-product from the energy and industrial production

processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a by-product from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component. CO_2 produced from naturally occurring CO_2 reservoirs and used in industrial applications other than EOR is included in this analysis. Neither by-product CO_2 generated from energy or industrial production processes nor CO_2 separated from crude oil and natural gas are included in this analysis for a number of reasons.

Depending on the raw materials that are used, by-product CO_2 generated during energy and industrial production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either from fossil fuel combustion or from non-energy uses of fossil fuels). For example, ammonia is primarily manufactured using natural gas as both a feedstock and energy source. CO_2 emissions from natural gas combustion for ammonia production are accounted for in the CO_2 from Fossil Fuel Combustion source category of the Energy sector and, therefore, are not included under CO_2 Consumption. Likewise, CO_2 emissions from natural gas used as feedstock for ammonia production are accounted for in this chapter under the Ammonia Manufacture source category and, therefore, are not included here.[11]

CO_2 is produced as a by-product 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. The amount of CO_2 separated from crude oil and natural gas has not been estimated.[12] Therefore, the only CO_2 consumption that is accounted for in this analysis is CO_2 produced from natural wells other than crude oil and natural gas wells 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 natural 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 U.S. 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). In 2004, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere were 1.2 Tg CO_2 Eq. (1,183 Gg) (see Table 4-39). This amount represents a decrease of 9 percent from the previous year and an increase of 29 percent from emissions in 1990. This increase was due to an increase in the Mississippi facility's reported production for use in other commercial applications.

Table 4-39: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.9	860
1998	0.9	912
1999	0.8	849
2000	1.0	957
2001	0.8	818
2002	1.0	968
2003	1.3	1,293
2004	1.2	1,183

[11] One ammonia manufacturer located in Oklahoma is reportedly capturing approximately 35 MMCF/day (0.67 Tg/yr) of by-product CO_2 for use in EOR applications. According to the methodology used in this analysis, this amount of CO_2 would be considered to be sequestered and not emitted to the atmosphere. However, time series data for the amount of CO_2 captured from the ammonia plant for use in EOR applications are not available, and therefore all of the CO_2 produced by the ammonia plant is assumed to be emitted to the atmosphere and is accounted for in this chapter under Ammonia Manufacture.

[12] The United States is in the process of developing a methodology to account for CO_2 emissions from natural gas systems and petroleum systems for inclusion in future Inventory submissions. For more information see Annex 5.

Methodology

CO_2 emission estimates for 2001 through 2004 were based on production data for the two facilities currently producing CO_2 from naturally-occurring CO_2 reservoirs. 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). CO_2 produced from these two facilities that was used for EOR is assumed to remain sequestered and is not included in the CO_2 emissions totals. It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

CO_2 production data for the Jackson Dome, Mississippi facility for 2001 through 2004 and the percentage of total production that was used for EOR and in non-EOR applications were obtained from the Annual Reports for Denbury Resources, the operator of the facility (Denbury Resources 2002, 2003b, 2004, 2005). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2004 and reported the percentage of the total average annual production that was used for EOR. CO_2 production data for the Bravo Dome, New Mexico facility were obtained from the New Mexico Bureau of Geology and Mineral Resources for the years 1990 through 2003 (Broadhead 2005). According to the New Mexico Bureau, the amount of CO_2 produced from Bravo Dome for use in non-EOR applications is less than one percent of total production (Broadhead 2003a). Production data for 2004 were not available for Bravo Dome, so it is assumed that the production values for those years are equal to the 2003 value.

Denbury Resources acquired the Jackson Dome facility in 2001 and CO_2 production data for the Jackson Dome facility are not available for years prior to 2001. Therefore, for 1990 through 2000, CO_2 emissions from CO_2 consumption in commercial applications other than EOR are estimated based on the total annual domestic consumption of CO_2 in commercial applications other than EOR in 2001 multiplied by the percentage of the total CO_2 consumed in commercial applications other than EOR that originated from CO_2 production at the Jackson Dome and Bravo Dome facilities in 2001. The same procedure was followed in 2002, 2003, and 2004 with updated annual data. The total domestic commercial consumption of CO_2 in commercial applications other than EOR as reported by the U.S. Census Bureau was about 13,542 thousand metric tons in 2004. The total non-EOR CO_2 produced from the Jackson Dome and Bravo Dome natural reservoirs in 2004 was about 1,183 thousand metric tons, corresponding to 8.7 percent of the total domestic non-EOR commercial CO_2 consumption. The remaining 91.3 percent of the total annual non-EOR commercial CO_2 consumption is assumed to be accounted for in the CO_2 emission estimates from other categories (e.g., Ammonia Manufacture, CO_2 from Fossil Fuel Combustion, Wood Biomass and Ethanol Consumption).

Non-EOR commercial CO_2 consumption data (see Table 4-40) for years 1991 and 1992 were obtained from *Industry Report 1992* (U.S. Census 1993). Consumption data are not available for 1990, and therefore CO_2 consumption data for 1990 is assumed to be equal to that for 1991. Consumption data for 1993 and 1994 were obtained from *U.S. Census Bureau Manufacturing Profile, 1994* (U.S. Census 1995). Consumption data for 1996 through 2004 were obtained from the U.S. Census Bureau's *Industry Report, 1996, 1998, 2000, 2002, 2003, 2004* (U.S. Census 1997, 1999, 2001, 2003, 2004, 2005).

Table 4-40: CO_2 Consumption (Metric Tons)

Year	Metric Tons
1990	11,997,726
1998	12,716,070
1999	11,843,386
2000	13,354,262
2001	11,413,889
2002	11,313,478
2003	11,165,324
2004	13,542,492

Uncertainty

Uncertainty is associated with the number of facilities that are currently producing CO_2 from naturally occurring 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. For example, research has identified one ammonia production facility that is recovering CO_2 for use in EOR. Such CO_2 would be assumed to remain sequestered, however, time series data for the amount of recovered is not available and therefore all of the CO_2 produced by this plant is assumed to be emitted to the atmosphere and is allocated to Ammonia Manufacture. Recovery of CO_2 from ammonia production facilities for use in EOR is further discussed in this chapter under Ammonia Manufacture. 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.

There is also uncertainty associated with the assumption that 100 percent of the CO_2 used for EOR is sequestered. Operating experience with EOR systems indicates that 100 percent of the CO_2 used in EOR applications does not remain sequestered, but rather that it may be emitted to the atmosphere as leakage from equipment and reservoirs or recovered as a component of the crude oil produced. Potential sources of CO_2 emissions from EOR applications include leakage from equipment used to produce, transport, compress, and inject the CO_2, leakage from equipment used to process the crude oil produced, separate the CO_2 from the crude oil and recompress and recycle [reinject] the CO_2 recovered from the crude oil. Other potential sources of CO_2 emissions from EOR applications include leakage from the reservoir itself, either through migration of the injected CO_2 beyond the boundaries of the reservoir, chemical interactions between the injected CO_2 and the reservoir rock, and leakage via faults, fractures, oil and gas well bores, and water wells.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-41. CO_2 consumption CO_2 emissions were estimated to be between 1.0 and 1.4 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 14 percent below to 14 percent above the emission estimate of 1.2 Tg CO_2 Eq.

Table 4-41: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	1.2	1.0	1.4	-14%	+14%

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

Recalculations Discussion

Total CO_2 consumption values were updated for 2003, as was CO_2 production for Jackson Dome, based on revised data in the Census Bureau's Industry Reports and Denbury Resources' Annual Report, respectively. Data for the Bravo Dome were updated for the entire time series based on new production data from the facility. For Jackson Dome, revised 2003 production data resulted in a 33 percent increase in emissions from the previous estimate. For Jackson Dome, updated production data resulted in an approximate emissions decrease of 1 percent for 2001, 17 percent for 2002, and 11 percent for 2003. Revisions to the datasets resulted in a 1 percent decrease in CO_2 emissions from CO_2 consumption in 2002 and a 2 percent increase in CO_2 emissions from CO_2 consumption in 2003 relative to data published in the previous Inventory.

4.11. Zinc Production

Zinc production in the United States consists of both primary and secondary processes. Primary production techniques used in the United States are the electro-thermic 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 electro-thermic 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). Total zinc production has decreased by 15 percent in the United States since 1990 while world production has increased by 38 percent over this same period (USGS 1995, 2004).

During the electro-thermic 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 tons of zinc are produced for every ton of EAF dust treated (Viklund-White 2000).

In 2004, U.S. primary and secondary zinc production totaled 567,900 metric tons (USGS 2004). The resulting emissions of CO_2 from zinc production in 2004 were estimated to be 0.5 Tg CO_2 Eq. (502 Gg) (see Table 4-42). All 2004 CO_2 emissions result from secondary zinc production.

Table 4-42: CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.9	939
1998	1.1	1,140
1999	1.1	1,080
2000	1.1	1,129
2001	1.0	976
2002	0.9	927
2003	0.5	502
2004	0.5	502

After a gradual increase in total emissions from 1990 to 2000, largely due to an increase in secondary zinc production, 2004 emissions have decreased by nearly half that of 1990 (47 percent) due to the closing of an electro-thermic-process zinc plant in Monaca, PA (USGS 2004).

Methodology

Non-energy CO_2 emissions from zinc production result from those processes that use metallurgical coke or other carbon-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 electro-thermic and Waelz Kiln processes, were needed. Due to the limited amount of information available for these electro-thermic processes, only Waelz Kiln process-specific emission factors were developed. These emission factors were applied to both the Waelz Kiln process and the electro-thermic 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:

$$EF_{\text{Waelz Kiln}} = \frac{1.19\ \text{metric tons coke}}{\text{metric tons zinc}} \times \frac{0.84\ \text{metric tons C}}{\text{metric ton coke}} \times \frac{3.67\ \text{metric tons CO2}}{\text{metric ton C}} = \frac{3.66\ \text{metric tons CO2}}{\text{metric ton zinc}}$$

The USGS disaggregates total U.S. primary zinc production capacity into zinc produced using the electro-thermic 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 electro-thermic zinc production capacity is divided by total primary zinc production capacity to estimate the percent of primary zinc produced using the electro-thermic process. This percent is then multiplied by total primary zinc production to estimate the amount of zinc produced using the electro-thermic 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 electro-thermic 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 electro-thermic or Waelz Kiln process. In 1997, the Horsehead Corporation plant, located in Monaca, PA, produced 47,174 metric tons of secondary zinc using the electro-thermic process (Queneau et al. 1998). This is the only plant in the United States that uses the electro-thermic 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 electro-thermic 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 electro-thermic 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:

$$EF_{\text{EAF Dust}} = \frac{0.4\ \text{metric tons coke}}{\text{metric tons EAF Dust}} \times \frac{0.84\ \text{metric tons C}}{\text{metric ton coke}} \times \frac{3.67\ \text{metric tons CO2}}{\text{metric ton C}} = \frac{1.23\ \text{metric tons CO2}}{\text{metric ton EAF Dust}}$$

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 2003 activity data for primary and secondary zinc production (see Table 4-43) were obtained through the USGS *Mineral Yearbook: Zinc* (USGS 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004). Because data for 2004 are not yet available, 2004 data are assumed to equal 2003 data.

Table 4-43: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	341,400
1991	253,282	351,457
1992	271,867	365,623

1993	240,000	358,000
1994	216,600	361,000
1995	231,840	353,000
1996	225,400	378,000
1997	226,700	374,000
1998	233,900	426,000
1999	241,100	398,000
2000	227,800	440,000
2001	203,000	375,000
2002	181,800	366,000
2003	186,900	381,000
2004	186,900	381,000

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 electro-thermic and Waelz Kiln emissive zinc production processes. For primary zinc production, the amount of zinc produced annually using the electro-thermic process is estimated from the percent of primary-zinc production capacity that electro-thermic 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 electro-thermic process. The amount of secondary zinc produced using the electro-thermic 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 electro-thermic 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 electro-thermic process. Therefore, emission factors for the Waelz Kiln process were applied to both electro-thermic 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 4-44. Zinc production CO_2 emissions were estimated to be between 0.4 and 0.6 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 12 percent below and 13 percent above the emission estimate of 0.5 Tg CO_2 Eq.

Table 4-44: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	0.6	-12%	+13%

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

4.12. Lead Production

Lead production in the United States consists of both primary and secondary processes. In the United States, primary lead production, in the form of direct smelting, mostly occurs at a plant located in Missouri, while secondary production largely involves the recycling of lead acid batteries at 15 separate smelters located in 11 states throughout the United States (USGS 2004). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased, where 2004 secondary lead production accounted for approximately 88 percent of total lead production (USGS 1995, 2004). Both the primary lead and secondary lead production processes used in the United States emit CO_2 (Sjardin 2003).

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 40 percent from 2003 to 2004 due to the closing of one of two primary lead production plants in Missouri and has decreased by 63 percent since 1990 (USGS 1995, Gabby 2005)

In the United States, approximately 82 percent of secondary lead is produced by recycling lead acid batteries in either blast furnaces or reverberatory furnaces. The remaining 18 percent of secondary lead is produced from lead scrap. 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 by 3 percent from 2003 to 2004, but has increased by 17 percent since 1990.

In 2004, U.S. primary and secondary lead production totaled 1,258,00 metric tons (USGS 2004). The resulting emissions of CO_2 from 2004 production were estimated to be 0.3 Tg CO_2 Eq. (259 Gg) (see Table 4-45). The majority of 2004 lead production is from secondary processes, which account for 85 percent of total 2004 CO_2 emissions.

Table 4-45: CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.3	285
1998	0.3	308
1999	0.3	310
2000	0.3	311
2001	0.3	293
2002	0.3	290
2003	0.3	289
2004	0.3	259

After a gradual increase in total emissions from 1990 to 2000, total emissions have decreased by nine percent since 1990, largely due a decrease in primary production and a transition within the United States from primary lead production to secondary lead production, which is less emissive than primary production (USGS 2004).

Methodology

Non-energy CO_2 emissions from lead production result from primary and secondary production processes that use metallurgical coke or other carbon-based materials as reductants. For primary lead production using direct smelting, Sjardin (2003) provides an emission factor of 0.25 metric tons CO_2/ton lead. For secondary lead production, Sjardin (2003) provides 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 2003 activity data for primary and secondary lead production (see Table 4-46) were obtained through the USGS *Mineral Yearbook: Lead* (USGS 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003,

2004). Primary and secondary lead production data for 2004 were obtained from the USGS Lead Minerals Commodity Specialist (Gabby 2005).

Table 4-46: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
1991	345,900	885,000
1992	304,800	916,000
1993	334,900	893,000
1994	351,400	931,000
1995	374,000	1,020,000
1996	326,000	1,070,000
1997	343,000	1,110,000
1998	337,000	1,120,000
1999	350,000	1,110,000
2000	341,000	1,130,000
2001	290,000	1,100,000
2002	262,000	1,120,000
2003	245,000	1,140,000
2004	148,000	1,110,000

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 emissions 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 4-47. 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 (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 11 percent below and 11 percent above the emission estimate of 0.3 Tg CO_2 Eq.

Table 4-47: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	-11%	+11%

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

4.13. 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 carbon black, ethylene, ethylene dichloride, styrene, and methanol, while CO_2 emissions are presented here for only carbon black production. The CO_2 emissions from petrochemical processes other than carbon 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 carbon 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 intensely black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. 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. Styrene is a common precursor for many plastics, rubber, and resins. It can be found in many construction products, such as foam insulation, vinyl flooring, and epoxy adhesives. 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 2004 were 2.9 Tg CO_2 Eq. (2,895 Gg) and 1.6 Tg CO_2 Eq. (77 Gg), respectively (see Table 4-48 and Table 4-49). Emissions of CO_2 from carbon black production in 2004 increased four percent from the previous year, and there has been an overall increase in CO_2 emissions from carbon black production of 30 percent since 1990. CH_4 emissions from petrochemical production increased by seven percent from the previous year and increased 38 percent since 1990.

Table 4-48: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	2.2	3.0	3.1	3.0	2.8	2.9	2.8	2.9
CH_4	1.2	1.7	1.7	1.7	1.4	1.5	1.5	1.6
Total	**3.4**	**4.7**	**4.8**	**4.7**	**4.2**	**4.4**	**4.3**	**4.5**

Table 4-49: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	1990	1998	1999	2000	2001	2002	2003	2004
CO_2	2,221	3,015	3,054	3,004	2,787	2,857	2,777	2,895
CH_4	56	80	81	80	68	72	72	77

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 carbon black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[13] 4 kg CH_4/metric ton styrene, and 2 kg CH_4/metric ton methanol. Although the production of other chemicals may also result in CH_4 emissions, there were not sufficient data available to estimate their emissions.

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data for 1990 (see Table 4-50) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2004 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005) and the International Carbon Black Association (Johnson 2003, 2005).

Table 4-50: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1998	1999	2000	2001	2002	2003	2004
Carbon Black	1,307	1,775	1,798	1,769	1,641	1,682	1,635	1,704
Ethylene	16,542	23,474	25,118	24,971	22,521	23,623	22,957	25,660

[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 ($C_2H_2Cl_2$).

Ethylene Dichloride	6,282		11,080	10,308	9,866	9,294	9,288	9,952	12,111
Styrene	3,637		5,183	5,410	5,420	4,277	4,974	5,239	5,468
Methanol	3,785		5,860	5,303	4,876	3,402	3,289	3,166	2,937

Almost all carbon 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 carbon black feedstock is combusted to provide energy to the process. Carbon 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. carbon black plant produces carbon black using the thermal black process, and one U.S. carbon black plant produces carbon black using the acetylene black process (The Innovation Group 2004).

The furnace black process produces carbon black from "carbon black feedstock" (also referred to as "carbon 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 carbon black, the "primary feedstock" (i.e., carbon 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 carbon black feedstock are oxidized to provide heat to the production process and pyrolyze the remaining carbon black feedstock to carbon 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 carbon 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 carbon lost during the production process is the basis for determining the amount of CO_2 released during the process. The carbon content of national carbon black production is subtracted from the total amount of carbon contained in primary and secondary carbon black feedstock to find the amount of carbon lost during the production process. It is assumed that the carbon lost in this process is emitted to the atmosphere as either CH_4 or CO_2. The carbon content of the CH_4 emissions, estimated as described above, is subtracted from the total carbon lost in the process to calculate the amount of carbon emitted as CO_2. The total amount of primary and secondary carbon black feedstock consumed in the process (see Table 4-51) is estimated using a primary feedstock consumption factor and a secondary feedstock consumption factor estimated from U.S. Census Bureau (1999 and 2004) data. The average carbon black feedstock consumption factor for U.S. carbon black production is 1.43 metric tons of carbon black feedstock consumed per metric ton of carbon black produced. The average natural gas consumption factor for U.S. carbon black production is 341 normal cubic meters of natural gas consumed per metric ton of carbon black produced. The amount of carbon contained in the primary and secondary feedstocks is calculated by applying the respective carbon contents of the feedstocks to the respective levels of feedstock consumption.

Table 4-51: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	**1990**		**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Primary Feedstock	1,864		2,530	2,563	2,521	2,339	2,398	2,331	2,430
Secondary Feedstock	302		410	415	408	379	388	377	393

For the purposes of emissions estimation, 100 percent of the primary carbon black feedstock is assumed to be derived from petroleum refining byproducts. Carbon black feedstock derived from metallurgical (coal) coke production (e.g., creosote oil) is also used for carbon black production; however, no data are available concerning the annual consumption of coal-derived carbon black feedstock. Carbon black feedstock derived from petroleum refining byproducts is assumed to be 89 percent elemental carbon (Srivastava et al. 1999). It is assumed that 100 percent of the tail gas produced from the carbon 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 carbon black because of the lack of data concerning the relatively small amount of carbon black produced using the acetylene black and thermal black processes. The carbon black produced from the furnace black process is assumed to be 97 percent elemental carbon (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 carbon black production calculation are based on feedstock consumption, import and export data, and carbon black production data. The composition of carbon black feedstock varies depending upon the specific refinery production process, and therefore the assumption that carbon black feedstock is 89 percent carbon gives rise to uncertainty. Also, no data are available concerning the consumption of coal-derived carbon 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 carbon black production may be underreported by the U.S. Census Bureau. Finally, the amount of carbon 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 carbon black is produced using the furnace black process.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-52. Petrochemical production CH_4 emissions were estimated to be between 1.5 and 1.7 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 8 percent below to 6 percent above the emission estimate of 1.6 Tg CO_2 Eq. Petrochemical production CO_2 emissions were estimated to be between 2.5 and 3.1 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 14 percent below to 5 percent above the emission estimate of 2.9 Tg CO_2 Eq.

Table 4-52: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Carbon Black Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Petrochemical Production	CH_4	1.6	1.5	1.7	-8%	+6%
Petrochemical Production	CO_2	2.9	2.5	3.1	-14%	+5%

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

4.14. Silicon Carbide Production (IPCC Source Category 2B4) and Consumption

CH_4 is emitted from the production of silicon carbide (SiC), a material used as an industrial abrasive; CO_2 is emitted from the use of SiC for metallurgical and other non-abrasive applications. To make SiC, quartz (SiO_2) is reacted with carbon in the form of petroleum coke. During this reaction, CH_4 is produced from volatile compounds in the petroleum coke. While CO_2 is also emitted from the production process, the requisite data were unavailable for these calculations. CO_2 emissions associated with the use of petroleum coke in the SiC process are accounted for in the Non-Energy Uses of Fossil Fuels section in the Energy Chapter. CH_4 from SiC production in 2004 were 0.4 Gg CH_4 (0.01 Tg CO_2 Eq.) (see Table 4-53 and Table 4-54).

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). This consumption of SiC produces CO_2 emissions. Considering utilization of both domestically produced SiC and imported SiC in such applications, the amount of CO_2 emitted from SiC consumption in 2004 were 133 Gg CO_2 (0.1 Tg CO_2 Eq.) (see Table 4-53 and Table 4-54).

Table 4-53: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq.)

Year	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	0.1		0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+		+	+	+	+	+	+	+
Total	0.1		0.2	0.2	0.1	0.1	0.1	0.1	0.1

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 4-54: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Year	1990		1998	1999	2000	2001	2002	2003	2004
CO_2	100		190	137	130	94	105	111	133
CH_4	1		1	1	1	+	+	+	+

+ Does not exceed 0.5 Gg.

Methodology

Emissions of CH_4 were calculated by multiplying annual SiC production by an emission factor (11.6 kg CH_4/metric ton SiC). This emission factor was derived empirically from measurements taken at Norwegian SiC plants (IPCC/UNEP/OECD/IEA 1997).

Emissions of CO_2 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 carbon content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Production data for 1990 through 2004 were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS 1991a, 1992a, 1993a, 1994a, 1995a, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a, 2002a, 2003a, 2004a, 2005a). Silicon carbide consumption by major end use was obtained from the Minerals Yearbook: Silicon (USGS 1991b, 1992b, 1993b, 1994b, 1995b, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b, 2002b, 2003b, 2004b, 2005b) (see Table 4-55). Net imports were obtained from the U.S. Census Bureau (2005).

Table 4-55: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,464
1991	78,900	138,652
1992	84,300	159,902
1993	74,900	173,508
1994	84,700	179,055
1995	75,400	227,397
1996	73,600	240,781
1997	68,200	292,050
1998	69,800	329,040
1999	65,000	237,346
2000	45,000	225,280
2001	40,000	162,142
2002	30,000	180,956
2003	35,000	191,289
2004	35,000	229,693

Uncertainty

The emission factor used for silicon carbide production was based on one study of Norwegian plants. The applicability of this factor to average U.S. practices at silicon carbide plants is uncertain. 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. 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 4-56. Silicon carbide production CH_4 emissions were estimated to be between 0.0077 and 0.0094 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 10 percent below to 10 percent above the emission estimate of 0.0085 Tg CO_2 Eq. Silicon carbide consumption CO_2 emissions were estimated to be between 0.1 and 0.2 Tg CO_2 Eq. percent confidence level. This indicates a range of approximately 17 percent below to 18 percent above the emission estimate of 0.1 Tg CO_2 Eq.

Table 4-56: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Silicon Carbide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Silicon Carbide Production	CH_4	+	+	+	-10%	+10%
Silicon Carbide Consumption	CO_2	0.1	0.1	0.2	-17%	+18%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg.

4.15. 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 by-product and is released from reactor vents into the atmosphere.

Currently, the nitric acid industry controls for 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. Approximately 20 percent of nitric acid plants use NSCR (Choe et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce N_2O emissions.

N_2O emissions from this source were estimated to be 16.6 Tg CO_2 Eq. (54 Gg) in 2004 (see Table 4-57). Emissions from nitric acid production have decreased by 7 percent since 1990, with the trend in the time series closely tracking the changes in production.

Table 4-57: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.8	58
1998	20.9	67
1999	20.1	65
2000	19.6	63
2001	15.9	51
2002	17.2	56
2003	16.7	54
2004	16.6	54

Methodology

N_2O 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 for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg N_2O / metric ton HNO_3 for plants not equipped with NSCR (Choe et al. 1993). 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. An estimated 20 percent of HNO_3 plants in the United States are equipped with NSCR (Choe et al. 1993). Hence, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8$ kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 (see Table 4-58) was obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2001). Nitric acid production data for 1991 through 1992 (see Table 4-58) were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2002). Nitric acid production data for 1993 was obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2004). Nitric acid production data for 1994 through 2004 were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2005). The emission factor range was taken from Choe et al. (1993).

Table 4-58: Nitric Acid Production (Gg)

Year	Gg
1990	7,196
1991	7,191
1992	7,379
1993	7,486
1994	7,904
1995	8,018
1996	8,349
1997	8,556
1998	8,421
1999	8,113
2000	7,898
2001	6,416
2002	6,939
2003	6,747
2004	6,703

Uncertainty

The overall uncertainty associated with the 2004 N_2O emissions estimate from nitric acid production was calculated using the IPCC *Good Practice Guidance* 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 activity data inputs and their associated uncertainties and distributions are summarized in Table 4-59.

Table 4-59: Sources of Uncertainty in N_2O Emissions from Nitric Acid

			Uncertainty Range[a]		
Variable	Value	Distribution Type	Lower Bound	Upper Bound	Reference
National Production (Gg)	6,703	Normal	-10%	+10%	Expert Judgment
Plants With NSCR (%)	20%	Normal	-10%	+10%	Expert Judgment
Plants Without NSCR (%)	80%	Normal	-10%	+10%	Expert Judgment
Emission Factor for Plants With NSCR (kg N_2O/tonne HNO_3)	2.0	Normal	-10%	+10%	IPCC Good Practice
Emission Factor for Plants Without NSCR (kg	9.5	Normal	-10%	+10%	IPCC Good Practice

N_2O/tonne HNO_3)

[a] Parameters presented represent upper and lower bounds as a percentage of the mean, based on a 95 percent confidence interval.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-60. N_2O emissions from nitric acid production were estimated to be between 13.9 and 19.5 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 16 percent below to 17 percent above the 2004 emissions estimate of 16.6 Tg CO_2 Eq.

Table 4-60: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From Nitric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	16.6	13.9	19.5	-16%	+17%

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

Recalculations Discussion

The nitric acid production value for 2003 has been updated relative to the previous Inventory based on revised production data presented in C&EN (2005). The updated production data for 2003 resulted in an increase of 0.9 Tg CO_2 Eq. (6 percent) in N_2O emissions from nitric acid production for that year relative to the previous Inventory.

Planned Improvements

Planned improvements are focused on assessing the plant-by-plant implementation of NO_x abatement technologies to more accurately match plant production capacities to appropriate emission factors, instead of using a national profiling of abatement implementation.

4.16. 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 is the major producer, with three companies in four locations accounting for approximately one-third of world production (CW 2005). Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Approximately 90 percent of all adipic acid produced in the United States is used in the production of nylon 6,6 (CMR 2001). Food grade adipic acid is also 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. N_2O is generated as a by-product 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.[14] Only one small plant, representing approximately two percent of production, does not control

[14] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

for N_2O (Reimer 1999).

N_2O emissions from this adipic acid production were estimated to be 5.7 Tg CO_2 Eq. (19 Gg) in 2004 (see Table 4-61).

Table 4-61: N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	15.2	49
1998	6.0	19
1999	5.5	18
2000	6.0	19
2001	4.9	16
2002	5.9	19
2003	6.2	20
2004	5.7	19

National adipic acid production has increased by approximately 36 percent over the period of 1990 through 2004, to approximately one million metric tons. At the same time, emissions have been significantly reduced due to the widespread installation of pollution control measures.

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 estimates for 2003 and 2004 were unavailable and, thus, were calculated by applying a 4.4 and 4.2 percent production growth rate, respectively. The production for 2003 was obtained through linear interpolation between 2004 and 2002 reported production data. Subsequently, the growth rate for 2004 was based on the change between the estimated 2003 production data and the reported 2004 production data (see discussion below on sources of production data). 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 tons of product (Thiemens and Trogler 1991). Emissions are estimated using the following equation:

$$N_2O \text{ emissions} = (\text{production of adipic acid [metric tons \{MT\} of adipic acid]}) \times (0.3 \text{ MT } N_2O / \text{MT adipic acid}) \times (1 - [N_2O \text{ destruction factor} \times \text{abatement system utility factor}])$$

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. The N_2O abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999). For the one plant that uses thermal destruction and for which no reported plant-specific emissions are available, the abatement system utility factor is assumed to be 98 percent.

For 1990 to 2003, plant-specific production data needed to be estimated where direct emissions 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, actual plant production data were obtained for these two plants and used for emissions calculations.

National adipic acid production data (see Table 4-62) for 1990 through 2002 were obtained from the American Chemistry Council (ACC 2003). Production Data for 2003 were estimated based on linear interpolation of 2002 and 2004 reported data. Production data for 2004 were obtained from *Chemical Week*, Product Focus: Adipic Acid (CW 2005). Plant capacity data for 1990 through 1994 were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995). Plant capacity data for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacity data were taken from *Chemical Market Reporter* "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacity data for all four plants and 1999 plant capacity data for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacity data for 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2004, the plant capacities for these three plants were kept the same as the year 2000 capacities. Plant capacity data for 1999 to 2004 for the one remaining plant was kept the same as 1998.

Table 4-62: Adipic Acid Production (Gg)

Year	Gg
1990	735
1991	708
1992	724
1993	769
1994	821
1995	830
1996	839
1997	871
1998	862
1999	907
2000	925
2001	835
2002	921
2003	961
2004	1,002

Uncertainty

The overall uncertainty associated with the 2004 N_2O emissions estimate from adipic acid production was calculated using the IPCC *Good Practice Guidance* 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 activity data inputs and their associated uncertainties and distributions are summarized in Table 4-63.

Table 4-63: Sources of Uncertainty in N_2O Emissions from Adipic Acid Production

			Uncertainty Range[a]		
Variable	Value	Distribution Type	Lower Bound	Upper Bound	Reference
Company Specific Production (Gg): Plant 1	17	Normal	-10%	+10%	Expert Judgment
Company Specific Production (Gg): Plant 4	400	Normal	-10%	+10%	Expert Judgment
Estimated Production Growth Rates (2002-2003) (%) : Plants 2 and 3	4%	Normal	-25%	+25%	Expert Judgment
Estimated Production Growth Rates (2003-2004) (%) : Plants 2 and 3	4%	Normal	-25%	+25%	Expert Judgment

N_2O Destruction Factor (%): Plant 4	98%	Normal	-5%	+5%	IPCC Good Practice
Abatement System Utility Factor (%): Plant 4	98%	Normal	-5%	+5%	Expert Judgment
2002 Emission Estimate (Tg CO_2 Eq.): Plant 2	Confidential	Normal	-5%	+5%	Expert Judgment
2002 Emission Estimate (Tg CO_2 Eq.): Plant 3	Confidential	Normal	-5%	+5%	Expert Judgment

[a] Parameters presented represent upper and lower bounds as a percentage of the mean, based on a 95 percent confidence interval.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-64. N_2O emissions from adipic acid production were estimated to be between 3.2 and 8.3 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 45 percent below to 44 percent above the 2004 emission estimate of 5.7 Tg CO_2 Eq.

Table 4-64: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Adipic Acid Production	N_2O	5.7	3.2	8.3	-45%	+44%

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

Recalculations Discussion

The adipic acid industry-wide production value for 2003 was updated through linear interpolation between 2002 and 2004 reported production data. Newly published adipic acid production figures for 2004 were obtained from Chemical Week (CW 2005). The updated production data for 2003 resulted in an increase of 0.2 Tg CO_2 Eq. (3 percent) in N_2O emissions from adipic acid production for that year relative to the previous Inventory.

Planned Improvements

Improvement efforts will be focused on obtaining direct measurement data from the remaining two plants when and if they become available. If they become available, 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.

4.17. 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.[15] 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,

[15] [42 U.S.C § 7671, CAA § 601]

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 4-65 and Table 4-66.

Table 4-65: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.)

Gas	1990	1998	1999	2000	2001	2002	2003	2004
HFC-23	+	+	0.1	0.1	0.1	0.1	0.1	0.1
HFC-32	+	0.3	0.3	0.3	0.3	0.3	0.4	0.4
HFC-125	+	8.8	10.0	11.2	12.3	13.4	14.7	16.3
HFC-134a	+	35.2	40.2	45.4	49.7	53.5	56.8	61.6
HFC-143a	+	5.2	6.6	8.2	10.1	12.2	14.6	17.3
HFC-236fa	+	0.4	0.9	1.4	1.8	2.1	2.3	2.3
CF_4	+	+	+	+	+	+	+	+
Others*	0.4	4.6	4.8	4.6	4.5	4.6	4.6	5.3
Total	**0.4**	**54.5**	**62.8**	**71.2**	**78.6**	**86.2**	**93.5**	**103.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

* 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 4-66: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1998	1999	2000	2001	2002	2003	2004
HFC-23	+	4	4	5	5	6	6	7
HFC-32	+	430	439	443	463	501	557	631
HFC-125	+	3,134	3,571	4,006	4,390	4,787	5,262	5,821
HFC-134a	+	27,058	30,902	34,927	38,196	41,170	43,664	47,391
HFC-143a	+	1,369	1,738	2,162	2,647	3,203	3,834	4,543
HFC-236fa	+	64	142	214	281	341	369	367
CF_4	+	1	1	1	1	2	2	3
Others*	M	M	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 Mg

* 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.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—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.[16] In 1993, the use of HFCs in foam production and as an aerosol propellant 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 103.3 Tg CO_2 Eq. in 2004. 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

[16] R-404A contains HFC-125, HFC-143a, and HFC-134a.

with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

The end-use sectors that contribute the most toward emissions of HFCs and PFCs as ODS substitutes include refrigeration and air-conditioning (88.4 Tg CO_2 Eq., or approximately 85 percent), aerosols (11.1 Tg CO_2 Eq., or approximately 11 percent), and solvents (1.6 Tg CO_2 Eq., or approximately 2 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (31.9 Tg CO_2 Eq.), followed by retail food and refrigerated transport. In the aerosols end-use sector, non-MDI emissions make up a majority of the end-use sector emissions.

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/UNEP/OECD/IEA (1997). 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 15 end-uses and 5 others. These end-uses together account for 95 percent of emissions from this source category. 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, an additional 5 end-uses were included in the uncertainty estimate. Since the foams sector is not represented in the top 15, the two highest emitting foams end-uses were chosen to represent this sector, and two MDI aerosols end-uses were included to represent the MDI portion of the aerosols sector. Any end-uses included in previous years' uncertainty analysis were included in the current uncertainty analysis, whether or not those end-uses were included in the top 95 percent of emissions from ODS Substitutes.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption. Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed. The most significant sources of uncertainty for this source category include the emission factors for mobile air-conditioning and retail food refrigeration, as well as the stock (MT) of retail food refrigerant.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-67. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 90.5 and 124.4 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 13 percent below to 20 percent above the emission estimate of 103.3 Tg CO_2 Eq.

Table 4-67: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (Tg CO_2 Eq. and Percent)

Source	Gases	2004 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
Substitution of Ozone Depleting Substances	HFCs and PFCs	103.3	90.5	124.4	-13%	+20%

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

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 2.0 Tg CO_2 Eq. (3 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2003.

4.18. HCFC-22 Production (IPCC Source Category 2E1)

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product 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, however, U.S. production has declined to levels near those of the early to mid 1990s. 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 is generally vented to the atmosphere as an unwanted by-product, but it is sometimes captured for use in a limited number of applications.

Emissions of HFC-23 in 2004 were estimated to be 15.6 Tg CO_2 Eq. (1.3 Gg) (Table 4-68). This quantity represents a 26 percent increase from 2003 emissions and a 55 percent decline from 1990 emissions. The increase from 2003 emissions is due to an increase in HCFC-22 production, while the decline from 1990 emissions is primarily due to the steady decline in the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured). Three HCFC-22 production plants operated in the United States in 2004, two of which used thermal oxidation to significantly lower their HFC-23 emissions.

[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 4-68: HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	35.0	3
1998	40.1	3
1999	30.4	3
2000	29.8	3
2001	19.8	2
2002	19.8	2
2003	12.3	1
2004	15.6	1

Methodology

The methodology employed for estimating emissions is based upon measurements at individual HCFC-22 production plants. 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. The other plants periodically measure HFC-23 concentrations in the output stream using gas chromatography. This information is combined with information on quantities of critical feed components (e.g., HF) and/or products (HCFC-22) to estimate HFC-23 emissions using a material balance approach. HFC-23 concentrations are determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

Production data and emission estimates were prepared in cooperation with the U.S. manufacturers of HCFC-22 (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004; 2005; RTI 1997). Annual estimates of U.S. HCFC-22 production are presented in Table 4-69.

Table 4-69: HCFC-22 Production (Gg)

Year	Gg
1990	139
1991	143
1992	150
1993	132
1994	147
1995	155
1996	166
1997	165
1998	183
1999	166
2000	187
2001	152
2002	144
2003	138
2004	155

Uncertainty

A high level of confidence has been attributed to the HFC-23 concentration data employed because measurements were conducted frequently and accounted for day-to-day and process variability. The results of the Tier 1 quantitative uncertainly analysis are summarized in Table 4-70. HFC-23 emissions from HCFC-22 production were estimated to be between 14.0 and 17.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 10 percent above and 10 percent below the 2004 emission estimate of 15.6 Tg CO_2 Eq.

Table 4-70: Tier 1 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	15.6	14.0	17.2	-10%	+10%

[a] Range of emission reflect a 95 percent confidence interval.

4.19. 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 switch gear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 from electrical transmission and distribution systems were estimated to be 13.8 Tg CO_2 Eq. (0.6 Gg) in 2004. This quantity represents a 52 percent decrease from the estimate for 1990 (see Table 4-71 and Table 4-72). This decrease is believed to be a response to increases in the price of SF_6 during the 1990s and to growing awareness of the environmental impact of SF_6 emissions, through programs such as the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.

Table 4-71: SF_6 Emissions from Electric Power Systems and Original Equipment Manufactures (Tg CO_2 Eq.)

Year	Electric Power Systems	Original Equipment Manufacturers	Total
1990	28.3	0.3	**28.6**
1998	16.4	0.4	**16.7**
1999	15.5	0.6	**16.1**
2000	14.6	0.7	**15.3**
2001	14.7	0.7	**15.3**
2002	13.8	0.7	**14.5**
2003	13.4	0.7	**14.0**
2004	13.1	0.7	**13.8**

Table 4-72: SF_6 Emissions from Electric Power Systems and Original Equipment Manufactures (Gg)

Year	Emissions
1990	1.2
1998	0.7
1999	0.7
2000	0.6
2001	0.6
2002	0.6
2003	0.6
2004	0.6

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 to 2004 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2004 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems, which began in 1999; and, (2) utilities' transmission miles as reported in the 2001 and 2004 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2004, participating utilities represented between 31 percent and 39 percent of total U.S. transmission miles. For each year, the emissions reported by participating utilities were added to the emissions estimated for utilities that do not participate in the EPA's SF_6 Emission Reduction Partnership (i.e., non-partners).

Emissions from utilities participating in EPA's SF_6 Emission Reduction Partnership were estimated using a combination of reported data and, where reported data were unavailable, interpolated or extrapolated data. If a partner utility did not provide data for a historical year, emissions were interpolated between years for which data were available. For 2004, if no data was provided, estimates were calculated based on historical trends or partner-specific emission reduction targets (i.e., it was assumed that emissions would decline linearly towards a partners' future stated goal). In 2004, non-reporting partners account for approximately 2 percent of the total emissions attributable to utilities involved in the SF_6 Emission Reduction Partnership.

Emissions from non-partners in every year since 1999 were estimated using the results of a regression analysis that showed that the emissions of 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 49 partner utilities (representing approximately 31 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 less 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 it was assumed that non-partners have not implemented any changes that have resulted in reduced emissions since 1999.

The regression equations are:

Non-partner small utilities (less than 10,000 transmission miles, in kilograms):

$$\text{Emissions} = 0.874 \times \text{Transmission Miles}$$

Non-partner large utilities (more than 10,000 transmission miles, in kilograms):

$$\text{Emissions} = 0.558 \times \text{Transmission Miles}$$

Data on transmission miles for each non-partner utility for the years 2000 and 2003 was obtained from the 2001 and 2004 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004). Given that the U.S. transmission system grew by over 14,000 miles between 2000 and 2003, and that this increase probably occurred gradually, transmission mileage was assumed to increase exponentially at an annual rate of 0.7 percent between 2000 and 2003. This growth rate is assumed to continue through 2004.

As a final step, total emissions were determined for each year by summing the partner emissions (reported to the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), and the non-partner emissions (determined using the 1999 regression equation).

1990 to 1998 Emissions from Electric Power Systems

Because most participating utilities reported emissions only for 1999 through 2004, modeling SF_6 emissions from electric power systems for the years 1990 through 1998 was necessary. To do so, it was assumed that during this period, U.S. emissions followed the same trajectory as global emissions from this source. To estimate global emissions, the RAND survey of global SF_6 sales to electric utilities was used, together with the following equation, which is derived from the equation for emissions in the IPCC *Good Practice Guidance* (IPCC 2000):

Emissions (kilograms) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity 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, lowering the amount of SF_6 purchased by utilities for this purpose.

Sulfur hexafluoride purchased to refill existing equipment in a given year was assumed to be approximately equal to the SF_6 purchased by utilities in that year. Gas purchases by utilities and equipment manufacturers from 1961 through 2001 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 77.5 percent of the amount of gas purchased by electrical equipment manufacturers 30 years previous (e.g., in 1990, the nameplate capacity of retiring equipment was assumed to equal 77.5 percent of the gas purchased in 1960). The remaining 22.5 percent was assumed to have been emitted at the time of manufacture. The 22.5 percent emission rate is an average of IPCC SF_6 emission rates for Europe and Japan for years before 1996 (IPCC 2000). The 30-year lifetime for electrical equipment is also drawn from IPCC (2000). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1998.

To estimate U.S. emissions for 1990 through 1998, estimated 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. To estimate historical U.S. emissions, the factor for each year was multiplied by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 15.5 Tg CO_2 Eq.).

1990 to 2004 Emissions from Manufacture of Electrical Equipment

The 1990 to 2004 emissions estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 charged into new equipment. The quantity of SF_6 charged into 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 charged into new equipment for 2001 to 2004 were assumed to equal that charged into equipment in 2000. 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, EPA estimated the uncertainties associated with three variables: (1) emissions from electric power systems that participate in EPA's SF_6 Emission Reduction Partnership, (2) emissions from electric power systems that do not participate in the Partnership, and (3) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

The cumulative uncertainty of all partner data was estimated to be 5 percent, based on error propagation. There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2004 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, which is assumed to be 10 percent. In addition, there is uncertainty associated with the assumption that the emission factor used for non-partner utilities (which accounted

for approximately 65 percent of U.S. transmission miles) will remain at levels defined by partners who reported in 1999. However, the last source of uncertainty was not modeled.

For OEMs, uncertainty estimates are based on the assumption that SF_6 statistics obtained from NEMA have an uncertainty of 20 percent. Additionally, the OEMs SF_6 emissions rate has an uncertainty bounded by the proposed "actual" and "ideal" emission rates defined in O'Connell, et al. (2002). That is, the uncertainty in the emission rate is approximately 65 percent.

A Monte Carlo analysis was applied to estimate the overall uncertainty of the 2004 emission estimate for SF_6 from electrical transmission and distribution. For each defined parameter (i.e., equation coefficient, transmission mileage, and partner-reported and partner-estimated SF_6 emissions data for electric power systems; and SF_6 emission rate and statistics for OEMs), random variables were selected from probability density functions, all assumed to have normal distributions about the mean. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-73. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 12.0 and 15.7 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 13 percent below and 13 percent above the emission estimate of 13.8 Tg CO_2 Eq.

Table 4-73: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2004 Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	13.8	12.0	15.7	-13%	+13%

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

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 21 percent between 1995 and 1998, and emissions based on atmospheric measurements declined by 27 percent over the same period. However, U.S. emission patterns may differ from global emission patterns.

4.20. 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 by-product. 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 2004, 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 4-74 and Table 4-75, below. The rapid growth of this industry and the increasing complexity of semiconductor products which use more PFCs in the production process have led to an increase in emissions of 61 percent since 1990. The emissions growth rate began to slow after 1997, and emissions declined by 35 percent between 1999 and 2004. The initial implementation of PFC emission reduction methods such as process optimization and abatement technologies is responsible for this decline.

Table 4-74: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Year	1990	1998	1999	2000	2001	2002	2003	2004
CF_4	0.7	1.8	1.8	1.8	1.3	1.1	1.0	1.2
C_2F_6	1.5	3.6	3.7	3.0	2.1	2.2	2.1	2.2
C_3F_8	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
C_4F_8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
HFC-23	0.2	0.4	0.4	0.3	0.2	0.2	0.2	0.2
SF_6	0.5	1.3	1.3	1.1	0.8	0.7	0.8	0.9
NF_3*	0.0	0.1	0.1	0.1	0.1	0.3	0.2	0.3
Total	**2.9**	**7.1**	**7.2**	**6.3**	**4.5**	**4.4**	**4.3**	**4.7**

Note: Totals may not sum due to independent rounding.
* NF_3 emissions are presented for informational purposes, using a GWP of 8,000, and are not included in totals.

Table 4-75: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Year	1990	1998	1999	2000	2001	2002	2003	2004
CF_4	115	277	281	281	202	175	161	185
C_2F_6	160	391	397	324	231	244	228	245
C_3F_8	0	0	0	17	14	9	13	6
C_4F_8	0	0	0	0	0	5	8	9
HFC-23	15	37	37	23	16	15	17	20
SF_6	22	54	55	46	31	28	35	38
NF_3	3	9	9	11	12	32	30	31

Methodology

Emissions from semiconductor manufacturing were estimated using three distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, and 2000 and beyond. For 1990 through 1994, emissions were estimated using the most recent version of EPA's PFC Emissions Vintage Model (PEVM) (Burton and Beizaie 2001).[18] PFC emissions per square centimeter of silicon increase as the number of layers in semiconductor devices increases. Thus, PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest feature size, which leads to an increasing number of layers),[19] and (2)

[18] The most recent version of this model is v.3.2.0506.0507, completed in September 2005.

[19] By decreasing features of IC components, more components can be manufactured per device, which increases its

product type (memory vs. logic).[20] PEVM derives historical consumption of silicon (i.e., square centimeters) by linewidth technology from published data on annual wafer starts and average wafer size (Burton and Beizaie 2001). 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 IC) specific to product type (Burton and Beizaie 2001; ITRS 2005). The distribution of memory/logic devices ranges over the period covered from 52 percent logic devices in 1995 to 59 percent logic devices in 2000. These figures were used to determine emission factors that express emissions per average layer per unit of area of silicon consumed during product manufacture. The per-layer emission factor was based on the total annual emissions reported by participants in EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry in 1995 and later years.

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partnership participants (Burton and Mallya 2005). The emissions reported by the participants were divided by the ratio of the total layer-weighted capacity of the plants operated by the participants and the total layer-weighted capacity of all of the semiconductor plants in the United States; this ratio represents the share of layer-weighted capacity attributable to partnership participants. The layer-weighted capacity of a plant (or group of plants) consists of the silicon capacity of that plant multiplied by the estimated number of layers used to fabricate products at that plant. This method assumes that participants and non-participants have similar capacity utilizations and per-layer emission factors. Plant capacity, linewidth technology, products manufactured information is contained in the World Fab Watch (WFW) database, which is updated quarterly (see for example, Semiconductor Equipment and Materials Industry 2005).

The U.S. estimate for the years 2000 through 2004—the period during which partners began the consequential application of PFC-reduction measures—used a different estimation method. The emissions reported by Partnership participants 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), however, were estimated using PEVM and the method described above. (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. figure by the non-partner share of total layer-weighted silicon capacity for each year (as described above). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc. as well as revisions and additions to the world population of semiconductor manufacturing plants (see Semiconductor Equipment and Materials Industry 2005).[21]

Two different approaches were also used to estimate the distribution of emissions of specific PFCs. Before 1999, when there was no consequential adoption of PFC-reducing measures, a fixed distribution was assumed to apply to the entire U.S. industry. This distribution was based upon the average PFC 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 2004 period, the 1990 through 1999 distribution was assumed to apply to the non-Partners. Partners, however, began to report gas-specific emissions during this period. Thus, gas specific

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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 requires 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, 2005).

[20] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers (ITRS, 2005).

[21] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants in 2004 is below design capacity, the figure provided in WFW. 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 but approximately 70 percent of the design capacity.

emissions for 2000 through 2004 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.[22]

Partners estimate their emissions using a range of methods. For 2004, most participants cited a method at least as accurate as the IPCC's Tier 2c Methodology, recommended in the IPCC *Good Practice Guidance* (IPCC 2000). The partners with relatively high emissions typically use the more accurate IPCC 2b or 2a methods, multiplying estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from tool suppliers.

Data used to develop emission estimates were prepared in cooperation with the Partnership. Estimates of operating plant capacities and characteristics for participants and non-participants were derived from the Semiconductor Equipment and Materials Industry (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 to 2004). Estimates of silicon consumed by line-width from 1990 through 2004 were derived from information from VLSI Research (2005), and the number of layers per line-width was obtained from International Technology Roadmap for Semiconductors*:* 1998-2004 (Burton and Beizaie 2001, ITRS 2005).

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 both emissions and their uncertainty is:

U.S. emissions = Non-partnership share of MSI-layer capacity × PEVM estimate + Partnership submittal

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the three variables on the right side of the equation. Estimates of uncertainty for the three variables were in turn developed using the estimated uncertainties associated with the individual inputs to each variable, error propagation analysis, and expert judgment. For the first variable, the aggregate PFC emissions data supplied to the partnership, EPA estimated an uncertainty of approximately ±10 percent (representing a 95 percent confidence interval). For the second variable, the share of U.S. layer-weighted silicon capacity accounted for by non-Partners, an uncertainty of ±10 percent was assumed based on information from the firm that compiled the database (SMA 2003). For the third variable, the relative error associated with the PEVM estimate in 2004, EPA estimated an uncertainty of ±20 percent, using the calculus of error propagation and considering the aggregate average emission factor, world silicon consumption, and the U.S. share of layer-weighted silicon capacity.

Consideration was also given to the nature and magnitude of the potential bias that PEVM 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 PEVM overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. This bias is represented in the uncertainty analysis by deducting the absolute bias value from the PEVM emissions estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-76. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 3.8 and 6.1 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This range represents 23 percent below to 23 percent above the 2004 emission estimate of 4.7 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.

[22] In recent years, the Partnership started reporting gas-specific emissions using GWP values from the Third Assessment Report (TAR), while in previous years the vales were taken from the Second Assessment Report (SAR). The emissions reported here are restated using GWPs from the SAR.

Table 4-76: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate[a] ($Tg CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[b] ($Tg CO_2$ Eq.)		Uncertainty Range Relative to Emission Estimate[b] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, and SF_6	4.7	3.8	6.1	-23%	+23%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-74.

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

Planned Improvements

The method to estimate non-partner related emissions (i.e., PEVM) is not expected to change (with the exception of possible future updates to emission factors and added technology nodes). 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). 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).

4.21. 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. In 2004, the United States was the fourth largest producer of primary aluminum, with eight percent of the world total (USGS 2005). 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).

CO_2 is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon 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. (4,346 Gg) in 2004 (see Table 4-77). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here rather than in the Iron and Steel source category of the Industrial Processes sector.

Table 4-77: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	7.0	7,045
1998	6.4	6,359
1999	6.5	6,458
2000	6.2	6,244
2001	4.5	4,505
2002	4.6	4,596
2003	4.6	4,609

2004	4.3	4,346

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 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 85 percent and 81 percent, respectively, to 2.4 Tg CO_2 Eq. of CF_4 (0.4 Gg) and 0.4 Tg CO_2 Eq. of C_2F_6 (0.05 Gg) in 2004, as shown in Table 4-78 and Table 4-79. 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. Since 1990, aluminum production has declined by 38 percent, while the average CF_4 and C_2F_6 emission rates (per metric ton of aluminum produced) have been reduced by 76 and 69 percent respectively.

Table 4-78: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	16.2	2.2	18.4
1998	8.1	1.0	9.1
1999	8.0	1.0	9.0
2000	8.1	0.9	9.0
2001	3.5	0.5	4.0
2002	4.6	0.7	5.3
2003	3.3	0.5	3.8
2004	2.4	0.4	2.8

Note: Totals may not sum due to independent rounding.

Table 4-79: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.5	0.2
1998	1.2	0.1
1999	1.2	0.1
2000	1.2	0.1
2001	0.5	0.1
2002	0.7	0.1
2003	0.5	0.1
2004	0.4	+

+ Does not exceed 0.5 Gg

U.S. primary aluminum production for 2004—totaling 2.5 million metric tons—declined nearly 7 percent from 2003 production. Due to high electric power costs in various regions of the country, aluminum production has been curtailed at several U.S. smelters, which resulted in 2004 production levels that were approximately 31 percent lower than 2000 levels. The transportation industry remained the largest domestic consumer of primary aluminum, accounting for about 38 percent of U.S. consumption (USGS 2005).

Methodology

CO_2 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 achieved through 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 carbon 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. The CO_2 emission factor employed was estimated from the production of primary aluminum metal and the carbon consumed by the process. Emissions vary depending on the specific technology used by each plant (e.g., prebake or Søderberg). CO_2 process emissions were estimated using methodology recommended by the *Aluminum Sector Greenhouse Gas Protocol* (IAI, 2003.

The prebake process specific formula recommended by IAI (2003) accounts for various parameters, including net carbon consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, process formulas account 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. The Søderberg process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen and ash content.

In 2002, VAIP expanded its voluntary reporting to include direct CO_2 data. As agreed, process data have been reported for 1990, 2000, 2003 and 2004. 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 IAI (2003). Smelter specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, and 15 out of 16 operating smelters in 2003 and 2004. 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 16 smelters in 2004, and 5 out of 23 between 1990 and 2003), CO_2 emission estimates were estimated using the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which provide CO_2 emission factors for each technology type. During alumina reduction in a prebake anode cell process, approximately 1.5 metric tons of CO_2 are emitted for each metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997). Similarly, during alumina reduction in a Soderberg cell process, approximately 1.8 metric tons of CO_2 are emitted per metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997).

Aluminum production data for 15 out of the 16 operating smelters were reported under the VAIP in 2004. For the non-reporting smelter, production was estimated based on the difference between reporting smelters and national aluminum production levels. Between 1990 and 2003, production data were provided by 21 of the 23 operating U.S. smelters.

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 minutes/cell day))
Anode Effect Minutes/Cell-Day = Anode Effect Frequency/Cell-Day × Anode Effect Duration (minutes)

Smelter-specific slope coefficients that are based on field measurements yield the most accurate results. To estimate emissions between 1990 and 2003, smelter-specific coefficients were available and were used for 12 out of the 23 U.S. smelters. To estimate 2004 emissions, smelter-specific coefficients were available and were used for 5 out of the 16 operating U.S. smelters, representing approximately 35 percent of 2004 U.S. production. For the remaining 11 operating smelters, technology-specific slope coefficients from the IPCC *Good Practice Guidance* (IPCC 2000)

were applied. 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. In 2004, smelter-specific anode effect data was available for 15 of the 16 operating smelters. Where smelter-specific anode effect data were not available (i.e., 1 out of 16 smelters in 2004, 2 out of 23 smelters between 1990 and 2003), industry averages were used. For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. In 2004, smelter-specific production data was available for 15 of the 16 operating smelters; production at the one remaining smelter was estimated based on national aluminum production and capacity data (USAA 2005). Between 1990 and 2004, production data has been provided by 21 of the 23 U.S. smelters. Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by the IPCC *Good Practice Guidance* (IPCC 2000).

National primary aluminum production data for 1990 through 2001 (see Table 4-80) obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002). For 2002, 2003, and 2004, national aluminum production data were obtained from the United States Aluminum Association's *Primary Aluminum Statistics* (USAA 2004, 2005). The CO_2 emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 4-80: Production of Primary Aluminum (Gg)

Year	Gg
1990	4,048
1991	4,121
1992	4,042
1993	3,695
1994	3,299
1995	3,375
1996	3,577
1997	3,603
1998	3,713
1999	3,779
2000	3,668
2001	2,637
2002	2,705
2003	2,705
2004	2,517

Uncertainty

The overall uncertainties associated with the 2004 CO_2, CF_4, and C_2F_6 emission estimates were calculated using the IPCC Good Practice Guidance Tier 2 methodology. Uncertainty associated with the parameters used to estimate CO_2 emissions included that associated with production data, with the share of U.S. aluminum production attributable to each smelter type, and with the emission factors applied to production data to calculate emissions. Uncertainty surrounding production data was assumed to be characterized as described below, while other variables were modeled assuming triangular distributions. Emission factors were determined through expert elicitation to be 50 percent certain at a 95 percent confidence level, while the share of production attributed to smelter types were determined to be associated with a 25 percent uncertainty. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2 emissions 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, EPA estimated the uncertainties associated with three variables 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 emissions estimate for each smelter and for the U.S. aluminum industry as a whole.

All three types of data are assumed to be characterized by a normal distribution. The uncertainty of aluminum production estimates was assumed to be 1 percent or 25 percent, depending on whether a smelter's production was reported or estimated (Kantamaneni et al., 2001). The uncertainty of the anode effect frequency was assumed to be 2 percent for data that was reported; however, for the one smelter that did not report data, the uncertainty was estimated to be 78 percent (Kantamaneni et al., 2001). Similarly, the uncertainty in anode effect duration was assumed to be 5 percent for data that was reported, but 70 percent for data that was estimated (Kantamaneni et al., 2001). The uncertainties for estimated anode effect frequency and duration are based on the standard deviations of reported technology-specific anode-effect frequency and duration in the International Aluminum Institute's anode effect survey (IAI 2000).

For the three smelters that participated in the 2003 EPA-funded measurement study, CF_4 and C_2F_6 slope coefficient uncertainties were calculated to be 10 percent. For the remaining smelters, given the limited uncertainty data on site-specific slope coefficients (i.e., those developed using IPCC Tier 3b methodology), the overall uncertainty associated with the slope coefficients is conservatively assumed to be similar to that given by the IPCC guidance for technology-specific slope coefficients. Consequently, the uncertainty assigned to the slope coefficients ranged between 10 percent and 35 percent, depending upon the gas and the smelter technology type. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-81. Aluminum production-related CO_2 emissions were estimated to be between 3.0 and 5.6 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 30 percent below to 30 percent above the emission estimate of 4.3 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 2.2 and 2.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below to 12 percent above the emission estimate of 2.4 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.4 and 0.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below to 18 percent above the emission estimate of 0.43 Tg CO_2 Eq.

Table 4-81: Tier 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate	Uncertainty Range Relative to 2004 Emission Estimate[a]			
			(Tg CO_2 Eq.)		(%)	
		(Tg CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	4.3	3.0	5.6	-30%	+30%
Aluminum Production	CF_4	2.4	2.2	2.7	-10%	+12%
Aluminum Production	C_2F_6	0.4	0.4	0.5	-16%	+18%

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

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 U.S. 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

Relative to the previous Inventory report, CO_2 emission estimates for the period 1990 through 2003 were updated based on revisions to the estimation methodology. Previous CO_2 emission estimates were based on methodology and default emission factors defined by the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OED/IEA 1997). Current estimates were developed using a combination of process specific formulas (IAI 2003) and default emission factors

(IPCC/UNEP/OED/IEA 1997). The former approach was used where smelter-specific process data was available. Based on this revision, CO_2 emissions from aluminum production have increased by approximately 10 percent for each year during the 1990 to 2003 period relative to the previous report.

The smelter-specific emission factors used for estimating PFC emissions, as well as aluminum production levels, were revised to reflect recently-reported data concerning smelter operating parameters. The combination of these changes resulted in an average annual increase of approximately of less than .05 Tg CO_2 Eq. (0.4 percent) in PFC emissions from aluminum production for the period 1990 through 2003 relative to the previous report.

4.22. 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 years. It has largely replaced salt fluxes and SO_2, which are more toxic and corrosive than SF_6.

The magnesium industry emitted 2.7 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2004, representing a decrease of approximately 10 percent from 2003 emissions (see Table 4-82). The reduction in emissions compared to 2003 occurred despite a 3 percent increase in the amount of metal processed in 2004. There are currently plans to expand primary magnesium production in the United States to meet demand for magnesium metal by U.S. casting companies, which are in turn meeting demand for magnesium parts by the automotive sector. Recent antidumping duties imposed on Chinese imports by the U.S. International Trade Commission have shifted some U.S. demand to Canadian imports (USGS 2005). Anticipated increases in domestic primary production capacity combined with Canadian imports should be able to meet near-term U.S. demand (USGS 2005).

Table 4-82: 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
1998	5.8	0.2
1999	6.0	0.3
2000	3.2	0.1
2001	2.6	0.1
2002	2.6	0.1
2003	3.0	0.1
2004	2.7	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 production and 90 percent of the casting sector (i.e., die, sand, permanent mold, wrought, and anode casting). Emissions for 1999 through 2004 from primary production, some secondary production (i.e., recycling), and die casting were reported by Partnership participants. Emission factors for 2002 to 2004 for sand casting activities were also acquired through the Partnership. The 1999 through 2004 emissions from the remaining secondary production and casting were estimated by multiplying industry emission factors (kg SF_6 per metric ton of Mg produced or processed) by the amount of metal produced or consumed in the six major processes (other than primary production) that require SF_6 melt protection: 1) secondary production, 2) die casting, 3) sand casting, 4) permanent mold, 5) wrought products, and 6) anodes. The emission factors are provided below in Table 4-83. The emission factors for primary production and sand casting are

withheld to protect company-specific production information. However, the emission factor for primary production has not risen above the 1995 value of 1.1 kg SF_6 per metric ton.

Die casting emissions for 1999 through 2004, which accounted for 48 to 75 percent of all SF_6 emissions from U.S. casting and recycling processes during this period, were estimated based on information supplied by industry Partners. From 2000 to 2004, 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, emissions 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., secondary production, permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

Table 4-83: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Secondary	Die Casting	Permanent Mold	Wrought	Anodes
1999	1	2.14[a]	2	1	1
2000	1	0.73	2	1	1
2001	1	0.77	2	1	1
2002	1	0.70	2	1	1
2003	1	0.84	2	1	1
2004	1	0.78	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.

Data used to develop these 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 2004 were available from the USGS (USGS 2002, 2003, 2005a, 2005b). 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 1996. 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 2004). Sand casting emission factors for 2002 through 2004 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 factors for the other processes (i.e., secondary production, and permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-83.

Uncertainty

To estimate the uncertainty of the estimated 2004 SF_6 emissions from magnesium production and processing, EPA estimated the uncertainties associated with three variables (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 SF_6 Emission Reduction Partnership. If partners did not report emissions data during the current reporting year, SF_6 emissions data were estimated using available emission

factor and production information reported in prior years. The uncertainty associated with the extrapolated emission factor was assumed to be 25 percent, while that associated with the extrapolated production was assumed to be 30 percent. Between 1999 and 2004, non-reporting partners have accounted for between 0 and 17 percent of total estimated sector emissions. For those industry processes that are not represented in EPA's partnership, such as permanent mold, anode, and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-83). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. 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 at hot-chambered die casting machines on the order of 10 percent (Bartos et al. 2003). As is the case for other sources of SF_6 emissions, total SF_6 consumption data for magnesium production and processing in the United States were not available. Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, to what extent this technique is used in the United States is unknown.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-84. SF_6 emissions associated with magnesium production and processing were estimated to be between 2.4 and 3.1 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 11 percent below to 13 percent above the 2004 emissions estimate of 2.7 Tg CO_2 Eq.

Table 4-84: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	2.7	2.4	3.1	-11%	+13%

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

Recalculations Discussion

The emission calculation methodology was revised to reflect more accurate emission factor data for sand casting activities. Sand casting activity data now utilizes partner reported emission factors from 1990 through 2003 resulting in a slight increase in historical emissions of about 1 percent or less depending on the year. The emission estimate for 2002 was also adjusted downward slightly from the previously reported values. This revision reflects an update to historical secondary production data supplied by USGS. The change resulted in a decrease of 0.1 Tg CO_2 Eq. (5 percent) in SF_6 emissions from magnesium production and processing for 2002 relative to the previous report.

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 IPCC *Good Practice Guidance*, IPCC 2000) that all SF_6 utilized is emitted to the atmosphere. EPA-funded measurements of SF_6 in hot chamber die casting have indicated that the latter assumption may be incorrect, with observed SF_6 degradation on the order of 10 percent (Bartos et al. 2003). More recent EPA-funded measurement studies have confirmed this observation for cold chamber die casting (EPA 2004). 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. Additionally, as more companies join the

partnership, in particular those from sectors not currently represented, such as permanent mold and anode casting, emission factors will be refined to incorporate these additional data.

[BEGIN BOX]

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:

- *By-product emissions*. Some emissions do not result from the consumption or use of a chemical, but are the unintended by-products 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 4-85 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.[23] 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 2004, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Program 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 4-85: 2004 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	192.0	103.3
Aluminum Production	-	2.8
HCFC-22 Production	-	15.6
Semiconductor Manufacture	7.3	4.7

[23] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

Magnesium Production and Processing	2.7	2.7
Electrical Transmission and Distribution	23.3	13.8

- Not applicable.

[END BOX]

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 2004 are reported in Table 4-86.

Table 4-86: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
NO_x	**591**		**637**	**595**	**626**	**656**	**630**	**631**	**632**
Chemical & Allied Product Manufacturing	152		117	93	95	97	95	96	96
Metals Processing	88		81	78	81	86	76	76	76
Storage and Transport	3		15	13	14	15	14	14	14
Other Industrial Processes	343		424	409	434	457	442	442	443
Miscellaneous*	5		1	2	2	1	3	3	3
CO	**4,124**		**3,163**	**2,156**	**2,217**	**2,339**	**2,286**	**2,286**	**2,286**
Chemical & Allied Product Manufacturing	1,074		981	317	327	338	306	306	306
Metals Processing	2,395		1,544	1,138	1,175	1,252	1,174	1,174	1,174
Storage and Transport	69		65	148	154	162	195	195	195
Other Industrial Processes	487		535	518	538	558	576	576	576
Miscellaneous*	101		38	35	23	30	35	35	35
NMVOCs	**2,426**		**2,047**	**1,813**	**1,773**	**1,769**	**1,723**	**1,725**	**1,727**
Chemical & Allied Product Manufacturing	575		357	228	230	238	194	195	195
Metals Processing	111		71	60	61	65	62	63	63
Storage and Transport	1,356		1,204	1,122	1,067	1,082	1,093	1,094	1,096
Other Industrial Processes	364		402	398	412	381	369	369	370
Miscellaneous*	20		13	6	3	4	5	5	5

* 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.

Methodology

These emission estimates were obtained from preliminary data (EPA 2005), 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.

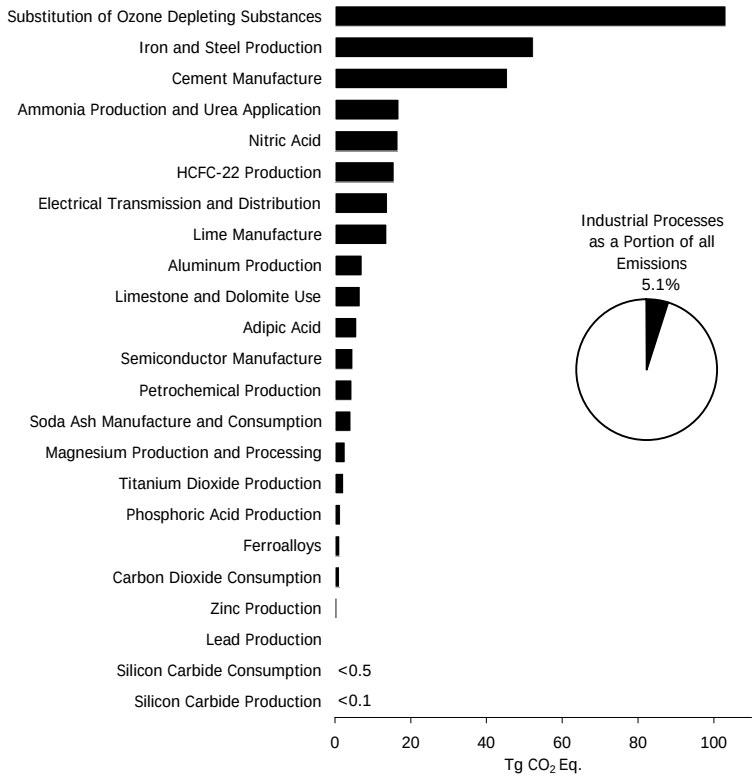


Figure 4-1: 2004 Industrial Processes Chapter Greenhouse Gas Sources

Descriptions of Figures: Industrial Processes

Figure 4-1 is a chart that illustrates the data presented in Table 4-1, industrial processes greenhouse gas sources in teragrams of CO_2 Eq. Substitution of ozone depleting substances is the greatest source, accounting for 103.3 Tg CO_2 Eq. Silicon carbide production is the smallest source, accounting for less than 0.1 Tg CO_2 Eq. In addition, there is a pie chart that indicates that industrial processes made up 5.1% of U.S. greenhouse gas emissions in 2004.

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 2004 (see Table 5-1). Indirect greenhouse gas emissions also result from solvent and other product use, and are presented in Table 5-2 in teragrams of CO_2 equivalent (Tg CO_2 Eq.) and gigagrams (Gg).

Table 5-1: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq. and Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
N_2O Product Usage								
Tg CO_2 Eq.	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Gg	14	15	15	15	15	15	15	15

Table 5-2: Indirect Greenhouse Gas Emissions from Solvent and Other Product Use (Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
NMVOCs	5,217	4,671	4,569	4,384	4,547	4,256	4,262	4,267
CO	4	1	46	46	45	46	46	46
NO_x	1	3	3	3	3	6	6	6

5.1. Nitrous Oxide Product Usage (IPCC Source Category 3D)

N_2O is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. N_2O is produced by thermally decomposing ammonium nitrate (NH_4NO_3), a chemical commonly used in fertilizers and explosives. The decomposition creates steam (H_2O) and N_2O through a low-pressure, low-temperature (500°F) reaction. Once the steam is removed through condensation, the remaining N_2O is purified, compressed, dried, and liquefied for storage and distribution. Two companies operate a total of five N_2O production facilities in the United States (CGA 2002).

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 2004 was approximately 17 Gg. N_2O emissions were 4.8 Tg CO_2 Eq. (15 Gg) in 2004 (see 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 5-3: N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.3	14
1998	4.8	15

1999	4.8	15
2000	4.8	15
2001	4.8	15
2002	4.8	15
2003	4.8	15
2004	4.8	15

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 that is used by each sector. This value was then multiplied by the associated emissions rate for each sector. After the emissions were calculated for each sector, they were added together to obtain a total estimate of N_2O product usage emissions. Emissions were determined using the following equation:

$$N_2O \text{ Product Usage Emissions} = \sum_i [\text{Total U.S. Production of } N_2O] \times [\text{Share of Total Quantity of } N_2O \text{ Usage by Sector i}] \times [\text{Emissions Rate for Sector i}]$$

where,

i = sector.

The share of total quantity of N_2O usage by subcategory represents the share of national N_2O produced that is used by the specific subcategory (i.e., anesthesia, food processing, etc.). In 2004, the medical/dental industry used an estimated 86 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. The N_2O was allocated across these subcategories, 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, approximately 97.5 percent of the N_2O is not metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 97.5 percent was used for this subcategory (Tupman 2002). 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 emissions factor of 100 percent for this subcategory (Heydorn 1997). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emissions rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 and 1996 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). These data were provided as a range. For example, in 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range for 1996 that falls within the production bounds described by Heydorn (1997). These data are considered more industry specific and current. The midpoint of the narrower production range (15.9 to 18.1 thousand metric tons) was used to estimate N_2O emissions for years 1993 through 2002 (Tupman 2003). Production data for 2004 was assumed to equal 2002 data.

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 2002 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). Due to unavailable data, the share of total quantity of N_2O usage data for 2004 was assumed to equal that of

2002. 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 substantiated by the *Encyclopedia of Chemical Technology* (Othmer 1990).

Table 5-4: N_2O Production (Gg)

Year	Gg
1990	16
1991	15
1992	15
1993	17
1994	17
1995	17
1996	17
1997	17
1998	17
1999	17
2000	17
2001	17
2002	17
2003	17
2004	17

Uncertainty

The overall uncertainty associated with the 2004 N_2O emissions estimate from N_2O product usage was calculated using the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance* 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 activity data inputs and their associated uncertainties and distributions are summarized in Table 5-5.

Table 5-5: Sources of Uncertainty in N_2O Emissions from N_2O Product Usage

			Uncertainty Range[a]		
Variable	Value	Distribution Type	Lower Bound	Upper Bound	Reference
Production (Gg)	17	Uniform	-7%	+7%	Expert Judgment
Market Share Medicine/Dentistry Anesthesia (analgesic property) (%)	0.86	Uniform	-2%	+2%	Expert Judgment
Market Share Food Processing Propellant (%)	0.06	Uniform	-23%	+23%	Expert Judgment
Emission Rate Medicine/Dentistry Anesthesia (analgesic property) (%)	0.98	Uniform	-3%	+3%	Expert Judgment

[a] Parameters presented represent upper and lower bounds as a percentage of the mean, based on a 95 percent confidence interval.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-81. N_2O emissions from N_2O product usage were estimated to be between 4.4 and 5.1 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 7 percent below to 7 percent above the 2004 emissions estimate of 4.8 Tg CO_2 Eq.

Table 5-6: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From N_2O Product Usage (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	4.8	4.4	5.1	-7%	+7%

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

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.

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-CH_4 volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based solvents. As some of industrial applications also employ thermal incineration as a control technology, combustion by-products, such as carbon monoxide (CO) and nitrogen oxides (NO_x), are also reported with this source category. Surface coatings accounted for approximately 41 percent of NMVOC emissions from solvent use in 2004, while "non-industrial"[2] uses accounted for about 38 percent and degreasing applications for 7 percent. Overall, solvent use accounted for approximately 25 percent of total U.S. emissions of NMVOCs in 2004; NMVOC emissions from solvent use have decreased 18 percent since 1990.

Although NMVOCs are not considered direct greenhouse gases, their role as precursors to the formation of ozone—which is a greenhouse gas—results in their inclusion in a greenhouse gas inventory. Emissions from solvent use have been reported separately by the United States to be consistent with the inventory reporting guidelines recommended by the IPCC. These guidelines identify solvent use as one of the major source categories for which countries should report emissions. 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 2004 are reported in Table 5-7.

Table 5-7: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
NO_x	**1**		**3**	**3**	**3**	**3**	**6**	**6**	**6**
Degreasing	+		+	+	+	+	+	+	+
Graphic Arts	+		1	+	+	+	+	+	+
Dry Cleaning	+		+	+	+	+	+	+	+
Surface Coating	1		2	3	3	3	6	6	6
Other Industrial Processes[a]	+		+	+	+	+	+	+	+
Non-Industrial Processes[b]	+		+	+	+	+	+	+	+
Other	NA		+	+	+	+	+	+	+
CO	**4**		**1**	**46**	**46**	**45**	**46**	**46**	**46**

[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.

[2] "Non-industrial" uses include cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Degreasing	+		+	+	+	+	+	+	+
Graphic Arts	+		+	+	+	+	+	+	+
Dry Cleaning	+		+	+	+	+	+	+	+
Surface Coating	+		1	46	46	45	46	46	46
Other Industrial Processes[a]	4		+	+	+	+	+	+	+
Non-Industrial Processes[b]	+		+	+	+	+	+	+	+
Other	NA		+	+	+	+	+	+	+
NMVOCs	**5,217**		**4,671**	**4,569**	**4,384**	**4,547**	**4,256**	**4,262**	**4,267**
Degreasing	675		337	363	316	331	310	310	311
Graphic Arts	249		272	224	222	229	214	214	214
Dry Cleaning	195		151	267	265	272	254	255	255
Surface Coating	2,289		1,989	1,865	1,767	1,863	1,744	1,746	1,748
Other Industrial Processes[a]	85		101	95	98	103	97	97	97
Non-Industrial Processes[b]	1,724		1,818	1,714	1,676	1,707	1,598	1,600	1,602
Other	+		3	40	40	42	40	40	40

[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.
+ Does not exceed 0.5 Gg.

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 2005), 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 data bases.

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 sector. CO_2 emissions from on-farm energy use are accounted in the Energy chapter.

Figure 6-1: 2004 Agriculture Chapter Greenhouse Gas Emission Sources

In 2004, the agricultural sector was responsible for emissions of 440.1 teragrams of CO_2 equivalent (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. CH_4 emissions from enteric fermentation and manure management represent about 20 percent and 7 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 agricultural residue burning were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 68 percent. Manure management and agricultural residue burning were also small sources of N_2O emissions.

Table 6-2 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2004, CH_4 emissions from agricultural activities increased by 2 percent while N_2O emissions decreased by 1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the indirect greenhouse gases carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**156.8**		**164.2**	**164.0**	**162.0**	**161.9**	**161.5**	**161.9**	**160.4**
Enteric Fermentation	117.9		116.7	116.8	115.6	114.6	114.7	115.1	112.6
Manure Management	31.2		38.8	38.1	38.0	38.9	39.3	39.2	39.4
Rice Cultivation	7.1		7.9	8.3	7.5	7.6	6.8	6.9	7.6
Agricultural Residue Burning	0.7		0.8	0.8	0.8	0.8	0.7	0.8	0.9
N_2O	**282.7**		**319.0**	**299.1**	**296.5**	**301.5**	**296.2**	**277.1**	**279.7**
Agricultural Soil Management	266.1		301.1	281.2	278.2	282.9	277.8	259.2	261.5
Manure Management	16.3		17.4	17.4	17.8	18.1	18.0	17.5	17.7
Agricultural Residue Burning	0.4		0.5	0.4	0.5	0.5	0.4	0.4	0.5
Total	**439.6**		**483.2**	**463.1**	**458.4**	**463.4**	**457.8**	**439.1**	**440.1**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**7,468**		**7,821**	**7,810**	**7,713**	**7,710**	**7,693**	**7,712**	**7,640**
Enteric Fermentation	5,612		5,559	5,563	5,507	5,459	5,463	5,481	5,362
Manure Management	1,484		1,848	1,816	1,811	1,850	1,871	1,865	1,875
Rice Cultivation	339		376	395	357	364	325	328	360
Agricultural Residue Burning	33		38	37	38	37	34	38	42
N_2O	**913**		**1,029**	**965**	**956**	**972**	**956**	**894**	**902**
Agricultural Soil Management	858		971	907	897	913	896	836	844
Manure Management	52		56	56	58	58	58	57	57
Agricultural Residue Burning	1		1	1	1	1	1	1	2

CO	**689**	**789**	**767**	**790**	**770**	**706**	**796**	**877**
NO_x	**28**	**35**	**34**	**35**	**35**	**33**	**34**	**39**

Note: Totals may not sum due to independent rounding.

6.1. Enteric Fermentation (IPCC Source Category 4A)

CH_4 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 by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domesticated animal types, 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 domesticated 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 or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related 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.

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2004 were 112.6 Tg CO_2 Eq. (5,362 gigagrams [Gg]), decreasing slightly since 2003 due to minor decreases in some animal populations and dairy cow milk production in some regions. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2004. Emissions from dairy cattle in 2004 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2004, emissions from enteric fermentation have decreased by 5 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. During this timeframe, populations of sheep have decreased by an average annual rate of about 4 percent per year while horse populations have remained relatively constant and the population of goats has increased by an average of 2 percent per year.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	**1990**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Beef Cattle	83.2	85.0	84.9	83.4	82.5	82.4	82.6	80.4
Dairy Cattle	28.9	26.3	26.6	27.0	26.9	27.1	27.3	27.0
Horses	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.3	1.2	1.2	1.2	1.1	1.1	1.0
Swine	1.7	2.0	1.9	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Total	**117.9**	**116.7**	**116.8**	**115.6**	**114.6**	**114.7**	**115.1**	**112.6**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990		1998	1999	2000	2001	2002	2003	2004
Beef Cattle	3,961		4,047	4,045	3,973	3,928	3,923	3,934	3,830
Dairy Cattle	1,375		1,251	1,265	1,283	1,280	1,288	1,299	1,285
Horses	91		94	93	94	95	95	95	95
Sheep	91		63	58	56	55	53	51	49
Swine	81		93	90	88	88	90	90	91
Goats	13		12	12	12	12	13	13	13
Total	**5,612**		**5,559**	**5,563**	**5,507**	**5,459**	**5,463**	**5,481**	**5,362**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimates 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., Intergovernmental Panel on Climate Change [IPCC] Tier 2) was therefore applied to estimating 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 describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

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 model cohorts of individual animal types and their specific emissions 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 National Agricultural Statistics Service (1995a,b; 1999a,c,d,f; 2000a,c,d,e; 2001a,c,d,f; 2002a,c,d,f; 2003a,c,d,f; 2004a,c,d,f, 2005a-d).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for other well-fed cattle consuming temperate-climate feed types. 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 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). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets in the United States.

To estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (e.g., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used 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 were multiplied by the 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. CH_4 emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2004. 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 1994a-b, 1995a,c, 1998a-b, 1999a,b,e, 2000b, 2004a,b,e,g,h, 2005a,d-h). Horse population data were obtained from the FAOSTAT database (FAO 2005), because USDA does not estimate U.S. horse populations annually. Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005i); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the *1992 and 1997 Census of Agriculture* (USDA 2005i). CH_4 emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). 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 (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

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 of this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique. These estimates were developed for the 2001 inventory estimates. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2004 activity data and emission factor input variables. Consequently, these uncertainty estimates were directly applied to the 2004 emission estimates.

A total of 185 primary input variables (178 for cattle and 8 for non-cattle) were identified as key input variables for uncertainty analysis. The 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). For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources.

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 as educated estimates.

The uncertainty ranges associated with the activity-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, in 19 out of 20 times (i.e., with 95 percent confidence), the total greenhouse gas emissions estimate from this source is within the range of approximately 100.2 to 132.9 Tg CO_2 Eq. (or that the actual CH_4 emissions are likely to fall within the range of approximately 11 percent below and 18 percent above the emission estimate of 112.6 Tg CO_2 Eq.). Among the individual 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. Consequently, the cattle sub-source categories together contribute to the largest degree of uncertainty in the inventory estimates of CH_4 emissions from livestock enteric fermentation. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b] (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a, b] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	112.6	100.2	132.9	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates and applied to 2004 estimates.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. Particular emphasis was placed this year on cattle population and growth data, and on evaluating the effects of data updates as described in the recalculations discussion below.

Recalculations Discussion

While there were no changes in the methodologies used for estimating CH_4 emissions from enteric fermentation, emissions were revised slightly due to changes in data. USDA published revised population estimates which affected historical emissions estimated for swine, sheep, goats, and poultry. Recent historical emission estimates also changed for certain beef and dairy populations as a result USDA inputs and the calving rate described below.

The dairy cow calving rate represents the percentage of dairy cows that produced live calves in a specific year (the remainder either birthed dead calves or had reproductive problems). This value is used to determine the percentage of dairy cows that are pregnant during the specified month as well as the portion of total calf births that are from dairy cows. The previous model versions assumed a constant calving rate of 93.4 percent (USDA:APHIS:VS 1996). Research revealed more recent statistics (USDA:APHIS:VS 2002), that revised this calving rate to 88.8 percent for cows and heifers that produced live calves during 2001. Modeling assumptions were thus revised to use the historic (93.4 percent) calving rate for all years through 2000 and the updated rate (88.8 percent) for subsequent periods.

Changes to previously reported emissions are summarized by the following: Year 2001 total (dairy and beef) cattle CH_4 emissions changed by just 0.1 percent. For 2002, beef cattle CH_4 emissions increased 4 Gg (0.1 percent) while

dairy cattle emissions decreased by 2 Gg (0.1 percent). An upward revision in historical goat populations from 1995 through for 2003 resulted in an increase in CH_4 emissions for each of those years. In 2003, this change affected emissions by less than 3 Gg (0.05 percent of total enteric fermentation emissions from all animals). Recent historical emission estimates for sheep and swine both changed (each by less than one half of one percent of respective 2003 emissions) 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. While EPA has no plans for methodological changes in the modeling framework, the opportunity exists to continue to refine the model's results through identifying and improving individual data inputs. Research is currently underway to identify updates of this nature.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. CH_4 is produced by the anaerobic decomposition of manure. N_2O is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.

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. A number of other factors related to how the manure is handled also affect the amount of CH_4 produced. 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 example, CH_4 production generally increases with rising temperature and residency time. Also, for non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of the manure also affects the amount of CH_4 produced. Manure composition varies by animal type, including the animal's digestive system and diet. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH_4-producing capacity. Range cattle fed a low energy diet of forage material produce manure with about 50 percent of the CH_4-producing potential of feedlot cattle manure. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal. Ultimately, a combination of diet types and the growth rate of the animals will affect the quantity and characteristics of the manure produced.

A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system. The production of N_2O 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 N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen 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. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate, and has the potential to encounter saturated conditions following rain events.

Certain N_2O emissions are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector. These are emissions from livestock manure and urine deposited on pasture, range, or

paddock lands, as well as emissions from manure and urine that is spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.).

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category. Estimates for CH_4 emissions in 2004 were 39.4 Tg CO_2 Eq. (1,875 Gg), 26 percent higher than in 1990. The majority of this increase was from swine and dairy cow manure, where emissions increased 32 and 38 percent, respectively. The increase in emissions from these animal types is primarily attributed to shifts by the swine and dairy industries towards larger facilities. 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, 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-specific weighted CH_4 conversion factor (MCF) values in combination with the 1992, and 1997 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005g). From 2003 to 2004, there was a 0.6 percent increase in CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations. A description of the emission estimation methodology is provided in Annex 3.10.

Total N_2O emissions from manure management systems in 2004 were estimated to be 17.7 Tg CO_2 Eq. (57 Gg). The 9 percent increase in N_2O emissions from 1990 to 2004 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high-rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2004, although swine populations periodically declined slightly throughout the time series. N_2O emissions showed a 0.9 percent increase from 2003 to 2004, due to minor shifts in animal population.

The population of beef cattle in feedlots increased over the period of 1990 to 2004, resulting in increased N_2O emissions from this sub-category of cattle. Although dairy cow populations decreased overall for the period 1990 to 2004, the population of dairies managing and storing manure on-site—as opposed to using pasture, range, or paddock or daily spread systems—increased. Over the same period, dairies also experienced a shift to more liquid manure management systems at large operations, which result in lower N_2O emissions then dry systems. The net result is a slight decrease in dairy cattle N_2O emissions over the period 1990 to 2004. As stated previously, N_2O emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for in the Agricultural Soil Management source category of the Agriculture sector.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**31.2**		**38.8**	**38.1**	**38.0**	**38.9**	**39.3**	**39.2**	**39.4**
Dairy Cattle	11.4		13.9	14.1	14.5	15.0	15.1	15.7	15.7
Beef Cattle	3.2		3.1	3.1	3.1	3.1	3.1	3.1	3.1
Swine	13.1		18.4	17.6	17.0	17.3	17.7	17.0	17.2
Sheep	0.2		0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+		+	+	+	+	+	+	+
Poultry	2.7		2.7	2.6	2.6	2.7	2.7	2.7	2.7
Horses	0.6		0.6	0.6	0.6	0.6	0.6	0.6	0.6
N_2O	**16.3**		**17.4**	**17.4**	**17.8**	**18.1**	**18.0**	**17.5**	**17.7**
Dairy Cattle	4.3		3.9	4.0	3.9	3.9	3.9	3.9	3.8
Beef Cattle	4.9		5.5	5.6	5.9	6.1	5.9	5.6	5.7
Swine	0.4		0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sheep	0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+		+	+	+	+	+	+	+
Poultry	6.3		7.2	7.2	7.2	7.3	7.4	7.3	7.4
Horses	0.2		0.2	0.2	0.2	0.2	0.2	0.2	0.2

Total	**47.4**	**56.2**	**55.6**	**55.9**	**56.9**	**57.3**	**56.7**	**57.1**

+ Does not exceed 0.05 Tg CO_2 Eq.
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	1998	1999	2000	2001	2002	2003	2004
CH_4	**1,484**	**1,848**	**1,816**	**1,811**	**1,850**	**1,871**	**1,865**	**1,875**
Dairy Cattle	544	660	672	691	713	720	746	749
Beef Cattle	153	149	148	149	148	147	146	145
Swine	622	874	837	812	826	843	811	820
Sheep	9	6	6	5	5	5	5	5
Goats	1	1	1	1	1	1	1	1
Poultry	128	129	125	125	129	127	127	127
Horses	27	28	28	28	29	29	29	29
N_2O	**52**	**56**	**56**	**58**	**58**	**58**	**57**	**57**
Dairy Cattle	14	13	13	13	13	13	13	12
Beef Cattle	16	18	18	19	20	19	18	19
Swine	1	1	1	1	1	1	1	1
Sheep	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+
Poultry	20	23	23	23	24	24	24	24
Horses	1	1	1	1	1	1	1	1

+ Does not exceed 0.5 Gg.
Note: Totals may not sum due to independent rounding.

Methodology

The methodologies presented in the IPCC *Good Practice Guidance* (IPCC 2000) form the basis of the CH_4 and N_2O emission estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of nitrogen produced (excretion rate by animal type times animal population);
- Amount of volatile solids produced (excretion rate by animal type times animal population);
- CH_4 producing potential of the volatile solids (by animal type);
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system, including the impacts of any biogas collection efforts);
- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions 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.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998d, 2000b) 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 2000c, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

Next, MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems and N_2O emission factors for all systems were set equal to default IPCC factors for temperate climates (IPCC 2000). 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 (see Annex 3.10 for detailed information on MCF derivations for liquid systems). The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems.

For each animal group, the base emission factors were weighted to incorporate the distribution of management systems used within each state to create an overall state-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a state was multiplied by the emission factor for that system and state, and then summed for all manure management systems in the state.

CH_4 emissions were estimated using the volatile solids (VS) production for all livestock. For poultry and swine animal groups, for example, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Lieberman and Pape, 2005). The resulting VS for each animal group were then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state-specific MCFs.

N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[1] production for all livestock wastes using livestock population data and nitrogen excretion rates based on measurements of excreted manure. For each animal group, TKN production was calculated using a national average nitrogen excretion rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

The data used to calculate the inventory estimates were based on a variety of sources. Animal population data for all livestock types, except horses and goats, were obtained from the United States Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-f). Horse population data were obtained from the FAOSTAT database (FAO 2005), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained from the Census of Agriculture (USDA 2005g). Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each state, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 2005g).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000b) for small operations and from estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2002a, 2002b). Data for layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000c). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2002a, 2002b). Manure management system usage data for other livestock were taken from previous estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel. These organizations include state NRCS offices, state extension services, state universities, USDA National Agriculture Statistics Service (NASS), and other experts

[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

(Deal 2000, Johnson 2000, Miller 2000, Poe et al. 1999, Stettler 2000, Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

MCFs for liquid systems were calculated based on average ambient temperatures of the counties in which animal populations were located. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2004). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, and 2002 Census data (USDA 2005g). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data; county population data for 1998 through 2001 were extrapolated based on 1997 and 2002 data; and county population data for 2003 to 2004 were assumed to be the same as 2002.

The maximum CH_4 producing capacity of the VS, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. VS excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for swine, poultry, bulls, and calves not on feed. In addition, VS production rates from Lieberman and Pape (2005) were used for dairy and beef cows, heifers, and steer for each year of the inventory. N_2O emission factors and MCFs for dry systems were taken from *Good Practice Guidance* (IPCC 2000).

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) to determine the uncertainty associated with estimating N_2O and CH_4 emissions from livestock manure management. Because no substantial modifications were made to the inventory methodology since the development of these estimates, it is expected that this analysis is applicable to the uncertainty associated with the current manure management emission estimates.

The quantitative uncertainty analysis for this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate N_2O and CH_4 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2004 were estimated to be between 32.3 and 47.3 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 18 percent below to 20 percent above the 2004 emission estimate of 39.4 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.9 and 21.9 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the 2004 emission estimate of 17.7 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	39.4	32.3	47.3	-18%	+20%
Manure Management	N_2O	17.7	14.9	21.9	-16%	+24%

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

The primary factors that contribute to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact CH_4 generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1992, 1997, and 2002 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the CH_4 generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

The IPCC *Good Practice Guidance* (IPCC 2000) published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing CH_4 at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, a MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to this methodology. The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of VS from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon temperatures differ substantially from ambient temperatures and whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default N_2O emission factors published in the IPCC *Good Practice Guidance* (IPCC 2000) were derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce CH_4 at different rates, and would in all likelihood produce N_2O at different rates, although a single N_2O emission factor was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that N_2O emissions from these systems may be lower than predicted by the IPCC default factors. At this time, there are insufficient data available to develop U.S.-specific N_2O emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Uncertainty also exists with the maximum CH_4 producing potential of VS excreted by different animal groups (i.e., B_o). The B_o values used in the CH_4 calculations are published values for U.S. animal waste. However, there are several studies that provide a range of B_o values for certain animals, including dairy and swine. The B_o values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much CH_4 as manure from a milking cow. However, the data available for B_o values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens.

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 2003 and 2004 Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure nitrogen data were quality assured 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 waste management system type for the full time series, between national level estimates for nitrogen excreted and the sum of county estimates for the full time series.

Recalculations Discussion

No changes have been incorporated into the overall methodology for the manure management emission estimates. However, changes were made to the 2004 calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS, and 2002 USDA Census of Agriculture data (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-g). The population data in the most recent final estimates reflect some adjustments due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data and the state distributions from the 1992, 1997, and 2002 Census of Agriculture.

This change resulted in an average annual increase of 0.6 Tg CO_2 Eq. (2 percent) in CH_4 emissions and an average annual increase of 0.1 Tg CO_2 Eq. (0.6 percent) in N_2O emissions from manure management for the period 1990 through 2004.

Planned Improvements

Although an effort was made to introduce the variability in VS production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine VS production would be useful in future inventory estimates.

Research will be initiated into the estimation and validation of the maximum CH_4-producing capacity of animal manure (B_o), for the purpose of obtaining more accurate data to develop emission estimates.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004. These data will be investigated and evaluated for incorporation into future estimates.

Currently, 2004 temperature data are not incorporated into the 2004 model for the estimates of MCFs; 2003 data were used for 2004. The temperature data will be updated in the next year's inventory.

The methodology to calculate MCFs for liquid systems will be examined to determine how to account for a maximum temperature in the liquid systems. Additionally, available research will be investigated to develop a relationship between ambient air temperature and temperature in liquid waste management systems in order to improve that relationship in the MCF methodology.

Currently, temperate zone MCFs are used for non-liquid waste management systems, including pasture, range, and paddock, daily spread, solid storage, and drylot operations. However, there are some states that have an annual average temperature that would fall below 15°C (i.e., classified as "cool" zones). Therefore, CH_4 emissions from certain non-liquid waste management systems may be overestimated; however, the difference is expected to be relatively small due to the low MCFs for all "dry" management systems. The use of both cool and temperate MCFs for non-liquid waste management systems will be investigated for future inventories.

The 2002 Census of Agriculture data became available in mid-2004 and have already been incorporated into animal population estimates. EPA will also incorporate these data into future estimates of waste management system usage data for swine and dairy. For these animal groups, the percent of waste by management system is estimated using data broken out by geographic region and farm. Farm-size distribution data reported in the 1992 and 1997 Census

of Agriculture are currently used to determine the percentage of animals utilizing the various manure management systems; farm-size data from the 2002 Census of Agriculture will be incorporated into next year's inventory.

The development of the National Ammonia Emissions Inventory for the United States (EPA 2004) used similar data sources to the current estimates of emissions from manure management, and through the course of development of the ammonia inventory, updated waste management distribution data were identified. Future inventory estimates will incorporate these updated data.

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 the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil to develop. 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 (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 more shallow 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 that is available to decompose (i.e., organic fertilizer use, soil type, rice variety,[2] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over an entire growing season because 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 eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields,

[2] 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.

usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. CH_4 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 for the stubble to decay aerobically), the amount of organic material that is available for 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 (Table 6-9 and Table 6-10). In 2004, CH_4 emissions from rice cultivation were 7.6 Tg CO_2 Eq. (360 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2004, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall increase of 6 percent over the fourteen-year period, due to an overall increase in primary crop area.[3]

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. Price is the primary factor affecting rice area in Arkansas, as farmers will plant more of what is most lucrative amongst soybeans, rice, and cotton. Government support programs have also been influential by affecting the price received for a rice crop (Slaton 2001b, Mayhew 1997). California rice area is primarily influenced by price and government programs, but is also affected by water availability (Mutters 2001). In Florida, rice acreage is largely a function of the price of rice relative to sugarcane and corn. Most rice in Florida is rotated with sugarcane, but sometimes it is more profitable for farmers to follow their sugarcane crop with sweet corn or more sugarcane instead of rice (Schueneman 1997, 2001b). In Louisiana, rice area is influenced by government support programs, the price of rice relative to cotton, soybeans, and corn, and in some years, weather (Saichuk 1997, Linscombe 2001b). For example, a drought in 2000 caused extensive saltwater intrusion along the Gulf Coast, making over 32,000 hectares unplantable. The dramatic decrease in ratooned area in Louisiana in 2002 was the result of hurricane damage to that state's rice-cropped area. In Mississippi, rice is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997, 2001b). In Missouri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between rice and soybeans or cotton, and government support programs (Stevens 1997, Guethle 2001b). In Oklahoma, the state having the smallest harvested rice area, rice acreage is limited to the areas in the state with the right type of land for rice cultivation. Acreage is limited to growers who can afford the equipment, labor, and land for this intensive crop (Lee 2003). Texas rice area is affected mainly by the price of rice, government support programs, and water availability (Klosterboer 1997, 2001b).

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1998	1999	2000	2001	2002	2003	2004
Primary	**5.1**	**5.8**	**6.3**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**
Arkansas	2.1	2.7	2.9	2.5	2.9	2.7	2.6	2.8
California	0.7	0.8	0.9	1.0	0.8	0.9	0.9	1.1
Florida	+	+	+	+	+	+	+	+
Louisiana	1.0	1.1	1.1	0.9	1.0	1.0	0.8	1.0
Mississippi	0.4	0.5	0.6	0.4	0.5	0.5	0.4	0.4
Missouri	0.1	0.3	0.3	0.3	0.4	0.3	0.3	0.3
Oklahoma	+	+	+	+	+	+	+	+
Texas	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.4
Ratoon	**2.1**	**2.1**	**2.0**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**
Arkansas	+	+	+	+	+	+	+	+
Florida	+	0.1	0.1	0.1	+	+	+	+
Louisiana	1.1	1.2	1.2	1.3	1.1	0.5	1.0	1.1

[3] The 11 percent decrease occurred between 1992 and 1993 and 2001 and 2002; the 17 percent increase happened between 1993 and 1994.

Texas	0.9	0.8	0.7	0.7	0.6	0.5	0.5	0.5
Total	**7.1**	**7.9**	**8.3**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**

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

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1998	1999	2000	2001	2002	2003	2004
Primary	**241**	**279**	**300**	**260**	**283**	**274**	**255**	**284**
Arkansas	102	126	138	120	138	128	124	132
California	34	39	43	47	40	45	43	50
Florida	1	2	2	2	1	1	+	1
Louisiana	46	53	52	41	46	45	38	45
Mississippi	21	23	27	19	22	22	20	20
Missouri	7	12	16	14	18	15	15	17
Oklahoma	+	+	+	+	+	+	+	+
Texas	30	24	22	18	18	18	15	19
Ratoon	**98**	**98**	**95**	**97**	**81**	**52**	**73**	**77**
Arkansas	+	+	+	+	+	+	+	+
Florida	2	3	4	2	2	2	2	2
Louisiana	52	59	58	61	52	25	50	50
Texas	45	36	33	34	27	24	22	24
Total	**339**	**376**	**395**	**357**	**364**	**325**	**328**	**360**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommends utilizing harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This methodology is followed with the use of U.S.-specific emission factors derived from rice field measurements. 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 *Good Practice Guidance* (IPCC 2000).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2004 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 2004 Summary* (USDA 2005). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001a) and Arthur Kirstein (2003), Florida agricultural extension agents, Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida, and Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company. Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003, 2004, 2005). Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a; Wilson 2002, 2003, 2004, 2005). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), about 60 percent of the primary area in 2001 (Deren 2002), about 54 percent of the primary area in 2002 (Kirstein 2003), about 100 percent of the primary area in 2003 (Kirstein 2004), and about 77 percent of the primary area in 2004 (Cantens 2005). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, increased to approximately 40 percent in 2000, returned to 30 percent in 2001, dropped to 15 percent in 2002, rose to 35 percent in 2003, and returned to 30 percent in 2004 (Linscombe 1999, 2001a, 2002,

2003, 2004, 2005; Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the entire 1990 to 1999 period, increased to 50 percent in 2000 due to an early primary crop, and then decreased to 40 percent in 2001, 37 percent in 2002, 38 percent in 2003, and 35 percent in 2004 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990-2004 (Guethle 1999, 2000, 2001a, 2002, 2003, 2004, 2005; Lee 2003, 2004, 2005; Mutters 2002, 2003, 2004, 2005; Street 1999, 2000, 2001a, 2002, 2003; Walker 2004, 2005).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1998	1999	2000	2001	2002	2003	2004
Arkansas								
Primary	485,633	600,971	657,628	570,619	656,010	608,256	588,830	629,300
Ratoon*	0	202	202	0	0	0	0	0
California	159,854	185,350	204,371	221,773	190,611	213,679	205,180	238,770
Florida								
Primary	4,978	8,094	7,229	7,801	4,562	5,077	2,315	5,077
Ratoon	2,489	4,047	4,673	3,193	2,752	2,734	2,315	2,734
Louisiana								
Primary	220,558	250,911	249,292	194,253	220,963	216,512	182,113	215,702
Ratoon	66,168	75,273	74,788	77,701	66,289	32,477	63,739	64,711
Mississippi	101,174	108,458	130,716	88,223	102,388	102,388	94,699	94,699
Missouri	32,376	57,871	74,464	68,393	83,772	73,654	69,203	78,915
Oklahoma	617	19	220	283	265	274	53	158
Texas								
Primary	142,857	114,529	104,816	86,605	87,414	83,367	72,845	88,223
Ratoon	57,143	45,811	41,926	43,302	34,966	30,846	27,681	30,878
Total Primary	***1,148,047***	***1,326,203***	***1,428,736***	***1,237,951***	***1,345,984***	***1,303,206***	***1,215,237***	***1,350,844***
Total Ratoon	***125,799***	***125,334***	***121,589***	***124,197***	***104,006***	***66,056***	***93,735***	***98,323***
Total	**1,273,847**	**1,451,536**	**1,550,325**	**1,362,148**	**1,449,991**	**1,369,262**	**1,308,972**	**1,449,167**

* Arkansas ratooning occurred only in 1998 and 1999.

Note: Totals may not sum due to independent rounding.

To determine what seasonal 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 which involved atypical or nonrepresenative 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[4] 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 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.

[4] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 g/m^2/day in Lindau and Bollich 1993) was excluded since this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

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 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 were not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean, therefore a lognormal-type statistical distribution was applied in the Tier 2 Monte Carlo analysis.

Uncertainty regarding primary cropping area is an additional consideration. Uncertainty associated with primary rice-cropped area for each state was obtained from expert judgment, and ranged from 1 percent to 5 percent of the mean area. A normal distribution, truncated to avoid negative values, of uncertainty was assumed about the mean for areas.

Another source of uncertainty lies in the ratooned areas, which are not compiled regularly. Although ratooning accounts for only 5 to 10 percent of the total rice-cropped area, it is responsible for 15 to 30 percent of total emissions. For states that have never reported any ratooning, it is assumed that no ratooning occurred in 2004 with complete certainty. For states that regularly report ratooning, uncertainty is estimated to be between 3 percent and 5 percent (based on expert judgment) and is assumed to have a normal distribution, truncated to avoid negative values. For Arkansas, which reported ratooning in 1998 and 1999 only, a triangular distribution was assumed, with a lower boundary of 0 percent ratooning and an upper boundary of 0.034 percent ratooning based on the maximum ratooned area reported in 1998 and 1999.

A final source of uncertainty is in the practice of flooding outside of the normal rice season. According to agricultural extension agents, all of the rice-growing states practice this on some part of their rice acreage. Estimates of these areas range from 5 to 68 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, however, 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 6-12. Rice cultivation CH_4 emissions in 2004 were estimated to be between 2.5 and 19.4 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 67 percent below to 157 percent above the 2004 emission estimate of 7.6 Tg CO_2 Eq.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Rice Cultivation	CH_4	7.6	2.5	19.4	-67%	+157%

[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. In addition, this year calculation spreadsheets were linked directly to source data spreadsheets to minimize transcription errors, and a central, cross-cutting agricultural data spreadsheet was created to prevent use of incorrect or outdated data.

Recalculations Discussion

For the previous Inventory report, 2000 data for rice area harvested in Oklahoma were unavailable. Data were updated for the current Inventory based on information received from Lee (2005). This change resulted in a 0.02 percent increase in emission estimates for 2000 relative to the previous Inventory report.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[5] 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 in 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 cultivation of organic soils (i.e., soils with a high organic matter content, otherwise known as histosols).[6] 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. Indirect emissions occur through two pathways: 1) volatilization and subsequent atmospheric deposition of applied N;[7] and 2) surface runoff and leaching of applied 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 due to anthropogenic activity on all land-use types (croplands, grasslands, as well as forest lands and settlements), are included in this section.

Figure 6-2: Direct and Indirect N_2O Emissions from Agricultural Soils

Agricultural soils are responsible for the majority of U.S. N_2O emissions. Estimated emissions from this source in 2004 were 261.6 Tg CO_2 Eq. (844 Gg N_2O) (see Table 6-13 and Table 6-14). Annual agricultural soil management N_2O emissions fluctuated between 1990 and 2004; however, overall emissions were 1.7 percent lower in 2004 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer

[5] 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 nitrogen gas (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).

[6] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

[7] These processes entail volatilization of applied N as ammonia (NH_3) and oxides of N (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.

use, and crop production.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Direct	**150.4**		**166.6**	**147.6**	**165.4**	**165.9**	**169.9**	**155.4**	**170.9**
Cropland	108.2		129.7	117.9	124.9	131.8	121.7	117.7	133.8
Grassland	42.2		36.9	29.6	40.5	34.2	48.2	37.7	37.2
Indirect (All Land-Use Types)*	**115.7**		**134.5**	**133.6**	**112.8**	**117.0**	**107.9**	**103.8**	**90.6**
Total	**266.1**		**301.1**	**281.2**	**278.2**	**282.9**	**277.8**	**259.2**	**261.5**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Direct	**485**		**538**	**476**	**534**	**535**	**548**	**501**	**551**
Cropland	349		418	380	403	425	392	380	431
Grassland	136		119	96	131	110	155	122	120
Indirect (All Land-Use Types)*	**373**		**434**	**431**	**364**	**377**	**348**	**335**	**292**
Total	**858**		**971**	**907**	**897**	**913**	**896**	**836**	**844**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Table 6-15: Direct N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Cropland	**108.2**		**129.7**	**117.9**	**124.9**	**131.8**	**121.7**	**117.7**	**133.8**
Mineral Soils	105.3		126.8	115.1	122.0	128.9	118.8	114.8	130.8
Organic Soils	2.8		2.9	2.9	2.9	2.9	2.9	2.9	2.9
Grassland	**42.2**		**36.9**	**29.6**	**40.5**	**34.2**	**48.2**	**37.7**	**37.2**
Total	**150.4**		**166.6**	**147.6**	**165.4**	**165.9**	**169.9**	**155.4**	**170.9**

Note: Totals may not sum due to independent rounding.

Table 6-16: Indirect N_2O Emissions from all Land Use Types* (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Volatilization and Atm. Deposition	16.2		17.8	17.2	18.0	17.5	17.7	17.7	17.3
Surface Leaching & Run-Off	99.5		116.7	116.5	94.8	99.5	90.2	86.0	73.3
Total	**115.7**		**134.5**	**133.6**	**112.8**	**117.0**	**107.9**	**103.8**	**90.6**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Methodology

Current IPCC methods divide the N_2O source category into three components: 1) direct emissions from soils due to N additions to cropland and grassland mineral soils and from the drainage and cultivation of organic cropland soils; 2) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and 3) indirect emissions from soils and water induced by N additions and manure deposition to soils of all land-use types. The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of Tier 1 and 3 approaches as defined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), and later amended in the IPCC *Good Practice Guidance* (IPCC 2000) and *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003). Specifically, a Tier 3, process-based model (DAYCENT) is 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 DAYCENT-derived direct emissions from grasslands include emissions from

deposition of PRP manure as well as several land management practices such as seeding with forage legumes. The Tier 1 IPCC methodology is used to estimate direct emissions from non-major crops on mineral soils; the portion of the grassland direct emissions from PRP and forage legume N additions that were not estimated with the Tier 3 DAYCENT model; and direct emissions from drainage and cultivation of organic cropland soils. A combination of DAYCENT and the IPCC Tier 1 method is used to estimate indirect emissions from soils. 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 Agricultural 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 producing major crops, specifically corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton, which represent approximately 90 percent of total croplands in the United States. DAYCENT simulated 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 in national soil surveys (Soil Survey Staff 2005).

DAYCENT simulations were conducted for each major crop at the county scale in the United States. The county scale was selected because soil and weather data were available for every county with more than 100 acres of agricultural land. However, land management data (e.g., timing of planting, harvesting, and fertilizer application; intensity of cultivation, rate of fertilizer application) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States; most states correspond to one region, except for those with greater heterogeneity in agricultural practices, in which there are further subdivisions. Therefore, while several cropping systems were simulated for each county in an agricultural region, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested, amount of fertilizer added), did not differ among the counties in an agricultural region.

Nitrous oxide emission estimates from DAYCENT include the influence of N additions, crop type, irrigation, and other factors in aggregate, and therefore it is not possible to partition N_2O emissions by anthropogenic activity (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Consequently, emissions are not subdivided according to activity (e.g., N fertilization, manure amendments), as is suggested in the IPCC *Guidelines*, but the overall estimates are still more accurate than the more simplistic IPCC method, which is not capable of addressing the broader set of driving variables influencing N_2O emissions. Thus DAYCENT forms the basis for a more complete estimation of N_2O emissions than is possible with the IPCC methodology.

Nitrous oxide emissions from managed agricultural lands are the result of interactions between the combined anthropogenic interventions that are implemented (e.g., N fertilization and manure application) and natural background emissions of N_2O, which would occur regardless of anthropogenic management. To isolate anthropogenic emissions from natural background emissions of N_2O, DAYCENT was used to simulate emissions under potential native conditions for lands used to produce major crops, and the resulting estimates were subtracted from the N_2O emissions simulated under current crop management. The reported estimates of emissions from managed soils therefore represent the difference between simulated emissions from potential native conditions and emissions from cropland soils.

With these methods, DAYCENT was used to estimate direct N_2O emissions due to increased mineral N availability for the following practices: 1) the application of synthetic and organic commercial fertilizers, 2) the application of livestock manure, 3) the production of N-fixing crops, and 4) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, annual increases in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: 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).

- Managed manure production and application to croplands and grasslands: Manure N amendments were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). These values were adjusted for other years based on manure N production. Data sources to estimate manure production include USDA (1994b-c, 1995a-b, 1998a, 1998c, 1999a-c, 2000a, 2004a-e, 2005a-g), FAO (2005), Lange (2000), Poe et al. (1999), Anderson (2000), Deal (2000), Johnson (2000), Miller (2000), Milton (2000), Stettler (2000), Sweeten (2000), Wright (2000), Safley et al. (1992). Managed manure N production was adjusted for the amount of manure used for feed. Even with this adjustment, a portion of the remaining managed manure N was not applied to crop and grassland soils according to Edmonds et al. (2003). The difference between manure N applied to soils and remaining N in the managed manure was assumed to be lost through volatilization of N species during handling and storage. Instead of assuming that 10 percent of synthetic and 20 percent of organic N applied to soils is volatilized and 30 percent of applied N was leached/runoff as with IPCC methodology, volatilization and N leaching/runoff from manure that was amended to soils was internally calculated by the DAYCENT process-based model.

- Nitrogen-fixing crops and forages and retention of crop residue: The IPCC approach considers this information as separate activity data. However, they are not considered separate activity data for the DAYCENT simulations because residue production and N fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation 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.): Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2004f), USDA (2000b) 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), Langtson et al. (1922), Russell et al. (1922), Elliot and Tapp (1928), Elliot (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliot (1931), Brenner et al. (2002, 2001), Smith et al. (2002).

DAYCENT was used to simulate the influence of anthropogenic activity due to all of these activities, generating the U.S. estimate of direct N_2O emissions from mineral soils producing major crop types. Because the model is sensitive to actual interannual variability in weather patterns and other controlling variables, 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), rather than having a linear, monotonic response, which would occur using the IPCC method. The ability of DAYCENT to capture these interactions is largely the reason for more accurate estimates of N_2O emissions, compared to the more simplistic IPCC Tier 1 approach.

Mineral N was subject to volatilization and leaching/runoff according to the climatic conditions, soil type and condition, crop type, and land management practices such as cultivation and irrigation, as simulated by DAYCENT. The resulting amounts were then applied in the calculation of indirect emissions as described below (i.e., in the section entitled Indirect N_2O Emissions from Managed Soils of All Land-Use Types).

Non-Major Crop Types on Mineral Cropland Soils

For mineral cropland soils producing non-major crop types, the Tier 1 IPCC methodology was used to estimate direct N_2O emissions. Estimates of direct N_2O emissions from N applications to non-major crop types were based on the annual increase in mineral soil N from the following practices: 1) the application of synthetic commercial fertilizers, 2) the production of N-fixing crops, and 3) the retention of crop residues. No organic amendments (i.e., manure N, other organic commercial fertilizers) were considered here because they were assumed to be applied to

crops simulated by DAYCENT. This assumption is reasonable because DAYCENT simulations included the 5 major cropping systems (corn, hay, sorghum, soybean, wheat), which are the land management systems receiving the vast majority (approximately 95 percent) of manure applications to cropped land in the United States (Kellogg et al. 2000, Edmonds et al. 2003), and manure accounts for approximately 95 percent of total organic amendments.

Annual synthetic fertilizer N additions to non-major crop types were calculated by process of elimination. For each year, fertilizer amounts for each of the following were summed: fertilizer applied to major crops (as simulated by DAYCENT—approximately 75 percent of the U.S. total), fertilizer applied to forest lands (less than 1 percent of the U.S. total), and fertilizer applied in settlements (approximately 10 percent of the U.S. total). The sum was then subtracted from total fertilizer use in the United States. This difference, approximately 15 percent of total synthetic fertilizer N used in the United States, was assumed to be applied to non-major crop types. Non-major crop types include: a) fruits, nuts, and vegetables, which were estimated to receive approximately 5 percent of total U.S. N fertilizer use (TFI 2000); and b) other annual crops not simulated by DAYCENT (barley, oats, tobacco, sugarcane, sugar beets, sunflower, millet, peanuts, etc.), which account for approximately 10 percent of total U.S. fertilizer use. The non-volatilized portion was obtained by multiplying the amount of fertilizer added to non-major crop types by the default IPCC volatilization fraction (IPCC/UNEP/OECD/IEA 1997, IPCC 2000). In addition to synthetic fertilizer N, N in soils due to the cultivation of non-major N-fixing crops (e.g., edible legumes) was included in these estimates. Finally, crop residue N was derived from information on crop production yields, residue management (retained vs. burned or removed), mass ratios of aboveground residue to crop product, dry matter fractions, and N contents of the residues (IPCC/UNEP/OECD/IEA 1997). The activity data for these practices were obtained from the following sources:

- Annual production statistics for crops whose residues are left on the field: USDA (1994a, 1998b, 2000c, 2001, 2002, 2003), Schueneman (1999, 2001), Deren (2002), Schueneman and Deren (2002), Cantens (2004), Lee (2003, 2004).

- Mass ratios of aboveground residue to crop product, dry matter fractions, and N contents for N-fixing crops: Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), IPCC/UNEP/OECD/IEA (1997).

- Aboveground residue to crop mass ratios, residue dry matter fractions, and residue N contents of non-N fixing crops: Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), Barnard and Kristoferson (1985), Karkosh (2000).

The total increase in soil mineral N from applied fertilizers, N-fixing crops, and crop residues was multiplied by the IPCC default emission factor to derive an estimate of cropland direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC Tier 1 method was used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions were obtained for 1982, 1992, and 1997 from the Natural Resources Inventory (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998). These areas were linearly interpolated and extrapolated to estimate areas for the missing years. To estimate annual emissions, the total temperate areas were multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical areas were multiplied by the average of the IPCC default emission factors for temperate and tropical regions.

Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and IPCC Tier 1 methods 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, that may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate N_2O emissions from grasslands at the county scale resulting from manure deposited by livestock directly onto the pasture (i.e., Pasture/Range/Paddock manure; which is simulated internally within the model), N fixation from legume seeding, sewage sludge amendments, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. The simulations used the same weather and soils data as discussed under the section for Major Crop Types. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using managed manure N production data according to methods described under the Methodology Section for Major Crop Types. Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limits its use as an amendment to croplands. Sewage sludge was estimated from data compiled by EPA (1993, 1997, 1999, 2003), Bastian (2002, 2003, 2005), and Metcalf and Eddy (1991). DAYCENT generated per area estimates of N_2O emissions (g N_2O-N m^{-2}) from pasture and rangelands, which were then scaled to the entire county by multiplying the emissions estimate by reported pasture and rangeland areas in the county; summing results across all counties produced the national estimate. Grassland area data were obtained from the National Resources Inventory (USDA 2000b). The 1997 NRI data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2004, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994.

Manure N additions from grazing animals are modeled internally within the DAYCENT. Comparisons with estimates of total manure deposited on PRP (see Annex 3.11) showed that DAYCENT accounted for approximately 75 percent of total PRP manure. It is reasonable that DAYCENT did not account for all PRP manure because the NRI data do not include all grassland areas, such as federal grasslands. N_2O emissions from the portion of PRP manure N not accounted for by DAYCENT were estimated using the IPCC Tier 1 method with default emission factors (IPCC/UNEP/OECD/IEA 1997). Fixed N additions from forage legumes are also model outputs generated by DAYCENT. Comparisons with estimates of total N fixation by forage legumes showed that DAYCENT accounted for approximately 52 percent of total forage legume fixation. N_2O emissions from the portion of fixed legume N not accounted for by DAYCENT were estimated using the IPCC Tier 1 method with default emission factors (IPCC/UNEP/OECD/IEA 1997). Emission estimates from DAYCENT and the IPCC method were summed to provide total national emissions for grasslands in the United States.

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 total direct N_2O emissions from agricultural soil management (see Table 6-13 and Table 6-14).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types

This section describes methods 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 or organic amendments (e.g., manure, sewage sludge), or deposition of PRP manure, or during storage, treatment, and transport of managed manure. Through atmospheric deposition, volatilized nitrogen can be returned to soils, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil mineral N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity. The nitrate is subject to denitrification in water bodies, which leads to additional 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 agriculture, forestry, and other land-use activities.

N Transport from Managed Soils

Similar to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was exported from application sites through volatilization, and leaching and surface runoff. DAYCENT was used to simulate the amount of N transported from major cropland types and grasslands as NO_x and NH_3 through volatilization, and as NO_3 in leachate and runoff. N transport from non-major croplands, settlements, forest lands, and grasslands not accounted for by DAYCENT (i.e., from land areas that were not simulated with DAYCENT) were obtained by applying the IPCC default fractions for volatilization and for leaching and runoff to total fertilizer and manure N amounts applied or deposited on to these lands. Manure N from managed systems assumed to be volatilized during storage, treatment, and transport was also estimated and included as a source of N for indirect emissions.

Indirect N_2O Emissions from N Transport

The N transport from managed soils and from storage, treatment, and transport of managed manure were summed for both volatilization and leaching or surface runoff. The IPCC default emission factors for indirect N_2O were applied to the respective total amounts of N for each pathway to estimate emissions and then summed to obtain the total indirect N_2O emissions due to the use and management of U.S. croplands, grasslands, forest lands, and settlements (Table 6-16).

Uncertainty

Uncertainty was estimated differently for each of the following three components of N_2O emissions from agricultural soil management: 1) Direct emissions calculated by DAYCENT; 2) Direct emissions not calculated by DAYCENT; and 3) Indirect emissions.

For direct emissions calculated using DAYCENT, uncertainty was associated with the activity data, the model inputs, and the structure of the model (i.e., underlying model equations and parameterization). Uncertainties in activity data were evaluated based on variation in weather patterns, soil characteristics, and N application rates associated with crop types, years, and agricultural regions. Total uncertainty in N inputs was estimated to contribute 20 percent to the uncertainty in N_2O estimates (Mosier 2004); uncertainties in weather patterns contributed 19 percent (Thornton et al. 2000), and variation in soil characteristics contributed an additional 12 percent (Del Grosso 2005). Their combined uncertainty is approximately 30.1 percent using the sum-of-squares method. To estimate the uncertainty associated with the model structure, an effective emission factor was computed from DAYCENT outputs and compared with N_2O measurements from various cropped soils over the annual cycle (Del Grosso et al. 2005). The uncertainty associated with the effective emission factor was estimated at 57 percent (Del Grosso 2005). Simple error propagation led to an overall uncertainty for direct emissions of ±64 percent. Direct N_2O emissions not calculated by DAYCENT were assumed to have similar uncertainties and assigned the same value of ±64 percent.

Indirect emissions from agricultural soil management, which were calculated according to the default IPCC methodology, were estimated to have an uncertainty of ±286 percent (EPA 2004).

The results of the uncertainty analysis are summarized in Table 6-17. Agricultural soil management N_2O emissions in 2004 were estimated to be between 47.1 and 475.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 82 percent above and below the 2004 emission estimate of 261.6 Tg CO_2 Eq.

Table 6-17: Tier 1 Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2004 (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty (%)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)	
				Lower Bound	Upper Bound
Agricultural Soil Management	N_2O	261.5	82%	47.1	475.9

Recalculations Discussion

Minor changes were made from previous reports, including adjustments in activity data and the use of a revised version of the DAYCENT model. The residue N fractions for dry edible beans, dry edible peas, Austrian winter peas, lentils, and wrinkled seed peas were revised to 0.0168. The source of activity data for pasture and rangelands was changed from NASS, which only provides partial accounting of pasture land area, to the National Resources Inventory, which provides county-level estimates for both pasture and rangelands for the entire country. This resulted in DAYCENT accounting for a larger portion of total grassland than last year. Also, a different soils database was used this year. Last year, the VEMAP 0.5^{o} resolution cell that contains the geographic center of each county was identified, and the dominant soil type was extracted and applied across the county. This year, surface soil texture and depth from the STATSGO soil map unit that intersected the geographical center of the largest cluster of agricultural land in each county was extracted and used for the simulations. Sewage sludge was simulated as an application to croplands in the previous year's inventory. However, croplands are less likely to be amended with sewage sludge due to the heavy metal content and other toxins associated with human waste. Therefore, in the current inventory, sewage sludge amendments to agricultural lands were simulated as an application to grasslands. Regarding the model revision, DAYCENT was modified to more realistically represent the grain filling period for crops (anthesis), and different cultivars of corn and soybean were simulated in various regions of the country to better represent the life span of the plants, particularly the days to maturity.

These changes, summarized in Table 6-18, resulted in an increase in emissions estimates for all years, ranging from an increase of 2 percent to 26 percent.

Table 6-18: Changes and Percent Difference in N_2O Emission Estimates for Agricultural Soil Management (Tg CO_2 Eq. and Percent)

Year	1990-2003 Inventory	1990-2004 Inventory	Percent Difference
1990	253.0	266.1	5.2
1991	247.6	278.5	12.5
1992	233.2	252.5	8.3
1993	247.6	312.7	26.3
1994	238.3	261.5	9.7
1995	244.7	308.1	25.9
1996	267.3	314.4	17.6
1997	252.0	276.6	9.7
1998	267.7	301.1	12.5
1999	243.4	281.2	15.5
2000	263.9	278.2	5.4
2001	257.1	282.9	10.0
2002	252.6	277.8	10.0
2003	253.5	259.2	2.2

[BEGIN BOX]

Box 6-1. Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC methodology used here is an example of a Tier 1 approach (IPCC/UNEP/OECD/IEA 1997), in which activity data from different N sources (e.g., synthetic fertilizer, manure, N fixation, etc.) are multiplied by the appropriate default IPCC emission factors to estimate N_2O emissions on a source by source basis. The Tier 3 approach used here utilizes a process-based model (i.e., DAYCENT) and is based on the environmental conditions at a specific location in addition to the N inputs. Consequently, it is necessary to not only know the amount of N

inputs but the conditions under which the anthropogenic activity is increasing mineral N in a soil profile. The Tier 1 approach requires a minimal amount of activity data that is generally readily available in most countries (total N applied to crops), calculations are simple, and the methodology is highly transparent. In contrast, the Tier 3 approach requires more refined activity data (e.g., crop specific N amendment rates, daily climate, soil class, etc.), considerable computational resources and programming expertise, and the methodology is less transparent. The advantage of the Tier 3 approach is that the accuracy of estimates is expected to be greater using the advanced model, which accounts for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics). Emissions due to anthropogenic activity may be enhanced or dampened, depending on the specific environmental conditions. 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; e.g., N added as fertilizer or through fixation contributes to N_2O emission for that year, but cannot be stored in soils and contribute to N_2O emission in subsequent years. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years. The Tier 1 approach also assumes that only N from fertilizer and organic matter additions contributes to indirect N_2O emissions whereas the Tier 3 approach assumes that once N is in the plant/soil system, including residue N and soil organic matter, it can be cycled and lost through the two indirect pathways which contribute to N_2O emissions. Overall, the Tier 3 approach in this analysis (DAYCENT) estimates higher indirect emissions and lower direct emissions than IPCC methodology, particularly for N-fixing crops. This was primarily because of greater losses through volatilization and through leaching and surface runoff than was estimated using the IPCC Tier 1 methodology. For example, in 2004 direct soil N_2O emissions from agricultural sources were 225 vs. 171 Tg CO_2 Eq. for IPCC and DAYCENT/IPCC methodologies while indirect emissions from all sources were 80 and 91 Tg CO_2 Eq. for IPCC and DAYCENT/IPCC.

[END BOX]

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, soils types, and climate patterns. N_2O measurement data were available for seven sites in the United States and one in Canada, representing 25 different combinations of fertilizer treatments and cultivation practices. NO_3 leaching data were available for three sites in the United States representing nine different combinations fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.74 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively.

Spreadsheets containing input data required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked and no errors were found. Spreadsheets containing input data and emission factors required for the Tier 1 approach used for non-major crops and grasslands not simulated by DAYCENT were checked and no errors were found. However, assumptions on the application of sewage sludge were questioned during the review process. A corrective action was taken to apply sewage sludge to grasslands in the simulations, rather than croplands, which are unlikely to receive sewage sludge due its high metal content and other toxins. Total emissions and emissions from the different categories were compared with inventories from previous years and differences were consistent with the methodological differences (see Recalculations section for further discussion).

Planned Improvements

Four major improvements are planned for the soil N_2O inventory. The first improvement will be to incorporate land survey data from the National Resources Inventory (NRI) (USDA 2000b) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture which are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1982 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; the major disadvantage to this land survey is that most crops are grown in rotation, and NASS data provide no information regarding rotation histories.

In contrast, NRI is designed to track rotation histories, and this is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Moreover, 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 N_2O inventory methods more consistent with those used to estimate net C fluxes for agricultural soils.

The second planned improvement will be to achieve consistency in N fertilization rates and organic amendments between the soil C and soil N_2O inventories. Currently, each inventory is using a combination of shared and different sources to model these activities. As part of this activity, manure amendments will be more realistically distributed among major crops, non-major crop types, and grasslands, according to methods used in the soil C inventory (see Annex 3.13). The goal will be to ensure that each is using the most accurate information in a consistent manner.

The third planned improvement is to develop a more rigorous uncertainty analysis. The current analysis is incomplete because there are additional uncertainties in activity data that were not addressed, such as N input rates, variation in county level weather patterns, and soil characteristics. For example, a single soil and climate type were used in the simulations for each county, but there can be considerable heterogeneity in these environmental variables. Consequently, there is inherent uncertainty in the current emission estimates which is not addressed. A Monte Carlo approach will be used to capture uncertainty in soil and weather input data at the county scale, as well as further elaboration of uncertainties from N inputs due to fertilization and organic amendments. The analysis will also address uncertainties in other key soil management practices such as irrigation and tillage histories. Uncertainties in the DAYCENT model structure will be further evaluated to address bias, which is not included in the effective emission factor analysis. Also, a more rigorous methodology will be developed for the IPCC Tier 1 calculations.

The fourth planned improvement deals with emissions from native rangelands. Emissions from unimproved rangelands with low to moderate grazing intensities are not much higher than emissions under native conditions. Subtracting the native land emissions is likely to underestimate the anthropogenic influence on emissions rates from rangelands, which are controlled by livestock grazing regimes. Therefore, future inventories will be modified to avoid subtracting native grassland emissions from simulations of livestock grazing in rangelands.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Large quantities of agricultural crop residues are produced by farming activities. A variety of ways exist to utilize or dispose of these residues. For example, agricultural residues can be left on or plowed back 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 carbon 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. Of these residues, less than 5 percent is burned each year, except for rice.[8] Annual emissions from this source over the period 1990 through 2004 have remained relatively constant, averaging approximately 0.7 Tg CO_2 Eq. (36 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 746 Gg of CO, and 32 Gg of NO_x (see Table 6-19 and Table 6-20).

[8] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Table 6-19: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0.4
Barley	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+
Soybeans	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.4**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-20: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**33**	**38**	**37**	**38**	**37**	**34**	**38**	**42**
Wheat	7	6	5	5	5	4	6	5
Rice	4	3	4	4	4	3	5	4
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	17	16	17	16	15	17	20
Barley	1	1	+	1	+	+	+	+
Soybeans	7	10	10	10	11	10	9	12
Peanuts	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**689**	**789**	**767**	**790**	**770**	**706**	**796**	**877**
Wheat	137	128	115	112	98	80	117	108
Rice	86	65	77	76	77	61	96	75
Sugarcane	18	23	23	24	23	23	22	19
Corn	282	347	336	353	338	319	359	420
Barley	16	13	10	12	9	8	10	10
Soybeans	148	211	204	212	222	212	189	242
Peanuts	2	2	2	2	3	2	3	3
NO_x	**28**	**35**	**34**	**35**	**35**	**33**	**34**	**39**
Wheat	4	3	3	3	3	2	3	3
Rice	3	2	3	3	3	2	3	3
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	8	8	8	8	8	9	10
Barley	1	+	+	+	+	+	+	+

Soybeans	14	20	19	20	21	20	18	23
Peanuts	+	+	+	+	+	+	+	+

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).[9] In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:[10]

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)[11]

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned in situ) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

Emissions of CH_4 and CO were calculated by multiplying the amount of carbon released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C or CO-C/C). Similarly, N_2O and NO_x emissions were calculated by multiplying the amount of nitrogen released by the appropriate IPCC default emission ratio (i.e., N_2O-N/N or NO_x-N/N).

The crop residues that are 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 2004 Summary* (USDA 2005). Rice production data for Florida and Oklahoma, which are not collected by USDA, were estimated by applying average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005) and for Arkansas (USDA 1994, 1998, 2003, 2005) to Oklahoma acreages[12] (Lee 2003, 2004, 2005). The production data for the crop types whose residues are burned are presented in Table 6-21.

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

[9] The IPCC Good Practice Guidance (IPCC 2000) provided no updates to the methodology for estimating field burning of agricultural residues.

[10] Note: 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.

[11] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

[12] Rice production yield data are not available for Oklahoma so the Arkansas values are used as a proxy.

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 the agricultural extension agents in each state and reports of the California Air Resources Board (Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Guethle 1999, 2000, 2001, 2002, 2003, 2004, 2005; Klosterboer 1999a, 1999b, 2000, 2001, 2002, 2003; Lee 2005; Lindberg 2002, 2003, 2004, 2005; Linscombe 1999a, 1999b, 2001, 2002, 2003, 2004, 2005; Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001, 2002, 2003; Walker 2004, 2005; Wilson 2003, 2004, 2005) (see Table 6-22 and Table 6-23). The estimates provided for Florida remained constant over the entire 1990 through 2004 period, while the estimates for all other states varied over the time series. 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 declined between 1990 and 2004 because of a legislated reduction in rice straw burning (Lindberg 2002) (see Table 6-23).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum 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 carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen 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 for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-21: Agricultural Crop Production (Gg of Product)

Crop	1990	1998	1999	2000	2001	2002	2003	2004
Wheat	74,292	69,327	62,475	60,641	53,001	43,705	63,814	58,738
Rice	7,113	8,414	9,392	8,705	9,794	9,602	9,084	10,495
Sugarcane	25,525	31,486	32,023	32,762	31,377	32,253	30,715	26,576
Corn*	201,534	247,882	239,549	251,854	241,377	227,767	256,278	299,917
Barley	9,192	7,655	5,922	6,919	5,407	4,940	6,059	6,080
Soybeans	52,416	74,598	72,223	75,055	78,671	75,010	66,778	85,484
Peanuts	1,635	1,798	1,737	1,481	1,940	1,506	1,880	1,933

*Corn for grain (i.e., excludes corn for silage).

Table 6-22: Percentage of Rice Area Burned by State

State	1990-1998	1999	2000	2001	2002	2003	2004
Arkansas	13%	13%	13%	13%	16%	22%	17%
California	variable[a]	27%	27%	23%	13%	14%	11%
Florida[b]	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	0%	5%	4%	3%	3%	3%
Mississippi	10%	40%	40%	40%	8%	65%	28%
Missouri	5%	5%	8%	5%	5%	4%	4%
Oklahoma	90%	90%	90%	90%	90%	100%	88%
Texas	1%	2%	0%	0%	0%	0%	0%

[a] Values provided in Table 6-23.
[b] Although rice is cultivated in Florida, crop residue burning is illegal. Therefore, emissions remain 0 throughout the time series.

Table 6-23: Percentage of Rice Area Burned in California, 1990-1998

Year	Percentage

1990	75%
1991	75%
1992	66%
1993	60%
1994	69%
1995	59%
1996	63%
1997	34%
1998	35%

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	Carbon Fraction	Nitrogen 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 6-25: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of carbon compound released (units of C) relative to mass of total carbon released from burning (units of C).
[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen 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, as well as 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.

Based on expert judgment, the uncertainty in production for all crops considered here is estimated to be 5 percent. Residue/crop product ratios can vary among cultivars. For all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. An uncertainty of 10 percent was applied to the residue/crop product ratios for all crops. Based on the range given for measurements of soybean dry matter fraction (Strehler and Stützle 1987), residue dry matter contents were assigned an uncertainty of 3.1 percent for all crop types. Burning and combustion efficiencies were assigned an uncertainty of 5 percent based on expert judgment.

The N_2O emission ratio was estimated to have an uncertainty of 28.6 percent based on the range reported in IPCC/UNEP/OECD/IEA (1997). The uncertainty estimated for the CH_4 emission ratio was 40 percent based on the range of ratios reported in IPCC/UNEP/OECD/IEA (1997).

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-26. CH_4 emissions from field burning of agricultural residues in 2004 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 75 percent below and 96 percent above the 2004 emission estimate of 0.9 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to between 0.1 and 1.0 Tg CO_2 Eq. (or approximately 73 percent below and 85 percent above the 2004 emission estimate of 0.5 Tg CO_2 Eq.).

Table 6-26: Tier 2 Monte Carlo Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	-75%	+96%
Field Burning of Agricultural Residues	N_2O	0.5	0.1	1.0	-73%	+85%

[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 field burning of agricultural residues 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 crops to attempt to identify any outliers or inconsistencies. No problems were found. In addition, this year, calculation spreadsheets were linked directly to source data spreadsheets to minimize transcription errors, and a central, cross-cutting agricultural data spreadsheet was created to prevent use of incorrect or outdated data.

Recalculations Discussion

The crop production data for 1997 through 2001 and for 2002 and 2003 were updated using USDA (2003) and USDA (2005), respectively. Data on the rice area harvested in 2000 in Oklahoma was previously unavailable so the area was assumed to be zero last year; this was revised this year based on new information (Lee 2005). Oklahoma rice data on yields and percentage of harvested area burned were also previously unavailable. Last year, the average rice yield for Florida was used as a proxy. This year it was determined that the average rice yield for Arkansas would be a more appropriate proxy, due to similar geography (Lee 2005). The IPCC default of three percent burned (used last year for Oklahoma) was revised to 90 percent this year because 90 percent is an appropriate assumption when data are not available (Lee 2005).

These changes, summarized in Table 6-27, resulted in a change in emissions estimates for CH_4 and N_2O for all years except 1992. From 1990 to 1997, emission estimates for both CH_4 and N_2O increased by less than 0.05 percent. From 1998 to 2001, emission estimates increased or decreased by less than 0.1 percent. From 2002 to 2003, emission estimates increased or decreased by less than 1 percent.

Table 6-27: Changes and Percent Difference in CH_4 and N_2O Emission Estimates for Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

	CH_4			N_2O		
Year	1990-2003 Inventory	1990-2004 Inventory	Percent Difference	1990-2003 Inventory	1990-2004 Inventory	Percent Difference
1990	0.69	0.69	0.03%	0.37	0.37	0.02%
1991	0.65	0.65	0.02%	0.36	0.36	0.02%
1992	0.76	0.76	0.00%	0.41	0.41	0.00%
1993	0.61	0.61	0.02%	0.34	0.34	0.01%
1994	0.81	0.81	0.01%	0.46	0.46	0.01%
1995	0.66	0.66	0.02%	0.38	0.38	0.01%
1996	0.75	0.75	0.00%	0.42	0.42	0.00%

1997	0.77	0.77	0.00%	0.45	0.45	0.00%
1998	0.79	0.79	0.05%	0.46	0.46	0.02%
1999	0.77	0.77	-0.05%	0.45	0.45	-0.04%
2000	0.79	0.79	-0.02%	0.46	0.46	-0.01%
2001	0.77	0.77	-0.08%	0.46	0.46	-0.04%
2002	0.71	0.71	-0.21%	0.43	0.43	0.01%
2003	0.79	0.80	0.30%	0.44	0.44	0.78%

Planned Improvements

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.

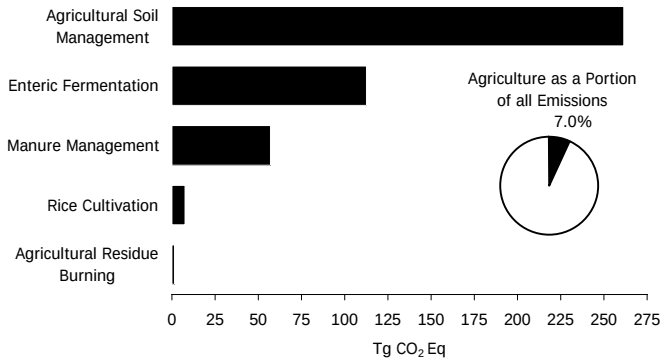
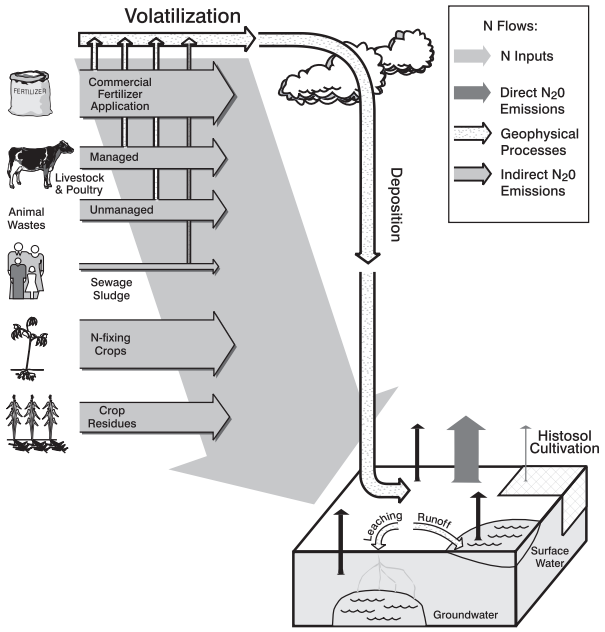


Figure 6-1: 2004 Agriculture Chapter GHG Sources

Figure 6-2

Direct and Indirect N_2O Emissions from Agricultural Soils



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also 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.

Descriptions of Figures: Agriculture

Figure 6-1 illustrates the data presented in Table 6-1. Agricultural soil management is the greatest source, responsible for 261.5 Tg CO_2 eq. Agricultural residue burning is the smallest source, accounting for 1.4 CO_2 eq. In addition, there is a pie chart that indicates that agriculture processes made up 7.0 % of U.S. greenhouse gas emissions in 2004.

Figure 6-2 illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the U.S. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emissions pathways are also 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.

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. IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) 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). Datasets available for the United States allow greenhouse gas flux to be estimated for the following subset of the categories defined by IPCC (2003): 1) *Forest Land Remaining Forest Land*; 2) *Cropland Remaining Cropland*; 3) *Land Converted to Cropland*, 4) *Grassland Remaining Grassland*, 5) *Land Converted to Grassland*, and 6) *Settlements Remaining Settlements*. In addition, fluxes from some categories are reported under other categories because U.S. data are insufficient for separating these fluxes.

The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon stocks and the application of synthetic fertilizers to forest soils. The greenhouse gas flux from agricultural lands (i.e., cropland and grassland) includes changes in organic carbon 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). Fluxes are reported for four 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 landfilled yard trimmings and food scraps, urban trees, and soil fertilization.

Unlike the assessments in other sectors, which are based on annual activity data, the flux estimates in this chapter, with the exception of CO_2 fluxes from wood products, urban trees, and liming, and N_2O emissions from forest and settlement soils, are based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest carbon 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. The forest carbon stocks are based on state surveys, so the estimated CO_2 fluxes at the national level differ from year to year. Agricultural mineral and organic soil carbon flux calculations are based primarily on national surveys, so these results are largely constant over multi-year intervals, with large discontinuities between intervals. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. In addition, because the most recent national forest, land-use, and municipal solid waste surveys were completed prior to 2004, the estimates of CO_2 flux from forests, agricultural soils, and landfilled yard trimmings and food scraps are based in part on extrapolation. Carbon dioxide flux from urban trees is based on neither annual data nor periodic survey data, but instead on data collected over the period 1990 through 1999. 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 2004 resulted in a net carbon sequestration of 780.1 Tg CO_2 Eq. (212.8 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 13 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 14 percent between 1990 and 2004. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Net carbon accumulation in landfilled yard trimmings and food scraps, cropland, and grassland also slowed over this period. Net carbon accumulation in urban trees increased.

Table 7-1: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Land-Use Category	1990		1998	1999	2000	2001	2002	2003	2004

[1] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of carbon from the atmosphere. Removal of carbon from the atmosphere is also referred to as "carbon sequestration."

Forest Land Remaining Forest Land	**(773.4)**		**(618.8)**	**(637.9)**	**(631.0)**	**(634.0)**	**(634.6)**	**(635.8)**	**(637.2)**
Changes in Forest Carbon Stocks[1]	(773.4)		(618.8)	(637.9)	(631.0)	(634.0)	(634.6)	(635.8)	(637.2)
Cropland Remaining Cropland	**(33.1)**		**(24.6)**	**(24.6)**	**(26.1)**	**(27.8)**	**(27.5)**	**(28.7)**	**(28.9)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions[2]	(33.1)		(24.6)	(24.6)	(26.1)	(27.8)	(27.5)	(28.7)	(28.9)
Land Converted to Cropland	**1.5**		**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**
Changes in Agricultural Soil Carbon Stocks[3]	1.5		(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Grassland Remaining Grassland	**(4.5)**		**7.5**	**7.5**	**7.4**	**7.4**	**7.4**	**7.3**	**7.3**
Changes in Agricultural Soil Carbon Stocks[4]	(4.5)		7.5	7.5	7.4	7.4	7.4	7.3	7.3
Land Converted to Grassland	**(17.6)**		**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**
Changes in Agricultural Soil Carbon Stocks[5]	(17.6)		(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Settlements Remaining Settlements[6]	**(83.2)**		**(84.2)**	**(86.8)**	**(85.9)**	**(89.7)**	**(89.9)**	**(93.8)**	**(97.3)**
Urban Trees	(58.7)		(73.3)	(77.0)	(77.0)	(80.7)	(80.7)	(84.3)	(88.0)
Landfilled Yard Trimmings and Food Scraps	(24.5)		(10.9)	(9.8)	(8.9)	(9.0)	(9.3)	(9.4)	(9.3)
Total	**(910.4)**		**(744.0)**	**(765.7)**	**(759.5)**	**(768.0)**	**(768.6)**	**(774.8)**	**(780.1)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
[1] Estimates include carbon stock changes on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*.
[2] Estimates include carbon stock changes in mineral soils and organic soils on *Cropland Remaining Cropland*, carbon stock changes in organic soils on *Land Converted to Cropland*, and liming emissions from all managed land.
[3] Estimates includes carbon stock changes in mineral soils only; organic soil carbon stock changes and liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.
[4] Estimates include carbon stock changes in mineral soils and organic soils on *Grassland Remaining Grassland*, and carbon stock changes in organic soils on *Land Converted to Grassland*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.
[5] Estimates include carbon stock changes in mineral soils only; organic soil carbon stock changes and liming emissions for this land use/land-use change category are reported under *Grassland Remaining Grassland* and *Cropland Remaining Cropland*, respectively.
[6] Estimates include carbon stock changes on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

Table 7-2: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg C)

Land-Use Category	1990		1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**(210.9)**		**(168.8)**	**(174.0)**	**(172.1)**	**(172.9)**	**(173.1)**	**(173.4)**	**(173.8)**
Changes in Forest Carbon Stocks[1]	(210.9)		(168.8)	(174.0)	(172.1)	(172.9)	(173.1)	(173.4)	(173.8)
Cropland Remaining Cropland	**(9.0)**		**(6.7)**	**(6.7)**	**(7.1)**	**(7.6)**	**(7.5)**	**(7.8)**	**(7.9)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions[2]	(9.0)		(6.7)	(6.7)	(7.1)	(7.6)	(7.5)	(7.8)	(7.9)
Land Converted to Cropland	**0.4**		**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**
Changes in Agricultural Soil Carbon Stocks[3]	0.4		(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Grassland Remaining Grassland	**(1.2)**		**2.1**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Changes in Agricultural Soil Carbon Stocks[4]	(1.2)		2.1	2.0	2.0	2.0	2.0	2.0	2.0
Land Converted to Grassland	**(4.8)**		**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**
Changes in Agricultural Soil Carbon Stocks[5]	(4.8)		(5.8)	(5.8)	(5.8)	(5.8)	(5.8)	(5.8)	(5.8)
Settlements Remaining Settlements[6]	**(22.7)**		**(23.0)**	**(23.7)**	**(23.4)**	**(24.5)**	**(24.5)**	**(25.6)**	**(26.5)**
Urban Trees	(16.0)		(20.0)	(21.0)	(21.0)	(22.0)	(22.0)	(23.0)	(24.0)
Landfilled Yard Trimmings and Food Scraps	(6.7)		(3.0)	(2.7)	(2.4)	(2.5)	(2.5)	(2.6)	(2.5)
Total	**(248.3)**		**(202.9)**	**(208.8)**	**(207.1)**	**(209.5)**	**(209.6)**	**(211.3)**	**(212.8)**

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
[1] Estimates include carbon stock changes on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*.
[2] Estimates include carbon stock changes in mineral soils and organic soils on *Cropland Remaining Cropland*, carbon stock

changes in organic soils on *Land Converted to Cropland*, and liming emissions from all managed land.
[3] Estimates includes carbon stock changes in mineral soils only; organic soil carbon stock changes and liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.
[4] Estimates include carbon stock changes in mineral soils and organic soils on *Grassland Remaining Grassland*, and carbon stock changes in organic soils on *Land Converted to Grassland*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.
[5] Estimates include carbon stock changes in mineral soils only; organic soil carbon stock changes and liming emissions for this land use/land-use change category are reported under *Grassland Remaining Grassland* and *Cropland Remaining Cropland*, respectively.
[6] Estimates include carbon stock changes on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

The application of synthetic fertilizers to forest and settlement soils in 2004 resulted in direct N_2O emissions of 6.8 Tg CO_2 Eq. (22 Gg) (Table 7-3 and Table 7-4). Direct N_2O emissions from fertilizer application increased by approximately 20 percent between 1990 and 2004.

Table 7-3: N_2O Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Land-Use Category	1990		1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**0.1**		**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
N_2O Emissions from Soils[1]	0.1		0.4	0.5	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements	**5.6**		**6.2**	**6.2**	**6.0**	**5.8**	**6.0**	**6.2**	**6.4**
N_2O Emissions from Soils[2]	5.6		6.2	6.2	6.0	5.8	6.0	6.2	6.4
Total	**5.7**		**6.5**	**6.7**	**6.4**	**6.2**	**6.4**	**6.6**	**6.8**

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in section 6.4 of the Agriculture chapter. Totals may not sum due to independent rounding.
[1] 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.
[2] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

Table 7-4: N_2O Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Land-Use Category	1990		1998	1999	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	**<1**		**1**	**2**	**1**	**1**	**1**	**1**	**1**
N_2O Emissions from Soils[1]	<1		1	2	1	1	1	1	1
Settlements Remaining Settlements	**18**		**20**	**20**	**19**	**19**	**19**	**20**	**21**
N_2O Emissions from Soils[2]	18		20	20	19	19	19	20	21
Total	**18**		**21**	**22**	**21**	**20**	**21**	**21**	**22**

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in section 6.4 of the Agriculture chapter. Totals may not sum due to independent rounding.
[1] 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.
[2] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

7.1. Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating carbon (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 carbon (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 also necessary for estimating C flux, which are:

- Harvested wood products in use.
- Harvested wood products in landfills.

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, 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 age, they continue to accumulate C until they reach maturity, at which point they store a relatively constant amount of C. 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 landfills, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the landfills.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The 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. Thus, the focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes are not 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 counts the carbon changes due to fires; however, it may not be possible to attribute the changes to the disturbance specifically. The IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (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 7-1. 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.

Figure 7-1: Forest Sector Carbon Pools and Flows

Approximately 33 percent (303 million hectares) of the U.S. land area is forested. Approximately 250 million hectares are located in the conterminous 48 states and form the basis for the estimates provided in this chapter. Seventy-nine percent of the 250 million hectares are classified as timberland, meaning they meet minimum levels of productivity and are available for timber harvest. Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forestlands. Of the remaining 51 million hectares, 16 million hectares are reserved forestlands (withdrawn by law from management for production of wood products) and 35 million hectares are lower productivity forestlands (Smith et al. 2004b). From the early 1970s to the early

1980s, forest land declined by approximately 2.4 million hectares. During the 1980s and 1990s, forest area increased by about 3.7 million hectares. These net changes in forest area represent average annual fluctuations of only about 0.1 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 can increase both the rate of growth and the eventual biomass density[2] of the forest, thereby increasing the uptake of C. Harvesting forests removes much of the aboveground C, but trees can grow on this area again and sequester C. 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 2004. Due to improvements in U.S. agricultural productivity, the rate of forest clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920, this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still affect C fluxes from forests in the East. In addition, C fluxes from eastern forests have been affected by a trend toward managed growth on private land. Collectively, these changes have nearly doubled the biomass density in eastern forests since the early 1950s. 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 landfills 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). 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 an average annual net sequestration of 627 Tg CO_2 Eq. (171 Tg C) over the period 1990 through 2004 (Table 7-5, Table 7-6, and Figure 7-2). 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 period, particularly before 1997. The increase in forest sequestration is due more to an increasing C density per area than to the increase in area of forestland. Forestland in the conterminous United States was approximately 246, 250, and 251 million hectares for 1987, 1997, and 2002, respectively, only a 2 percent increase over the period (Smith et al. 2004b). 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. National estimates are a composite of individual state surveys. Total sequestration declined by 18 percent between 1990 and 2004. Estimated sequestration in the litter carbon pool had the greatest effect on total change; the net rate of accumulation in litter decreased by 56 Tg CO_2 Eq. Aboveground biomass and soil carbon had the next largest effects on total change; the net rate of accumulation in these pools decreased by 28 and 24 Tg CO_2 Eq., respectively.

Table 7-5. Net Annual Changes in Carbon Stocks (Tg CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1998	1999	2000	2001	2002	2003	2004
Forest	**(563.3)**	**(412.7)**	**(423.2)**	**(420.2)**	**(420.2)**	**(420.2)**	**(420.2)**	**(420.2)**
Aboveground Biomass	(338.5)	(287.5)	(306.6)	(310.3)	(310.3)	(310.3)	(310.3)	(310.3)
Belowground Biomass	(64.8)	(55.1)	(59.5)	(60.3)	(60.3)	(60.3)	(60.3)	(60.3)
Dead Wood	(43.5)	(41.6)	(35.5)	(33.2)	(33.2)	(33.2)	(33.2)	(33.2)

[2] The term "biomass density" refers to the mass of vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent carbon by weight.

Litter	(82.9)	(12.4)	(24.9)	(26.6)	(26.6)	(26.6)	(26.6)	(26.6)
Soil Organic Carbon	(33.6)	(16.0)	3.2	10.1	10.1	10.1	10.1	10.1
Harvested Wood	**(210.1)**	**(206.1)**	**(214.7)**	**(210.8)**	**(213.8)**	**(214.4)**	**(215.6)**	**(217.0)**
Wood Products	(47.6)	(51.9)	(61.5)	(58.7)	(59.0)	(59.2)	(60.4)	(60.8)
Landfilled Wood	(162.4)	(154.2)	(153.1)	(152.1)	(154.8)	(155.3)	(155.1)	(156.2)
Total Net Flux	**(773.4)**	**(618.8)**	**(637.9)**	**(631.0)**	**(634.0)**	**(634.6)**	**(635.8)**	**(637.2)**

Note: 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. Forest estimates are based on interpolation and extrapolation of inventory data as described in the text 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.

Table 7-6. Net Annual Changes in Carbon Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1998	1999	2000	2001	2002	2003	2004
Forest	**(153.6)**	**(112.6)**	**(115.4)**	**(114.6)**	**(114.6)**	**(114.6)**	**(114.6)**	**(114.6)**
Aboveground Biomass	(92.3)	(78.4)	(83.6)	(84.6)	(84.6)	(84.6)	(84.6)	(84.6)
Belowground Biomass	(17.7)	(15.0)	(16.2)	(16.4)	(16.4)	(16.4)	(16.4)	(16.4)
Dead Wood	(11.9)	(11.4)	(9.7)	(9.1)	(9.1)	(9.1)	(9.1)	(9.1)
Litter	(22.6)	(3.4)	(6.8)	(7.2)	(7.2)	(7.2)	(7.2)	(7.2)
Soil Organic Carbon	(9.2)	(4.4)	0.9	2.8	2.8	2.8	2.8	2.8
Harvested Wood	**(57.3)**	**(56.2)**	**(58.5)**	**(57.5)**	**(58.3)**	**(58.5)**	**(58.8)**	**(59.2)**
Wood Products	(13.0)	(14.2)	(16.8)	(16.0)	(16.1)	(16.1)	(16.5)	(16.6)
Landfilled Wood	(44.3)	(42.1)	(41.8)	(41.5)	(42.2)	(42.3)	(42.3)	(42.6)
Total Net Flux	**(210.9)**	**(168.8)**	**(174.0)**	**(172.1)**	**(172.9)**	**(173.1)**	**(173.4)**	**(173.8)**

Note: 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. Forest estimates are based on interpolation and extrapolation of inventory data as described in the text 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.

Stock estimates for forest and harvested wood C storage pools are presented in Table 7-7. 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 7-3 shows county-average carbon densities for live trees on forestland, including both above- and belowground biomass.

Table 7-7. Carbon Stocks (Tg C) in Forest and Harvested Wood Pools

Carbon Pool	1990	1998	1999	2000	2001	2002	2003	2004	2005
Forest	**39,508**	**40,417**	**40,529**	**40,645**	**40,760**	**40,874**	**40,989**	**41,103**	**41,218**
Aboveground Biomass	14,334	14,938	15,016	15,100	15,184	15,269	15,354	15,438	15,523
Belowground Biomass	2,853	2,967	2,982	2,998	3,014	3,031	3,047	3,064	3,080
Dead Wood	2,409	2,488	2,499	2,509	2,518	2,527	2,536	2,545	2,554
Litter	4,492	4,565	4,569	4,575	4,583	4,590	4,597	4,604	4,612
Soil Organic Carbon	15,420	15,460	15,464	15,463	15,460	15,458	15,455	15,452	15,449
Harvested Wood	**1,915**	**2,365**	**2,421**	**2,480**	**2,537**	**2,595**	**2,654**	**2,713**	**2,772**
Wood Products	1,134	1,248	1,262	1,279	1,295	1,311	1,327	1,344	1,360
Landfilled Wood	781	1,117	1,159	1,200	1,242	1,284	1,327	1,369	1,411
Total Carbon Stock	**41,423**	**42,782**	**42,951**	**43,125**	**43,297**	**43,470**	**43,643**	**43,816**	**43,990**

Note: Forest C stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, or trees on non-forest land (e.g., urban trees). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest estimates are based on interpolation and extrapolation of inventory data as described in the text 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 2004 requires estimates of C stocks for 2004 and 2005.

Figure 7-2: Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools

Figure 7-3: Average Carbon Density in the Forest Tree Pool in the Conterminous United States During 2005

Methodology

The methodology described herein is consistent with IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) and the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). Estimates of net C flux from forest pools were derived from periodic and annualized inventories of forest stocks. Net changes in C stocks were interpolated between survey years. Carbon emissions from harvested wood were determined by accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion).[3] Different data sources were used to estimate the C stocks and stock change in: (1) forests (aboveground and belowground biomass, dead wood, and litter); (2) forest soils; and (3) harvested wood products. Therefore, these pools are described separately below.

Live Biomass, Dead Wood, and Litter Carbon

The estimates of non-soil forest C stocks are based on data derived from forest surveys. Forest survey data were obtained from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (Frayer and Furnival 1999, Smith et al. 2001). Surveys provide estimates of the merchantable volume of wood and other variables that are used to estimate C stocks. Estimates of temporal change such as growth, mortality, harvests, or area change are derived from repeated surveys, which were conducted every 5 to 14 years, depending on the state. Historically, the FIA program did not conduct detailed surveys of all forest land, but instead focused on land capable of supporting timber production (timberland).[4] Over time, however, individual state surveys gradually started to include reserved and less productive forest land. The C stock estimates provided here include all forest land. See Annex 3.12 for discussion of how past data gaps on these lands were filled.

Temporal and spatial gaps in surveys were addressed with the new national plot design and annualized sampling (Alerich et al. 2005), which were recently introduced by FIA. 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. Sampling is designed such that partial inventory cycles provide usable, unbiased samples of forest inventory. Thus, many states have relatively recent partial inventories, yet not all states are currently surveyed this way. All annualized surveys initiated since 1998 have followed the new national plot design for all forestland, including reserved and less productive land.

For each periodic or annualized inventory in each state, each C pool was estimated using coefficients from the FORCARB2 model (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004a). Estimates of C stocks made by the FORCARB2 coefficients at the plot level are organized somewhat differently than the standard IPCC pools reported in Table 7-7. However, the estimators are compatible with reorganizing the

[3] The wood product stock and flux estimates presented here use the production approach, meaning that they do not account for C stored in imported wood products, but do include C stored in exports, even if the logs are processed in other countries. This approach is used because it follows the precedent established in previous reports (Heath et al. 1996).

[4] 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. Productivity is at a minimum rate of 20 cubic feet of industrial wood per acre per year. The remaining portion of forest land is classified as either reserved forest land, which is forest land withdrawn from timber use by statute or regulation, or other forest land, which includes less productive forests on which timber is growing at a rate less than 20 cubic feet per acre per year. In 2002, there were about 199 million hectares of timberland in the conterminous United States, which represented 79 percent of all forest land over the same area (Smith et al. 2004b).

pools following IPCC *LULUCF Good Practice Guidance* (2003). For example, the biomass pools here include the FORCARB2 pools of live trees and understory vegetation, each of which are divided into aboveground versus belowground portions. Calculations for the tree portion of the aboveground biomass C pool were made using individual-tree or volume-to-biomass conversion factors for different types of forests, depending on the data available for each survey (Jenkins et al. 2003, Smith et al. 2003). Biomass was converted to C mass by dividing by two because dry biomass is approximately 50 percent C (IPCC/UNEP/OECD/IEA 1997). The other portion of aboveground biomass, live understory C, was estimated from inventory data using tables presented in Birdsey (1996). Litter C was estimated from inventory data using the equations presented in Smith and Heath (2002). Down dead wood was estimated using a FORCARB2 simulation and U.S. forest statistics (Smith et al. 2001).

Forest Soil Carbon

Estimates of soil organic carbon stocks are based solely on forest area and on average soil C density for each broad forest type group. Thus, any changes in soil C stocks are due to changes in total forest area or the distribution of forest types within that area. Estimates of the organic C content of soils are based on the national STATSGO spatial database (USDA 1991) and follow methods of Amichev and Galbraith (2004). These data were overlaid with FIA survey data to estimate soil C on forest land by broad forest type group.

Forest Carbon Stocks and Fluxes

The overall approach for determining forest C stock change was to estimate forest C stocks based on data from two forest surveys conducted several years apart. Carbon stocks were calculated separately for each state based on inventories available since 1990 and for the most recent inventory prior to 1990. For each pool in each state in each year, C stocks were estimated by linear interpolation between survey years. Similarly, fluxes were estimated for each pool in each state by dividing the difference between two successive stocks by the number of intervening years between surveys. Stocks and fluxes since the most recent survey were based on extrapolating estimates from the last two surveys. C stock and flux estimates for each pool were summed over all states to form estimates for the conterminous United States. Data sources and methods for estimating individual C pools are described more fully in Annex 3.12.

Harvested Wood Carbon

Estimates of C stock changes in wood products and wood discarded in landfills were based on the methods described by Skog and Nicholson (1998). Carbon stocks in wood products in use and wood products stored in landfills were estimated from 1910 onward based on historical data from the USDA Forest Service (USDA 1964, Ulrich 1989, Howard 2001), and historical data as implemented in the framework underlying the North American Pulp and Paper (NAPAP, Ince 1994), the Timber Assessment Market, and the Aggregate Timberland Assessment System Timber Inventory models (TAMM/ATLAS, Haynes 2003, Mills and Kincaid 1992). Beginning with data on annual wood and paper production, the fate of C in harvested wood was tracked for each year from 1910 through 2004, and included the change in C stocks in wood products, the change in C in landfills, and the amount of C emitted to the atmosphere (CO_2 and CH_4) both with and without energy recovery. To account for imports and exports, the production approach was used, meaning that C in exported wood was counted as if it remained in the United States, and C in imported wood was not counted.

Uncertainty

The forest survey data that underlie the forest C estimates are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. However, forest survey data that are currently available generally exclude timber stocks on most forest land in Alaska, Hawaii, and U.S. territories. For this reason, estimates have been developed only for the conterminous United States. Within the conterminous United States, the USDA Forest Service mandates that forest area data are accurate within 3 percent at the 67 percent confidence level (one standard error) per 405,000 ha (10^6 acres) of timberland (Aldrich et al. 2005). For larger areas, the uncertainty in area is concomitantly smaller. For growing stock volume data on timberland, the accuracy is targeted to be 5 or 10 percent for each 28.3 million m^3 (10^9 cubic feet) at the same confidence level. An analysis

of uncertainty in growing stock volume data for timber producing land in the Southeast by Phillips et al. (2000) found that nearly all of the uncertainty in their analysis was due to sampling rather than the regression equations used to estimate volume from tree height and diameter. Standard errors for growing stock volume ranged from 1 to 2 percent for individual states and less than 1 percent for the 5-state region. However, the total standard error for the change in growing stock volume was estimated to be 12 to 139 percent for individual states, and 20 percent for the 5-state region. The high relative uncertainty for growing stock volume change in some states was due to small net changes in growing stock volume. However, the uncertainty in volume change may be smaller than was found in this study because estimates from samples taken at different times on permanent survey plots are correlated, and such correlation reduces the uncertainty in estimates of changes in volume or C over time (Smith and Heath 2000).

In addition to uncertainty in data summarized for inventory surveys, there is uncertainty associated with the estimates of specific C stocks in those forest ecosystems. Estimates for these pools are derived from extrapolations of site-specific studies to all forest land since survey data on these pools are not generally available. Such extrapolation introduces uncertainty because available studies may not adequately represent regional or national averages. Uncertainty may also arise due to: (1) modeling errors (e.g., relying on coefficients or relationships that are not well known); and (2) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that there is little consensus from available data sets on the effect of land-use change and forest management activities (such as harvest) on soil C stocks. For example, while Johnson and Curtis (2001) found little or no net change in soil C following harvest, on average, across a number of studies, many of the individual studies did exhibit differences. Heath and Smith (2000a) noted that the experimental design in a number of soil studies limited their usefulness for determining effects of harvesting on soil C. Because soil C stocks are large, estimates need to be very precise, since even small relative changes in soil C sum to large differences when integrated over large areas. The soil C stock and stock change estimates presented herein are based on the assumption that soil C density for each broad forest type group stays constant over time. As more information becomes available, the effects of land use and of changes in land use and forest management will be better accounted for in estimates of soil C (see "Planned Improvements" below).

A quantitative uncertainty analysis was developed for the estimates of C stock and flux presented here. The analysis incorporated the information discussed above as well as preliminary uncertainty analyses of previous C estimates developed according to the same or similar methodologies as applied here (Heath and Smith 2000b, Smith and Heath 2000, Skog et al. 2004). Some additional details on the analysis are provided in Annex 3.12. The uncertainty analysis was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology—Monte Carlo Simulation technique. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-8. The 2004 flux estimate for forest C stocks is estimated to be between -794.7 and -476.3 Tg CO_2 Eq. at a 95 percent confidence level (i.e., 19 out of every 20 Monte Carlo stochastic simulations fall within this interval). This indicates a relative range of 24.7 percent below to 25.2 percent above the 2004 flux estimate of -637.2 Tg CO_2 Eq. The 95 percent confidence intervals for the two principal components of total flux are -546 to -294 Tg CO_2 Eq. for forest ecosystems and -297 to -136 Tg CO_2 Eq. for harvested wood.

Table 7-8: Tier 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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 Land Remaining Forest Land: Changes in Forest Carbon Stocks	CO_2	(637.2)	(794.7)	(476.3)	-25%	+25%

Note: Parentheses indicate negative values or net sequestration.
[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

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 since 1952. The main purpose of the Forest Inventory and Analysis 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 procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (FIA Database Retrieval System).

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 (FIA Database Retrieval System). 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).

Recalculations Discussion

The overall scheme for developing annualized estimates of C stocks based on the individual state surveys is similar to that presented in the previous Inventory (EPA 2005). The change from the previous year's methods involves the use of survey data. This year, the emphasis was on using all available state surveys in the FIADB, with RPA data used as necessary to estimate pre-1990 stocks. In the previous inventory, the FIADB was used to supplement the RPA datasets. Additionally, the FIADB has been updated over the last year.

The modifications and updates to the forest inventory data are detailed in Table A-180 in Annex 3.12 (the forest carbon methodology annex) and can be compared with forest inventories identified in a similar table in the previous U.S. Greenhouse Gas Inventory (EPA 2005). These changes are reflected in estimates of forest carbon stocks. Biomass stocks prior to 1996 were revised upward slightly, and biomass stocks after 1997 were revised downward. Stocks of dead wood were revised downward throughout, with greater changes in more recent years. The net effect is an average decrease in estimated forest carbon stocks of less than 1 percent for the period 1990 through 2003. These comparisons can be independently calculated by referring to Table A-183 in this Inventory and the analogous table in the previous Inventory (EPA 2005). Overall, these changes resulted in an average annual decrease of 206 Tg CO_2 Eq. (24 percent) in the net change in forest carbon stocks for the period 1990 through 2003.

Planned Improvements

The ongoing annualized surveys by the FIA Program will improve precision of forest C estimates as new state surveys become available (Gillespie 1999). In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent plots will substantially improve resolution of C pools at the plot level.

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). 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. However, many forests in the Eastern United States are re-growing on abandoned agricultural land. During such regrowth, soil and forest floor C stocks often increase substantially over many years or even decades, especially on highly eroded agricultural land. In addition, with deforestation, soil C stocks often decrease over many years. A new methodology is being developed to account for these changes in soil C over time. This methodology includes estimates of area changes among land uses (especially forest and agriculture), estimates of the rate of soil C stock gain with afforestation, and estimates of the rate of soil C stock loss with deforestation over time. This topic is important because soil C stocks are large, and soil C flux estimates contribute substantially to

total forest C flux, as shown in Table 7-6 and Figure 7-2.

The estimates of C stored in harvested wood products are currently being revised using more detailed wood products production and use data, and more detailed parameters on disposition and decay of products.

An additional planned improvement is to develop a consistent representation of the U.S. managed land base. Currently, the forest C and the agricultural soil C inventories are the two major analyses addressing land-use and management impacts on C stocks. The forest inventory relies on the activity data from the FIA Program to estimate anthropogenic impacts on forest land, while the agricultural soil C inventory relies on the USDA National Resources Inventory (NRI). Recent research has revealed that the classification of forest land is not consistent between the FIA and NRI, leading to some double-counting and gaps in the current forest C and agricultural soil C inventories (e.g., some areas classified as forest land in the FIA are considered rangeland in the NRI). Consequently, the land bases are in the process of being compared between the inventories to determine where overlap or gaps occur, and then ensure that the inventories are revised to have a consistent and complete accounting of land-use and management impacts across all managed land in the United States.

N_2O Fluxes from Soils (IPCC Source Category 5A1)

Of the 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 fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once at approximately 20 years). Thus, although the rate of fertilizer application for the area of forests that receives fertilizer in any given year is relatively high, average annual applications, inferred by dividing all forest land by the amount of fertilizer added to forests in a given year, is quite low. Nitrous oxide (N_2O) emissions from forest soils for 2004 were almost 7 times higher than the baseline year (1990). The trend toward increasing N_2O emissions is a result of an increase in fertilized area of pine plantations in the southeastern United States. Total 2004 forest soil N_2O emissions are roughly equivalent to 3.9 percent of the total forest soil carbon flux, and 0.06 percent of the total sequestration in standing forests, and are summarized in Table 7-9.

Table 7-9. N_2O Fluxes from Soils in Forest Land Remaining Forest Land (Tg CO_2 Eq. and Gg)

Forest Land Remaining Forest Land: N_2O Fluxes from Soils	**1990**		**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Tg CO_2 Eq.	0.1		0.4	0.5	0.4	0.4	0.4	0.4	0.4
Gg	<1		1	2	1	1	1	1	1

Note: These estimates include direct N_20 emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in section 6.4 of the Agriculture chapter. These estimates include emissions from both *Forest Land Remaining Forest Land*, and from *Land Converted to Forest Land*.

Methodology

For soils within *Forest Land Remaining Forest Land*, the IPCC Tier 1 approach was used to estimate N_2O from soils. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted for timber, and about 60 percent of national total harvested forest area are in the Southeastern United States. Consequently, 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 (North Carolina Sate Forest Nutrition Cooperative 2002). 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 midpoint of the reported range of N fertilization rates (150 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; however, it should be expected that emissions from the small areas of fertilized forests in other regions would be insubstantial because the majority of trees planted and harvested for timber are in the Southeastern United States (USDA Forest Service 2001). Area data for pine plantations receiving fertilizer in the Southeast were not available for 2002, 2003 and 2004, so data from 2001 were substituted for these years. The proportion of N additions that

volatilized from forest soils was assumed to be 10 percent of total amendments, according to the IPCC's default. The unvolatilized N applied to forests was then multiplied by the IPCC default emission factor of 1.25 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 sector.

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 carbon availability, O_2 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. The IPCC default methodology used here does not incorporate any of these variables and only accounts for variations in estimated fertilizer application rates and estimated areas of forested land receiving fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic fertilizers are captured, so applications of organic fertilizers are not accounted for here.

Uncertainties exist in the fertilizer application rates, the area of forested land receiving fertilizer, and the emission factors used to derive emission estimates. Uncertainty was calculated according to a modified IPCC Tier 1 methodology. The 95 percent confidence interval of the IPCC default emission factor for synthetic fertilizer applied to soil, according to Chapter 4 of IPCC (2000), ranges from 0.25 to 6 percent. While a Tier 1 analysis should be generated from a symmetrical distribution of uncertainty around the emission factor, an asymmetrical distribution was imposed here to account for the fact that the emission factor used was not the mean of the range given by IPCC. Therefore, an upper bound of 480 percent and a lower bound of 80 percent were assigned to the emission factor. The higher uncertainty percentage is shown below, but the lower bound reflects a truncated distribution. The uncertainties in the area of forested land receiving fertilizer and fertilization rates were conservatively estimated to be ±54 percent (Binkley 2004). The results of the Tier 1 quantitative uncertainty analysis are summarized in Table 7-10. N_2O fluxes from soils were estimated to be between 0.01 and 2.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 96 percent below and 483 percent above the 2004 emission estimate of 0.4 Tg CO_2 Eq.

Table 7-10: Tier 1 Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in Forest Land Remaining Forest Land (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Forest Land Remaining Forest Land: N_2O Fluxes from Soils	N_2O	0.4	<0.1	2.3	-96%	483%

Note: This includes direct N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Planned Improvements

Area data for southeastern pine plantations receiving fertilizer will be updated with more recent datasets, and the indirect N_2O emissions from fertilization of forests, which are currently reported in the Agriculture chapter, will be reported here.

7.2. 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.

7.3. Cropland Remaining Cropland (IPCC Source Category 5B1)

Soils contain both organic and inorganic forms of carbon (C), but soil organic carbon (SOC) stocks are the main source or sink for atmospheric CO_2 in most soils. Changes in inorganic carbon stocks are typically minor. In addition, soil organic carbon 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. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) 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. In addition, the IPCC Guidelines recommends reporting CO_2 emissions that result from liming of soils with dolomite and limestone.

Typical well-drained mineral soils contain from 1 to 6 percent organic carbon by weight, although some mineral soils that experience long-term saturation 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 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 within the first 10 years following conversion; after that, C stocks continue to decline 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 will 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 oxidation. 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 soils.

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.

The last category of the IPCC methodology addresses emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Lime 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.

For U.S. agricultural soils, CO_2 emissions and removals[5] due to changes in mineral soil C stocks are estimated using a Tier 3 approach employing a process-based model for the majority of annual crops, Tier 2 IPCC method for the remaining crops (vegetables, perennial/horticultural crops, tobacco and rice), and a Tier 1 method for additional changes in mineral soil C stocks that were not addressed with the Tier 2 or 3 approaches (i.e., variation in manure N

[5] Note that removals occur through crop and forage uptake of CO_2 into biomass C that is later incorporated into soils pools.

production and thus areas amended with manure relative to 1997, as well as gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment). Emissions from organic soils are also estimated using a Tier 2 IPCC method. Emissions from liming are estimated using a Tier 2 IPCC method that relies on national aggregate statistics of lime application and newly published research on emissions from liming of agricultural soils (West and McBride 2005).

Of the three sub-source categories, land-use and land management of mineral soils was the most important component of total net C stock change between 1990 through 2004 (see Table 7-11 and Table 7-12). In 2004, mineral soils were estimated to remove about 63.2 Tg CO_2 Eq. (17 Tg C). However, this rate of C storage in mineral soils represented about a 7 percent decline since the initial reporting year of 1990. Emissions from organic soils had the second largest flux, emitting about 30.3 Tg CO_2 Eq. (8 Tg C) in 2004. Liming emitted another 4.0 Tg CO_2 Eq. (1 Tg C) in 2004. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 28.9 Tg CO_2 Eq. (8 Tg C) in 2004, which was the average rate of change per year over the 1990 through 2004 reporting period.

Table 7-11: Net Soil C Stock Changes and Liming Emissions in Cropland Remaining Cropland (Tg CO_2 Eq.)

Soil Type	1990		1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(67.6)		(59.6)	(59.3)	(60.7)	(62.5)	(62.8)	(62.7)	(63.2)
Organic Soils[1]	29.9		30.3	30.3	30.3	30.3	30.3	30.3	30.3
Liming of Soils[2]	4.7		4.7	4.5	4.3	4.4	5.0	3.7	4.0
Total Net Flux	**(33.0)**		**(24.6)**	**(24.6)**	**(26.1)**	**(27.8)**	**(27.5)**	**(28.7)**	**(28.9)**

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.
[1] Also includes emissions due to drainage of organic soils on *Land Converted to Cropland*
[2] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Table 7-12: Net Soil C Stock Changes and Liming Emissions in Cropland Remaining Cropland (Tg C)

Soil Type	1990		1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(18.4)		(16.3)	(16.2)	(16.6)	(17.0)	(17.1)	(17.1)	(17.2)
Organic Soils[1]	8.1		8.3	8.3	8.3	8.3	8.3	8.3	8.3
Liming of Soils[2]	1.3		1.3	1.2	1.2	1.2	1.4	1.0	1.1
Total Net Flux	**(9.0)**		**(6.7)**	**(6.7)**	**(7.1)**	**(7.6)**	**(7.5)**	**(7.8)**	**(7.9)**

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.
[1] Also includes emissions due to drainage of organic soils on *Land Converted to Cropland*
[2] Also includes emissions from liming in *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Net increase in soil carbon stocks was largely due to annual cropland enrolled in the Conservation Reserve Program, 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 7-4 through Figure 7-7. The high rates of sequestration in mineral soils occurred in the Midwest, where there were the largest amounts of cropland managed with conservation tillage adoption. Rates were also high in Great Plains due to enrollment in the Conservation Reserve Program. 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.

Figure 7-4: Net C Stock Change for Mineral Soils in Cropland Remaining Cropland, 1990-1992

Figure 7-5: Net C Stock Change for Mineral Soils in Cropland Remaining Cropland, 1993-2004

Figure 7-6: Net C Stock Change for Organic Soils in Cropland Remaining Cropland, 1990-1992

Figure 7-7: Net C Stock Change for Organic Soils in Cropland Remaining Cropland, 1993-2004

The estimates presented here are restricted to C stock changes associated with land use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly N_2O from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane (CH_4) from flooded rice cultivation. These emissions are accounted for under the Agriculture sector, along with non-CO_2 greenhouse gas emissions from field burning of crop residues and CH_4 and N_2O emissions from livestock digestion and manure management.

Methodology

The following section includes a description of the methodology used to estimate changes in soil carbon stocks due to: 1) agricultural land-use and management activities on mineral soils; 2) agricultural land-use and management activities on organic soils; and 3) CO_2 emissions that result from liming of soils with dolomite and limestone for *Cropland Remaining Cropland*.

Mineral and Organic Soil Carbon Stock Changes

Soil C stock changes were estimated for agricultural land (i.e., *Cropland Remaining Cropland*, *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 ca. 400,000 points in agricultural land of the conterminous United States and Hawaii.[6] 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 collected for each NRI point on a 5-year cycle beginning in 1982. Currently, the NRI is being revised to collect data annually from a subset of points. However, at present, no additional national-level data are available after 1997.

NRI points were classified as *Cropland Remaining Cropland* if the land use had been cropland since the first year of the NRI in 1982. Cropland includes all land used to produce food or fiber, as well as forage that is harvested and used as feed (e.g., hay and silage).

A new Tier 3 model-based approach was developed to estimate C stock changes for soils used to produce a majority of annual crops in the United States (i.e., all crops except vegetables, tobacco, perennial/horticultural crops, and rice). The Century biogeochemical model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993) was used to simulate the changes in C stocks for this Tier 3 approach. The model simulates carbon (C) dynamics and other elements in cropland, grassland, forest and savanna ecosystems. It uses monthly weather data as input, along with information about soil physical properties. Input data on land use and management can be 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, temperature and water dynamics; in addition to turnover, stabilization, and mineralization of soil organic matter carbon and nutrient (N, K, S) elements.

[6] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

An IPCC Tier 2 method was used to estimate C stock changes for cropland on mineral soils that were not addressed with the Tier 3 method, in addition to emissions from drained organic soils (Ogle et al. 2003). Emissions for liming were computed using a Tier 2 methodology that relies on national aggregate statistics of lime application and newly published research on emissions from liming of agricultural soils (West and McBride 2005).

Two additional stock change calculations were made for mineral soils using Tier 1 (IPCC default) emission factors. These calculations accounted for activities that were not addressed by the Tier 3 or Tier 2 methods, including the amount of area receiving manure amendments relative to 1997,[7] and enrollment patterns in the Conservation Reserve Program after 1997.

Further elaboration on the methodology and data used to estimate stock changes from mineral and organic soils are described below and in Annex 3.13.

Mineral Soils

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated for the majority of crops (i.e., all crops except vegetable crops, tobacco, perennial/horticultural crops, and rice) using the Century biogeochemical model. National estimates were obtained by using the model to simulate historical land-use and management patterns as recorded in the USDA National Resources Inventory (NRI) survey. For these simulations of soil organic C dynamics, land-use, and management activities were grouped into inventory time periods (i.e., time "blocks") for 1980-84, 1985-89, 1990-94 and 1995-2000, using NRI data from 1982, 1987, 1992, and 1997, respectively.

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 the inventory period were estimated from data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003).

Monthly weather data, aggregated to county-scale from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) database (Daly et al. 1994), were used to drive the model simulations. Soil attributes were obtained from an NRI database, which were assigned based on field visits and soil series descriptions. Where more than one inventory point was located in the same county (i.e., same weather) and having the same land-use/management histories and soil type, data inputs to the model were identical and, therefore, these points were clustered for simulation purposes. For the 370,738 NRI points representing non-federal cropland and grassland, there were a total of 170,279 clustered points that represent the unique combinations of climate, soils, land use, and management in the modeled data set. Each NRI cluster point was run 100 times as part of the uncertainty assessment, yielding a total of over 14 million simulation runs for the analysis. Carbon stock estimates from Century were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values. Mean changes in C stocks and 95 percent confidence intervals were estimated for 1990 to 1994 and 1995 to 2000 (see Uncertainty section for more details). C stock changes from 2001 to 2004 were assumed to be similar to the 1995 to 2000 block because no additional activity data are currently available from the NRI for the latter years.

[7] The Tier 2 and 3 portions of the inventory use manure amendments based on 1997 values because application rates and the amount of land amended with manure have only been estimated for 1997 (Edmonds et al. 2003). However, manure N production and thus rates of application do vary from year to year. The effect of this variation on soil C stocks is discussed further in Annex 3.13.

Tier 2 Approach

Mineral SOC stocks were estimated using a Tier 2 method for vegetable crops, tobacco, perennial/horticultural crops and rice in 1982, 1992, and 1997. In addition, the Tier 2 method was used to estimate C stock changes for crops that were rotated with vegetables, tobacco, perennial/horticultural crops and rice. The Century model has not been fully tested to address its adequacy for estimating C stock changes associated with these crops and rotations. Data on climate, soil types, land-use and land management activity were used to classify land area to apply appropriate stock change factors. Major Land Resource Areas (MLRA) formed the base spatial unit for mapping climate regions in the United States; each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).[8] Major Land Resource Areas were classified into climate regions according to the IPCC categories using the PRISM climate-mapping program 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 the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003). 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 which 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. 2006b).[9] 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 *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (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 Inventory, 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 2000) as described above. Euliss and Gleason (2002) provided activity data on wetland restoration of Conservation Reserve Program Land. Manure N amendments over the inventory time period were based on application rates and areas amended with manure N from Edmonds et al. (2003).

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 annual change in stocks between 1982 and 1992; annual C flux for 1993 through 2004 was determined by calculating the annual change in stocks between 1992 and 1997.

Additional Mineral C Stock Change Calculations

[8] The polygons displayed in Figure 7-4 through Figure 7-7 are the Major Land Resource Areas.

[9] Stock change factors have been derived from published literature to reflect changes in tillage, cropping rotations and intensification, land-use change between cultivated and uncultivated conditions, and drainage of organic soils.

Annual C flux estimates for mineral soils between 1990 and 2004 were adjusted to account for additional C stock changes associated with variation in manure N production and thus areas amended with manure relative to 1997, as well as gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment.

Manure N application rates and cropland areas receiving manure amendments were based on 1997 estimates from Edmonds et al. (2003) for the Tier 3 Century simulations and the Tier 2 IPCC methods (described above). However, manure N production[10] varies from year to year (see Annex 3.13, Table A-204), and thus the amendment rates also vary through time. Consequently, manure N production data were used to approximate the relative amount of manure available for application based on the difference between manure N production in 1997 and other years in the reporting period. Higher manure N production relative to 1997 was assumed to increase the amount of area amended with manure, and thus lead to more soil C storage, while less manure N production relative to 1997 was assumed to reduce the amount of C added to soils from this activity. The rate of increase or decrease in soil C stocks was estimated at 0.22 metric tons C per hectare per year for the net increase or decrease in amended land area, which depended on the available manure N for application relative to 1997. The stock change rate is based on country-specific factors using the IPCC method (see Annex 3.13 for further discussion).

To estimate the impact of enrollment in the Conservation Reserve Program after 1997, the change in enrollment acreage relative to 1997 was derived based on Barbarika (2004) for 1998 through 2004, and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year. Similar to manure amendments, the stock change rate is based on country-specific factors using the IPCC method (see Annex 3.13 for further discussion).

Organic Soils

Annual C emissions from drained organic soils in cropland were estimated using methods provided in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003), except that U.S.-specific C loss rates were used in the calculations rather than default IPCC rates (Ogle et al. 2003). Similar to 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 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 2004.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology. The annual amounts of limestone and dolomite applied (see Table 7-13) 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). 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, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004, 2005; USGS 2005). To develop these data, 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).

[10] Manure N production does not include the Pasture/Range/Paddock manure for this analysis. Also, the poultry manure production values have been reduced by 4.8 percent that is used for feed.

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 2004 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2004 data, the previous year's fractions were applied to a 2004 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2005* (USGS 2005).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the U.S. Geological Survey from 1995 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 7-13: Applied Minerals (Million Metric Tons)

Mineral	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Limestone	19.01	20.31	17.98	15.61	16.69	17.30	17.48	16.54	14.88	16.89	15.86	16.10	20.45	14.73	15.71
Dolomite	2.36	2.62	2.23	1.74	2.26	2.77	2.50	2.99	6.39	3.42	3.81	3.95	2.35	2.25	2.40

Note: These numbers represent amounts applied to all agricultural land, not just *Cropland Remaining Cropland*.

Uncertainty

Uncertainty associated with the *Cropland Remaining Cropland* category includes the uncertainty associated with changes in agricultural soil carbon stocks (including both mineral and organic soils) and soil liming emissions.

Mineral and Organic Soil Carbon Stock Changes

Uncertainties in Mineral Soil C Stock Changes

Tier 3 Approach

The uncertainty analysis for the Tier 3 Century inventory had three components: 1) Monte-Carlo approach to address uncertainties in model inputs, 2) an empirically-based approach for quantifying uncertainty inherent in the structure of the Century model, and 3) scaling uncertainty associated with the NRI survey (i.e., scaling from the individual NRI points to the entire U.S. agricultural land base using the expansion factors).

For the model input uncertainty, probability distribution functions (PDFs) were developed for fertilizer rates, manure application and tillage practices. PDFs for fertilizer were based on survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure applications for specific crops was incorporated in the analysis based on total manure available for use in each county, a weighted average application rate, and the crop-specific land area amended with manure (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments – see Edmonds et al. 2003). Together with the total area for each crop within a county, this yielded a probability that a given crop at a specific NRI point would either receive manure or not in the Monte Carlo analysis. If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N

amendments (i.e., producers often reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates (ERS 1997). For tillage uncertainty, transition matrices were constructed from CTIC data to represent tillage changes for two time periods, combining the first two and the second two management blocks (i.e., 1980-1989, 1990-2000). A Monte Carlo analysis was conducted with 100 iterations in which inputs values were randomly drawn from the PDFs to simulate the soil C stocks for each NRI cluster of points (i.e., inventory points in the same county were grouped into clusters if they had the same land-use/management history and soil type) using the Century model.

An empirically-based uncertainty estimator was developed to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed effect modeling analysis comparing modeled soil C stocks with field measurements from 45 long-term agricultural experiments with over 800 treatments, representing a variety of tillage, cropping, and fertilizer management practices (Ogle et al. 2006a). The final model included variables for organic matter amendments, N fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, setting-aside cropland from production, and inclusion of bare fallow in the rotation. Each of these variables met an alpha level of 0.05, and accounted for significant biases in the modeled estimates from Century. For example, Century tended to under-estimate the influence of organic amendments on soil C storage, so a variable was added to adjust the estimate from Century. Random effects captured the dependence in time series and data collected from the same long-term experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. For each carbon stock estimate from the Monte Carlo analysis, the structural uncertainty estimator was applied to adjust the value accounting for bias and prediction error in the modeled values.

Finally, uncertainty in the land-use and management statistics from the NRI were incorporated into the analysis based on the sampling variance for the clusters of NRI points. The emission estimate for 2004 and associated 95 percent confidence interval are provided in Table 7-14. The uncertainty in the inventory estimate of 62.5 Tg CO_2 Eq. was ±3 percent for *Cropland Remaining Cropland* that were estimated using the Tier 3 model-based inventory approach.

Table 7-14: Quantitative Uncertainty Estimates for C Stock Changes in Mineral Soils occurring within Cropland Remaining Cropland that were Estimated Using the Tier 3 Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Stock Change Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland	(62.5)	(60.9)	(64.2)	-3%	+3%

Tier 2 Approach

For the Tier 2 IPCC method, a Monte Carlo approach was used to simulate a range of values with 50,000 iterations by randomly selecting values from probability distribution functions (Ogle et al. 2003). PDFs for stock change factors were derived from a synthesis of 91 published studies, which addressed the impact of management on SOC storage. Uncertainties in land-use and management activity data were also derived from a statistical analysis. The NRI has a two-stage sampling design that allowed PDFs to be constructed assuming a multivariate normal distribution accounting for dependencies in activity data. PDFs for the tillage activity data, as provided by the CTIC, were constructed on a bivariate normal distribution with a log-ratio scale, accounting for the negative dependence among the proportions of land under conventional and conservation tillage practices. PDFs for the agricultural areas receiving manure were derived assuming a normal distribution from county-scale area amendment estimates derived from the USDA Census of Agriculture (Edmonds et al. 2003). Lastly, enrollment in wetland restoration programs was estimated from contract agreements, but due to a lack of information, PDFs were constructed assuming a nominal ±50 percent uncertainty range.

The results of the uncertainty analysis for the Tier 2 portion of the analysis are summarized in Table 7-15. Mineral soils in *Cropland Remaining Cropland*, which were estimated using the Tier 2 approach, had a stock change between a gain of 4.03 to a loss of 6.6 Tg CO_2 Eq., at a 95 percent confidence level. This indicates a range of 430 percent below to 441 percent above the 2004 stock change estimate of 1.22 Tg CO_2 Eq.

Table 7-15: Quantitative Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Cropland Remaining Cropland that were Estimated Using the Tier 2 Inventory Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate[a] (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland	1.2	(4.0)	6.6	-430%	+441%

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

Additional Mineral C Stock Change Calculations

A ±50 percent uncertainty was assumed for additional adjustments to the mineral soil C stocks between 1990 and 2004, accounting for additional C stock changes associated with variation in manure N production and thus areas amended with manure relative to 1997, as well as gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment. The estimated adjustment for 2004 and associated 95 percent confidence interval are provided in Table 7-16.

Table 7-16: Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Cropland Remaining Cropland that were Estimated Using the Tier 1 Inventory Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland (Variation in Manure Amendments Relative to 1997)	(0.4)	(0.6)	(0.2)	-50%	+50%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 1997)	(1.5)	(2.3)	(0.8)	-50%	+50%

Uncertainties in Organic Soil C Stock Changes

Uncertainty in carbon emissions from organic soils were estimated in the same manner described for mineral soil using the Tier 2 method and Monte Carlo Analysis. PDFs 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 (above) for additional discussion. Organic soils in cropland were estimated to emit between 20.2 and 43.3 Tg CO_2 Eq. at a 95 percent confidence level (Table 7-17). This indicates a range of 33 percent below to 43 percent above the 2004 stock change estimate of 30.3 Tg CO_2 Eq.

Table 7-17: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Organic Soils Occurring Within Cropland Remaining Cropland (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change	Uncertainty Range Relative to Stock Change Estimate[a]

	Estimate ($Tg CO_2$ Eq.)	($Tg CO_2$ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soil C Stocks: Cropland Remaining Cropland[b]	30.3	20.2	43.3	-33%	+43%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] *Cropland Remaining Cropland* and *Land Converted to Cropland* are both reported in this section because cropland on organic soils has not been subdivided into land use/land use change categories.

Additional Uncertainties in Mineral and Organic Soil C Stock Changes

The time-series calculations were consistent for each reporting year of the inventory in terms of methodology, with the only difference in reported values stemming from the changes in land-use and management activities across U.S. agricultural land. For the Tier 2 method, the same stock change and organic soil emission factors (i.e., emission factors) were used each year in order to calculate the impact of land use and management on SOC stocks. Moreover, parameterization of the Tier 3 model was not adjusted from year to year. There is no evidence that changing management practices has a quantitatively different impact on SOC stocks over the inventory period as represented in each of these models, and it was assumed the Tier 2 stock change/emission factors and Tier 3 parameters were robust for addressing land-use and management impacts over the time series.

The agricultural soil C inventory has undergone several improvements during the past few years, such as the development of the Tier 3 inventory method to estimate mineral soil C stock changes for the majority of U.S. cropland. However, some limitations remain in the analysis. First, the current agricultural soil C inventory includes some points designated as non-agricultural land-uses in the NRI if the points were categorized as agricultural land use in either 1992 or 1997, but were urban, water, or miscellaneous non-cropland (e.g., roads and barren areas) in the other year. The impact on SOC storage that results from converting cropland to non-agricultural uses is not well-understood, and therefore, those points were not included in the calculations for mineral soils (emissions from organic soils, however, were computed for those points in the years that they were designated as an agricultural use). Similarly, the effect of aquaculture (e.g., rice cultivation followed by crayfish production in flooded fields) on soil C stocks has not been estimated due to a lack of knowledge. Second, the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, this methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

Uncertainties in CO_2 Emissions from Liming

Uncertainties in the estimates of emissions from liming result from both the emission factors and the activity data. The emission factors used for limestone and dolomite take into account the fate of carbon following application to soils, including: dissolution of liming constituents; leaching of bicarbonates into the soil and transport to the ocean; and emissions to the atmosphere (West and McBride 2005). The carbon accounting behind these emission factors entails assumptions about several uncertain factors. First, it is uncertain what fraction of agricultural lime is dissolved by nitric acid (HNO_3)—a process that releases CO_2—and what portion reacts with carbonic acid (H_2CO_3), resulting in the uptake of CO_2. The fractions can vary depending on soil pH and nitrogen fertilizer use. The second major source of uncertainty is the fraction of bicarbonate (HCO_3^-) that leaches through the soil profile and is transported into groundwater, which can eventually be transferred into rivers and into the ocean. This fraction can vary depending on the soil pH and whether calcium (Ca^{2+}) and magnesium (Mg^{2+}) liming constituents that might otherwise accompany HCO_3^-, are taken up by crops, remain in the upper soil profile, or are transported through or out of the soil profile. Finally, the emission factors do not account for the time that is needed for leaching and transport processes to occur.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this reporting could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals*

Yearbook excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

Uncertainty regarding limestone and dolomite activity data inputs were estimated at plus or minus 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 factors: 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.

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 7-18. Carbon dioxide emissions from Liming of Agricultural Soils in 2004 were estimated to be between 0.3 and 7.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 94 percent below to 96 percent above the 2004 emission estimate of 4.0 Tg CO_2 Eq.

Table 7-18: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emissions (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
Liming of Agricultural Soils[1]	CO_2	4.0	0.3	7.8	-94%	96%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[1] Also includes emissions from liming in *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

QA/QC and Verification

With the development of a Tier 3 inventory, there was considerable effort required to review inventory procedures and results. Quality control measures included checking input data, model execution scripts, and results to ensure data were properly handled through the inventory process. Errors were found in these steps and corrective actions were taken. Results were compared against field measurements and a statistical relationship was developed to assess uncertainties in the model's predictive capability (discussed under the Uncertainty section). The comparisons included over 40 long-term experiments, representing about 800 combinations of management treatments across all of the sites. Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

The key difference in the current inventory compared to previous years is in the implementation of the Tier 3 model-based approach for mineral soils, which was used to estimate soil C stock changes in Agricultural Land (i.e., *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*). This entails several fundamental differences compared with the IPCC Tier 2 method, which is based on a classification of land areas into a number of discrete states based on a highly aggregated classification of climate, soil, and management (i.e., only 6 climate regions and 7 soil types and 11 management systems occur in U.S. agricultural land. 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 2 approach. The spatial resolution of the analysis is also finer in the Tier 3 method compared to the Tier 2 inventory (3037 counties vs. 181 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. Carbon 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, which 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 2 approach in which soil C stocks change only with discrete changes in management and/or land use, rather than a longer term trend such as gradual increases in crop productivity. By addressing these additional management influences on soil C stocks, the Tier 3 approach produced C stock change estimates that were 27-50 percent greater than the Tier 2 inventory approach used to report agricultural soil C in the previous year As noted above, these estimates include the C stock changes for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*.

A small adjustment was also made in the estimation of organic soils. There are some areas included in the land base that were converted during the 1990s between agricultural land and forest, miscellaneous non-agricultural, and urban land. In past inventories, emissions from drained organic soils were reported in this inventory even during the years that the land parcels were under a non-agricultural land use. These areas were removed in this year's inventory, and a re-calculation was done to obtain a more accurate CO_2 emissions estimate from drained organic soils under agricultural management. Estimated values were reduced by about 0.6 Tg CO_2 Eq. in each reporting year.

The quantity of applied minerals reported in the previous inventory for 2003 has been revised. Consequently, the reported emissions resulting from liming in 2003 have also changed. In the previous inventory, to estimate 2003 data, the previous year's fractions were applied to a 2003 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2004* (USGS 2004). 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 2003. These values have replaced those used in the previous inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

The emission factors used in the calculation of emissions due to liming have changed since the previous inventory. Previously, the default emission factor values from the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) formed the basis for these calculations using the IPCC Tier 1 method. A study published in 2005 provides new emission factors based on a more detailed accounting of the fate of carbon following application to soils (West and McBride 2005). The IPCC Tier 1 approach assumes that all inorganic C in the applied minerals evolves to CO_2. It is more likely, though, that some of the carbon may leach through the soil and travel by rivers to the ocean, where it precipitates as $CaCO_3$. Use of these new emission factors represents a Tier 2 approach as described in IPCC (2003), which should result in a more accurate accounting of emissions due to liming.

Overall, these changes resulted in an average annual decrease of 35.7 Tg CO_2 Eq. (224 percent) in agricultural soil carbon stocks for the period 1990 through 2003.

Planned Improvements

Four major improvements are planned for the next year. The first improvement is to incorporate new land-use and management activity data from the NRI. In the current inventory, NRI data only provide land-use and management

statistics through 1997, but it is anticipated that new statistics will be released in the coming year for 2000 through 2003. This will greatly improve the accuracy of land-use and management influences on soil C in the latter part of the time series.

The second planned improvement will be to achieve consistency in N fertilization rates and organic amendments between the soil C and soil N_2O inventories. Currently, each inventory is using a combination of shared and different sources to model these activities. The goal will be to ensure that each is using the most accurate information in a consistent manner.

The third improvement is to develop a consistent representation of the U.S. managed land base. More details on this planned improvement are provided previously in the chapter under *Forest Land Remaining Forest Land*. In addition, agricultural areas on organic soils and the mineral soils, which are estimated with the Tier 2 approach, will be further subdivided into land use and land use change subcategories in order to achieve consistency with reporting requirements.

The last improvement will be to further develop the uncertainty analysis to address the uncertainty inherent in the Century model results for agricultural land (i.e., *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Land Converted to Cropland*) in the Tier 3 method. In addition, uncertainties need to be addressed in the simulation of soil C stocks for the pre-NRI time period (i.e., before 1979). In the current analysis, inventory development focused on uncertainties in the last two decades because the management activity during the most recent time periods will likely have the largest impact on current trends in soil C storage. However, legacy effects of past management can also have a significant effect on current C stock trends, as well as trajectories of those C stocks in the near future. Therefore, a planned improvement in the upcoming year is to revise the inventory to address uncertainties in management activity prior to 1979.

7.4. Land Converted to Cropland (IPCC Source Category 5B2)

Background on agricultural carbon stock changes is provided in the *Cropland Remaining Cropland* (Section 1.3.1) and will only be summarized here. 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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) recommend reporting changes in soil organic C stocks due to: 1) agricultural land-use and management activities on mineral soils; 2) agricultural land-use and management activities on organic soils, and 3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral soil C stock changes are reported here for *Land Converted to Cropland*, but stock changes associated with management of organic soils and liming are reported in *Cropland Remaining Cropland* because it was not possible to subdivide those estimates by land use and land-use change categories (see Methodology section below for additional discussion).

Land-use and management of mineral soils in *Land Converted to Cropland* led to small losses of soil C during the early 1990s but this trend was reversed over the decade, so that these soils were gaining small amounts of C through the latter part of the time series (Table 7-19 and Table 7-20). The rate of change in soil C stocks was 2.8 Tg CO_2 Eq. (0.8 Tg C) in 2004.

Table 7-19: Net Soil C Stock Changes in Land Converted to Cropland (Tg CO_2 Eq.)

Soil Type	1990	1998	1999	2000	2001	2002	2003	2004
Mineral Soils	1.5	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Organic Soils[1]	-	-	-	-	-	-	-	-
Liming of Soils[1]	-	-	-	-	-	-	-	-
Total Net Flux	**1.5**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**

[1] Emissions from liming and organic soils from *Land Converted to Cropland* are reported in *Cropland Remaining Cropland*
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.

Table 7-20: Net Soil C Stock Changes in Land Converted to Cropland (Tg C)

Soil Type	1990	1998	1999	2000	2001	2002	2003	2004
Mineral Soils	0.4	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Organic Soils[1]	-	-	-	-	-	-	-	-
Liming of Soils[1]	-	-	-	-	-	-	-	-
Total Net Flux	**0.4**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**

[1] Emissions from liming and organic soils from *Land Converted to Cropland* are reported in *Cropland Remaining Cropland*
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.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils for *Land Converted to Cropland* is displayed in Figure 7-8 and Figure 7-9. 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 sequestration in the intermountain west and Central United States. These areas were gaining C following conversion because the cropland were irrigated or receiving higher fertilizer inputs relative to the previous land use.

Figure 7-8: Net C Stock Change for Mineral Soils in Land Converted to Cropland, 1990-1992

Figure 7-9: Net C Stock Change for Mineral Soils in Land Converted to Cropland, 1993-2004

The estimates presented here are restricted to C stock changes associated with land use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly N_2O from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane (CH_4) from flooded rice cultivation. These emissions are accounted for under the Agriculture sector, along with non-CO_2 greenhouse gas emissions from field burning of crop residues and CH_4 and N_2O emissions from livestock digestion and manure management.

Methodology

The following section includes a description of the methodology used to estimate changes in soil carbon stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Cropland*.

Mineral and Organic Soil Carbon Stock Changes

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2000).[11] Land use and some management information (e.g., crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning in 1982. NRI points were classified as *Land Converted to Cropland* if the land use was currently cropland but had been converted from another use since 1982. Cropland includes all land used to produce food or fiber, as well as forage that is harvested and used as feed (e.g., hay and silage).

A new Tier 3 model-based approach was developed to estimate C stock changes for soils on *Land Converted to Cropland* used to produce a majority of annual crops in the United States (i.e., all crops except vegetables, tobacco, perennial/horticultural crops, and rice), in addition to C stock changes for grassland soils. An IPCC Tier 2 method was used to estimate C stock changes on the remaining land base for *Land Converted to Cropland* on mineral soils that were not addressed with the Tier 3 method, in addition to emission estimates for organic soils (Ogle et al. 2003). Tier 1 methods were used to estimate additional changes in mineral soil C stocks due to manure

[11] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

amendments that were not included in the Tier 2 and 3 analyses.

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.

Mineral Soils

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model for grassland converted to cropland, with the exception of vegetable crops, tobacco, perennial/horticultural crops, and rice. National estimates were obtained by using the model to simulate historical land-use change patterns as recorded in the USDA National Resources Inventory.

Tier 2 Approach

Mineral SOC stock changes were estimated using a Tier 2 Approach for land converted from forest or federal land to cropland, in addition to grassland converted to perennial, horticultural, tobacco and rice cropland. These cropland areas have not been subdivided into land use/land use change categories, which is a planned improvement for the soil C inventory. Consequently the stock changes are reported in *Cropland Remaining Cropland*.

Additional Mineral C Stock Change Calculations

Annual C stock changes for *Land Converted to Cropland* on mineral soils between 1990 and 2004 were adjusted to account for additional C stock changes associated with variation in manure N production (see Annex 3.13, Table A-195) and thus areas amended with manure relative to 1997. Additional changes are reported in the *Cropland Remaining Cropland* section because it is not possible to subdivide these changes into the individual land use/land use change categories.

Organic Soils

Annual C emission estimates from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 Approach, and reported in *Cropland Remaining Cropland* because organic soil areas have not subdivided into land use/land use change categories. Differentiating organic soils *between Land Converted to Cropland* and *Cropland Remaining Cropland* is a planned future improvement for the soil C inventory.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Land Converted to Cropland* are reported in the *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application among land use and land use change categories.

Uncertainty

Uncertainty associated with the *Land Converted to Cropland* category includes the uncertainty associated with changes in mineral soil carbon stocks.

Mineral and Organic Soil Carbon Stock Changes

Uncertainties in Mineral Soil C Stock Changes

Tier 3 Approach

The uncertainty analysis for *Land Converted to Cropland* using the Tier 3 approach 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 empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section has not been developed to estimate uncertainties in Century model results for *Land Converted to Cropland* but this is a planned improvement for the inventory. See the Tier 3 approach for mineral soils under *Cropland Remaining Cropland* for additional discussion. The inventory estimate for 2004 and associated 95 percent confidence interval are provided in Table 7-21. The uncertainty in the inventory estimate of 2.8 Tg CO_2 Eq. was -22 percent below the mean and +17 percent above the mean.

Table 7-21: Quantitative Uncertainty Estimates for C stock changes in mineral soils occurring within Land Converted to Cropland, which were estimated using the Tier 3 method (Tg CO_2 Eq. and Percent)

		Uncertainty Range Relative to Stock Change Estimate			
		(Tg CO_2 Eq.)		(%)	
Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Cropland	(2.8)	(2.2)	(3.3)	-22%	+17%

Uncertainties in Organic Soil C Stock Changes

Annual C emission estimates from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 Approach, and reported in the *Cropland Remaining Cropland* Section because organic soil areas have not subdivided into land use/land use change categories. Differentiating organic soils between *Land Converted to Cropland* and *Cropland Remaining Cropland* is a planned future improvement for the soil C inventory. See *Cropland Remaining Cropland* for discussion on the uncertainty estimation for drained organic soils in grasslands.

Additional Uncertainties in Mineral and Organic Soil C Stock Changes

Additional uncertainties are discussed in *Cropland Remaining Cropland*.

QA/QC and Verification

See *Cropland Remaining Cropland*.

Recalculations Discussion

See *Cropland Remaining Cropland*.

Planned Improvements

See *Cropland Remaining Cropland*.

7.5. Grassland Remaining Grassland (IPCC Source Category 5C1)

Background on agricultural carbon stock changes is provided in the *Cropland Remaining Cropland* section and will only be summarized here. 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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) recommend reporting changes in soil organic C stocks due to: 1) agricultural land-use and management activities on mineral soils; 2) agricultural land-use and management activities on organic soils, and 3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral and organic soil C stock

changes are reported here for *Grassland Remaining Grassland*, but stock changes associated with liming are reported in *Cropland Remaining Cropland* because it was not possible to subdivide those estimates by land use/land use change categories (see Methodology section below for additional discussion).

Land-use and management of mineral soils in *Grassland Remaining Grassland* increased soil C during the early 1990s, but this trend was reversed over the decade, with small losses of C prevailing during the latter part of the time series (see Table 7-22 and Table 7-23). Organic soils lost about the same amount of C in each year of the inventory. The overall trend shifted from small increases in soil C during 1990 to decreases during the latter years, estimated at 7.3 Tg CO_2 Eq. (2.0 Tg C) in 2004.

Table 7-22: Net Soil C Stock Changes in Grassland Remaining Grassland (Tg CO_2 Eq.)

Soil Type	1990	1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(8.8)	2.9	2.9	2.9	2.8	2.8	2.7	2.7
Organic Soils[1]	4.3	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Liming of Soils[2]	-	-	-	-	-	-	-	-
Total Net Flux	**(4.5)**	**7.5**	**7.5**	**7.4**	**7.4**	**7.4**	**7.3**	**7.3**

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.
[1] Also includes emissions due to drainage of organic soils in *Land Converted to Grassland.*
[2] Emissions from liming in *Grassland Remaining Grassland* are reported in *Cropland Remaining Cropland*.

Table 7-23: Net Soil C Stock Changes in Grassland Remaining Grassland (Tg C)

Soil Type	1990	1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(2.4)	0.8	0.8	0.8	0.8	0.8	0.7	0.7
Organic Soils[1]	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Liming of Soils[2]	-	-	-	-	-	-	-	-
Total Net Flux	**(1.2)**	**2.1**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**

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.
[1] Also includes emissions due to drainage of organic soils in *Land Converted to Grassland.*
[2] Emissions from liming in *Grassland Remaining Grassland* are reported in *Cropland Remaining Cropland*.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-10 through Figure 7-13. The highest rates of sequestration occurred in Major Land Resource Areas found in the southern portion of the United States, although these rates declined over the 1990s. Sequestration was driven by irrigation and seeding legumes. 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.

Figure 7-10: Net Soil C Stock Change for Mineral Soils in Grassland Remaining Grassland, 1990-1992

Figure 7-11: Net Soil C Stock Change for Mineral Soils in Grassland Remaining Grassland, 1993-2004

Figure 7-12: Net Soil C Stock Change for Organic Soils in Grassland Remaining Grassland, 1990-1992

Figure 7-13: Net Soil C Stock Change for Organic Soils in Grassland Remaining Grassland, 1993-2004

The estimates presented here are restricted to C stock changes associated with land use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly N_2O from

application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane (CH_4) from flooded rice cultivation. These emissions are accounted for under the Agriculture sector, along with non-CO_2 greenhouse gas emissions from field burning of crop residues and CH_4 and N_2O emissions from livestock digestion and manure management.

Methodology

The following section includes a description of the methodology used to estimate changes in soil carbon stocks due to agricultural land-use and management activities on mineral and organic soils for *Grassland Remaining Grassland*.

Mineral and Organic Soil Carbon Stock Changes

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2000).[12] Land use and some management information (e.g., irrigation. legume pastures) were collected for each NRI point on a 5-year cycle beginning in 1982. NRI points were classified as *Grassland Remaining Grassland* if the land use was grassland since 1982. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland 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.

A new Tier 3 model-based approach was developed to estimate C stock changes for mineral soils in *Grassland Remaining Grassland*. An IPCC Tier 2 method was used to estimate emissions from organic soils (Ogle et al. 2003). Tier 1 methods were used to estimate additional changes in C stocks in mineral soils due to manure amendments and sewage sludge additions to soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.13.

Mineral Soils

Tier 3 Approach

Mineral SOC 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 for grassland in different regions of the United States from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Manure application frequency to grassland and rates were estimated from data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003). Pasture/Range/Paddock (PRP) manure N additions were estimated internally in the Century model, as part of the grassland system simulations (i.e., PRP manure production was not an external input into the model). See the *Cropland Remaining Cropland* section for additional discussion on the Tier 3 methodology for mineral soils.

Tier 2 Approach

No Tier 2 method was used to estimate mineral soil C stock changes for *Grassland Remaining Grassland* because the Tier 3 Century-based method was used to estimate stock changes for the entire land base classified in this land use category.

[12] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2004 were adjusted to account for additional C stock changes associated with sewage sludge amendments.

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, and a projection for 2000, in dry mass units, were obtained from EPA reports (EPA 1993, 1999), and 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 can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is assumed to be rarely if ever amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at 0.33 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors using the IPCC method (see Annex 3.13 for further discussion).

The influence of variation in application of manure to grassland soils may also affect C stock changes in *Grassland Remaining Grassland*. However, the net impact is reported in *Cropland Remaining Cropland* because it was not possible to differentiate between manure amendments on cropland and grassland in reporting years other than 1997 but the manure is differentiated in the agricultural soil management section (i.e., Edmonds et al. 2003 only provides information on amendments for the 1997 reporting year). Note that variation in manure deposited directly onto Pasture/Range/Paddock was assumed to not increase soil C stocks. Much of the carbon in biomass is returned to soils in grassland systems, either through grazers as manure or directly in litter fall, and variation in the manure production is assumed to have a minimal impact on soil C stocks.

Organic Soils

Annual C emissions from grassland (*Grassland Remaining Grassland* and *Land Converted to Grassland*) on drained organic soils were estimated using methods provided in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003), except that U.S.-specific C loss rates were used in the calculations rather than default IPCC rates (Ogle et al. 2003). See the *Cropland Remaining Cropland* section for additional discussion on the estimation of C emissions from drained organic soils.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Grassland Remaining Grassland* are reported in the *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application among land use/land use change categories.

Uncertainty

Uncertainty associated with the *Grassland Remaining Grassland* category includes the uncertainty associated with changes in mineral and organic soil carbon stocks.

Mineral and Organic Carbon Stock Changes

Uncertainties in Mineral Soil C Stock Changes

Tier 3 Approach

The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 3 approach 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 empirically-based uncertainty estimator described in the *Cropland*

Remaining Cropland section has not been developed to estimate uncertainties in Century model results for *Grassland Remaining Grassland*, but this is a planned improvement for the inventory. See the Tier 3 approach for mineral soils under the *Cropland Remaining Cropland* section for additional discussion. The inventory estimate for 2004 and associated 95 percent confidence interval are provided in Table 7-24. The uncertainty in the inventory estimate of 3.96 Tg CO_2 Eq. was -44 percent and +39 percent.

Table 7-24: Quantitative Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Grassland Remaining Grassland, which were Estimated Using the Tier 3 Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Stock Change Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Grassland Remaining Grassland	4.0	2.2	5.5	-44%	+39%

Additional Mineral C Stock Change Calculations

A ±50 percent uncertainty was assumed for additional adjustments to the soil C stocks between 1990 and 2004 to account for additional C stock changes associated with amending grassland soils with sewage sludge. The estimated adjustment for 2004 and associated 95 percent confidence interval are provided in Table 7-25.

Table 7-25: Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Grassland Remaining Grassland, which were Estimated Using the Tier 2 Inventory Method (Tg CO_2 Eq. and Percent).

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Stock Change Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Grassland Remaining Grassland (Change in Soil C due to Sewage Sludge Amendments)	(1.3)	(1.9)	(0.6)	-50%	+50%

Uncertainties in Organic Soil C Stock Changes

Uncertainty in carbon emissions from organic soils were estimated using country specific factors and a Monte Carlo Analysis. PDFs 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. Organic soils in *Grassland Remaining Grassland* were estimated to emit between 2.2 and 7.7 Tg CO_2 Eq. at a 95 percent confidence level (Table 7-26). This indicates a range of 52 percent below to 68 percent above the 2004 flux estimate of 4.58 Tg CO_2 Eq.

Table 7-26: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Organic Soils Occurring within Grassland Remaining Grassland (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate [a] (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate [a] (%)

		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soil C Stocks: Grassland Remaining Grassland[b]	4.6	2.2	7.7	-52%	+68%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] *Grassland Remaining Grassland* and *Land Converted to Grassland* are both reported in this section because grassland on organic soils has not been subdivided into land use/land use categories.

Additional Uncertainties in Mineral and Organic Soil C Stock Changes

Minimal data exist on where and how much sewage sludge has been applied to U.S. agricultural land and the accounting of this activity appears to be much more difficult than the related-activity of using manure to amend agricultural soils. Consequently, there is considerable uncertainty in the application of sewage sludge, which is assumed to be applied to *Grassland Remaining Grassland*. However, some sludge may be applied to other agricultural land, but there is not sufficient information to further subdivide application among the agricultural land use/land use change categories. See section on "Additional Uncertainties in Soil C Stock Changes" in *Cropland Remaining Cropland* (Section 1.3.1) for discussion of other uncertainties.

QA/QC and Verification

See *Cropland Remaining Cropland*.

Recalculations Discussion

See *Cropland Remaining Cropland*.

Planned Improvements

See *Cropland Remaining Cropland*.

7.6. Land Converted to Grassland (IPCC Source Category 5C2)

Background on agricultural carbon stock changes is provided in the *Cropland Remaining Cropland* and will only be summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) recommend reporting changes in soil organic C stocks due to: 1) agricultural land-use and management activities on mineral soils; 2) agricultural land-use and management activities on organic soils, and 3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral soil C stock changes are reported here for *Land Converted to Grassland*, but stock changes associated with management of organic soils and liming are reported in *Cropland Remaining Cropland* because it was not possible to subdivide those estimates by land use and land-use change categories (see Methodology section below for additional discussion).

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks over the entire time series, which was largely caused by annual cropland converted into pasture (see Table 7-26 and Table 7-28). Stock change rates varied from 17.6 to 21.1 Tg CO_2 Eq. (4.8 to 5.8 Tg C)

Table 7-27: Net Soil C Stock Changes for Land Converted to Grassland (Tg CO_2 Eq.)

Soil Type	1990	1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(17.6)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Organic Soils[1]	-	-	-	-	-	-	-	-
Liming of Soils[2]	-	-	-	-	-	-	-	-
Total Net Flux	**(17.6)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**	**(21.1)**

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.

[1] Emissions from organic soils in *Land Converted to Grassland* are reported in *Grassland Remaining Grassland.*
[2] Emissions from liming in *Land Converted to Grassland* are reported in *Cropland Remaining Cropland.*

Table 7-28: Net Soil C Stock Changes for Land Converted to Grassland (Tg C)

Soil Type	1990		1998	1999	2000	2001	2002	2003	2004
Mineral Soils	(4.8)		(5.8)	(5.8	(5.8)	(5.8)	(5.8)	(5.8)	(5.8)
Organic Soils[1]	-		-	-	-	-	-	-	-
Liming of Soils[2]	-		-	-	-	-	-	-	-
Total Net Flux	**(4.8)**		**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**	**(5.8)**

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.
[1] Emissions from organic soils in *Land Converted to Grassland* are reported in *Grassland Remaining Grassland.*
[2] Emissions from liming in *Land Converted to Grassland* are reported in *Cropland Remaining Cropland.*

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils is displayed in Figure 7-14 and Figure 7-15. Soil C stock increased in most MLRAs for *Land Converted to Grassland*. The largest gains were in the southeast and northwest, and the amount of sequestration increased through the 1990s. The patterns were driven by conversion of annual cropland into continuous pasture.

Figure 7-14: Net Soil C Stock Change for Mineral Soils in Land Converted to Grassland, 1990-1992

Figure 7-15: Net Soil C Stock Change for Mineral Soils in Land Converted to Grassland, 1993-2004

The estimates presented here are restricted to C stock changes associated with the use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly N_2O from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane (CH_4) from flooded rice cultivation. These emissions are accounted for under the Agriculture sector, along with non-CO_2 greenhouse gas emissions from field burning of crop residues and CH_4 and N_2O emissions from livestock digestion and manure management.

Methodology

The following section includes a description of the methodology used to estimate changes in soil carbon stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Grassland*.

Mineral and Organic Soil Carbon Stock Changes

Soil C stock changes were estimated for *Land Converted to Grassland*, according to land-use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2000).[13] Land use and some management information (e.g., legume pastures, crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning in 1982. NRI points were classified as *Land Converted to Grassland* if the land use was currently grassland but had been converted from another use since 1982. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland 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.

[13] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

A new Tier 3 model-based approach was developed to estimate C stock changes for *Land Converted to Grassland* on mineral soils. An IPCC Tier 2 method was used to estimate C stock changes for portions of the land base for *Land Converted to Grassland* on mineral soils that were not addressed with the Tier 3 method, in addition to emission estimates for organic soils (Ogle et al. 2003). An IPCC Tier 2 method was used to estimate emissions from organic soils (Ogle et al. 2003). Tier 1 methods were used to estimate additional changes in mineral soil C stocks due to manure amendments that were not included in the Tier 2 and 3 analyses, and also for sewage sludge amendments. 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.

Mineral Soils

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model for cropland converted into grassland, with the exception of prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice. Similar to *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 USDA Economic Research Service Cropping Practices Survey (ERS 1997) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Manure application frequency and rates were simulated based on data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003). Pasture/Range/Paddock (PRP) manure N additions were estimated internally in the Century model, as part of the grassland system simulations (i.e., PRP manure was not an input into the model). See *Cropland Remaining Cropland* for additional discussion on the Tier 3 methodology for mineral soils.

Tier 2 Approach

Mineral SOC stock changes were estimated using a Tier 2 Approach for land converted to grassland from perennial, horticultural, tobacco and rice cropland. See *Cropland Remaining Cropland* for additional discussion on the Tier 2 methodology for mineral soils.

Additional Mineral C Stock Change Calculations

Annual C stock changes for *Land Converted to Grassland* on mineral soils between 1990 and 2004 were adjusted to account for additional C stock changes associated with sewage sludge amendments to soils, variation in manure N production (see Annex 3.13, Table A-204) and thus areas amended with manure relative to 1997. Additional changes due to sewage sludge amendments are reported in the *Grassland Remaining Grassland* because it is not possible to subdivide these changes into the individual land use/land use change categories. Similarly, additional changes due to manure amendments were reported in *Cropland Remaining Cropland*. See *Grassland Remaining Grassland* and *Cropland Remaining Cropland* for further elaboration on the methods used to estimate these additional changes in mineral soil C stocks.

Organic Soils

Annual C emission estimates from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 Approach, and reported in the *Grassland Remaining Grassland* Section because organic soil areas have not been subdivided into land use/land use change categories. Differentiating organic soils between *Land Converted to Grassland* and *Grassland Remaining Grassland* is a planned future improvement for the soil C inventory. See *Grassland Remaining Grassland* for discussion on the estimation of C emissions from drained organic soils.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Land Converted to Grassland* are reported in the *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application

among land use and land-use change categories.

Uncertainty

Uncertainty associated with the *Land Converted to Grassland* category includes the uncertainty associated with changes in mineral soil carbon stocks.

Mineral and Organic Soil Carbon Stock Changes

Uncertainties in Mineral Soil C Stock Changes

Tier 3 Approach

The uncertainty analysis for *Land Converted to Grassland* using the Tier 3 approach was based on the same method described *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section 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. See the Tier 3 approach for mineral soils under *Cropland Remaining Cropland* for additional discussion. The inventory estimate for 2004 and associated 95 percent confidence interval are provided in Table 7-29. The uncertainty in the inventory estimate of -16.0 Tg CO_2 Eq. was ±1 percent.

Table 7-29: Quantitative Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Land Converted to Grassland, which were Estimated Using the Tier 3 Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Stock Change Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Grassland	(16.0)	(15.8)	(16.1)	-1%	+1%

Tier 2 Approach

The uncertainty analysis for *Land Converted to Grassland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*. See the Tier 2 section under minerals soils in *Cropland Remaining Cropland* section for additional discussion. Mineral soils on *Land Converted to Grassland*, which were estimated using the Tier 2 approach, had a carbon stock change between -2.9 and -7.3 Tg CO_2 Eq. at a 95 percent confidence level (Table 7-30). This indicates a range of 43 percent below to 43 percent above the 2004 stock change estimate of -5.1 Tg CO_2 Eq.

Table 7-30: Quantitative Uncertainty Estimates for C Stock Changes in Mineral Soils Occurring within Land Converted to Grassland that were Estimated Using the Tier 2 Inventory Method (Tg CO_2 Eq. and Percent)

Source	2004 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate[a] (Tg CO_2 Eq.)		Uncertainty Range Relative to Stock Change Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Grassland	(5.1)	(7.3)	(2.9)	-43%	+43%

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

Uncertainties in Organic Soil C Stock Changes

Annual C emission estimates from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 Approach, and reported in the *Grassland Remaining Grassland* Section because organic soil areas have not subdivided into land use/land use change categories. Differentiating organic soils between *Land Converted to Grassland* and *Grassland Remaining Grassland* is a planned future improvement for the soil C inventory. See *Grassland Remaining Grassland* for discussion on the uncertainty estimation for drained organic soils in grassland.

Additional Uncertainties in Mineral and Organic Soil C Stock Changes

Additional uncertainties are discussed in *Cropland Remaining Cropland*.

QA/QC and Verification

See *Cropland Remaining Cropland*.

Recalculations Discussion

See *Cropland Remaining Cropland*.

Planned Improvements

See *Cropland Remaining Cropland*.

7.7. Settlements Remaining Settlements

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (IPCC Source Category 5E1)

As is the case with carbon in landfilled forest products, carbon contained in landfilled yard trimmings and food scraps can be stored for very long periods. In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps comprise a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are discarded in landfills. However, both the amount of yard trimmings and food scraps collected annually and the fraction that is landfilled have declined over the last decade. In 1990, nearly 51 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection or taken to disposal or composting facilities) (EPA 2005). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 18 percent decrease in the amount of yard trimmings collected. 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 35 percent in 2003 (the most recent year for which data are available; 2004 values are assumed equal to 2003). There is considerably less centralized composting of food scraps; generation has grown by 32 percent since 1990, though the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 78 percent in 2003. Overall, there has been a decrease in the yard trimmings and food scrap landfill disposal rate, which has resulted in a decrease in the rate of landfill carbon storage to 9.3 Tg CO_2 Eq. in 2004 from 24.5 Tg CO_2 Eq. in 1990 (Table 7-31 and Table 7-32).

Table 7-31: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	1990		1997	1998	1999	2000	2001	2002	2003	2004
Yard Trimmings	**(21.7)**		**(8.7)**	**(8.0)**	**(6.9)**	**(5.6)**	**(5.8)**	**(6.1)**	**(6.3)**	**(6.4)**
Grass	(2.4)		(0.8)	(0.8)	(0.6)	(0.5)	(0.6)	(0.6)	(0.7)	(0.7)
Leaves	(9.8)		(3.9)	(3.6)	(3.0)	(2.5)	(2.5)	(2.6)	(2.7)	(2.8)
Branches	(9.6)		(4.0)	(3.7)	(3.2)	(2.7)	(2.7)	(2.8)	(2.9)	(2.9)
Food Scraps	**(2.8)**		**(2.6)**	**(2.9)**	**(2.9)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.1)**	**(2.9)**
Total Net Flux	**(24.5)**		**(11.3)**	**(10.9)**	**(9.8)**	**(8.9)**	**(9.0)**	**(9.3)**	**(9.4)**	**(9.3)**

Note: Totals may not sum due to independent rounding.

Table 7-32: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990		1997	1998	1999	2000	2001	2002	2003	2004
Yard Trimmings	**(5.9)**		**(2.4)**	**(2.2)**	**(1.9)**	**(1.5)**	**(1.6)**	**(1.7)**	**(1.7)**	**(1.7)**
Grass	(0.6)		(0.2)	(0.2)	(0.2)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.7)		(1.1)	(1.0)	(0.8)	(0.7)	(0.7)	(0.7)	(0.7)	(0.8)
Branches	(2.6)		(1.1)	(1.0)	(0.9)	(0.7)	(0.7)	(0.8)	(0.8)	(0.8)
Food Scraps	**(0.8)**		**(0.7)**	**(0.8)**	**(0.8)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.8)**	**(0.8)**
Total Net Flux	**(6.7)**		**(3.1)**	**(3.0)**	**(2.7)**	**(2.4)**	**(2.5)**	**(2.5)**	**(2.6)**	**(2.5)**

Note: Totals may not sum due to independent rounding.

Methodology

Estimates of net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years. Carbon stock estimates were calculated by determining the mass of landfilled carbon resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the portion of carbon landfilled in previous years that decomposed.

To determine the total landfilled carbon 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 carbon storage factor of the landfilled yard trimmings and food scraps adjusted by mass balance; and 4) the rate of decomposition of the degradable carbon. 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 carbon 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: 2003 Facts and Figures* (EPA 2005). That report provides data for 1960, 1970, 1980, 1990, 1995, and 2000 through 2003. To provide data for some of the missing years in the 1990 through 1999 period, two earlier reports were used (*Characterization of Municipal Solid Waste in the United States: 1998 Update* (EPA 1999), and *Municipal Solid Waste in the United States: 2001 Facts and Figures* (EPA 2003)). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Values for 2004 are assumed to be equal to values for 2003. The reports do not subdivide discards of individual materials into volumes landfilled and combusted, although they provide an estimate of the proportion of overall wastestream discards managed in landfills and combustors (i.e., ranging from 81 percent and 19 percent respectively in 1990, to 80 percent and 20 percent in 2000).

The amount of carbon 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) carbon 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 carbon contents were determined by Barlaz (1998; 2005) (Table 7-33).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate. As demonstrated by Barlaz (1998; 2005), a portion of the initial carbon resists decomposition and is essentially persistent in the landfill environment; the modeling approach applied here builds on his findings. Barlaz (1998; 2005) 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 carbon 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 carbon content; the carbon remaining in the solid sample can be expressed as a

proportion of initial carbon (shown in the row labeled "CS" in Table 7-33).

For purposes of simulating U.S. landfill carbon flows, the proportion of carbon stored is assumed to persist in landfills; the remaining portion is assumed to degrade (and results in emissions of CH_4 and CO_2; the methane emissions resulting from decomposition of yard trimmings and food scraps are counted in the Waste chapter). The degradable portion of the carbon is assumed to decay according to first order kinetics. Grass and food scraps are assumed to have a half-life of 5 years; leaves and branches are assumed to have a half-life of 20 years.

For each of the four materials (grass, leaves, branches, food scraps), the stock of carbon in landfills for any given year is calculated according to the following formula:

$$LFC_{i,t} = \sum_{n} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k \times (t - n)}]\}$$

where,

t = the year for which carbon stocks are being estimated,
$LFC_{i,t}$ = the stock of carbon in landfills in year *t*, for waste *i* (grass, leaves, branches, food scraps)
$W_{i,n}$ = the mass of waste *i* disposed in landfills in year *n*, in units of wet weight
n = the year in which the waste was disposed, where $1960 \leq n \leq t$
MC_i = moisture content of waste *i*,
CS_i = the proportion of initial carbon that is stored for waste *i*,
ICC_i = the initial carbon content of waste *i*,
e = the natural logarithm, and
k = the first order rate constant for waste *i*, and is equal to 0.693 divided by the half-life for decomposition.

For a given year *t*, the total stock of carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials. The annual flux of carbon 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 carbon placed in a landfill in year n is tracked for each year t through the end of the inventory period (2004). For example, disposal of food scraps in 1960 resulted in depositing about 1,140,000 metric tons of carbon. Of this amount, 16 percent (180,000 metric tons) is persistent; the remaining 84 percent (960,000 metric tons) is degradable. By 1965, half of the degradable portion (480,000 metric tons) decomposes, leaving a total of 660,000 metric tons (the persistent portion, plus the remaining half of the degradable portion).

Continuing the example, by 2004, the total food scraps carbon originally disposed in 1960 had declined to 181,000 metric tons (i.e., virtually all of the degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed in subsequent years (1961 through 2004), the total landfill carbon from food scraps in 2004 was 30.5 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2004, yielding a value of 232.6 million metric tons (as shown in Table 7-34). In exactly the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 7-32) is the difference in the landfill carbon stock for a given year and the stock in the preceding year. For example, the net change in 2004 shown in Table 7-32 (2.5 Tg C) is equal to the stock in 2004 (232.6 Tg C) minus the stock in 2003 (230.0 Tg C).

When applying the carbon storage data reported by Barlaz (1998), an adjustment was made to the reported values so that a perfect mass balance on total carbon could be attained for each of the materials. There are four principal elements in the mass balance:

- Initial carbon content (ICC, measured),
- Carbon output as methane (CH_4-C, measured),
- Carbon output as carbon dioxide (CO_2-C, not measured), and

- Residual stored carbon (CS, measured).

In a simple system where the only carbon fates are CH_4, CO_2, and carbon storage, the following equation is used to attain a mass balance:

$$CH_4\text{-}C + CO_2\text{-}C + CS = ICC$$

The experiments by Barlaz and his colleagues (Barlaz 1998, Eleazer et al. 1997) did not measure CO_2 outputs in experiments. However, if the only decomposition is anaerobic, then $CH_4\text{-}C = CO_2\text{-}C$.[14] Thus, the system should be defined by:

$$2 \times CH_4\text{-}C + CS = ICC$$

The carbon outputs (=$2 \times CH_4$-C + CS) were less than 100 percent of the initial carbon mass for food scraps, leaves, and branches (75, 86, and 90 percent, respectively). For these materials, it was assumed that the unaccounted for carbon had exited the experiment as CH_4 and CO_2, and no adjustment was made to the measured value of CS.

In the case of grass, the outputs were slightly more (103 percent) than initial carbon mass. To resolve the mass balance discrepancy, it was assumed that the measurements of initial carbon content and methane mass were accurate. Thus, the value of CS was calculated as the residual of ICC (initial carbon content) minus ($2 \times CH_4$-C). This adjustment, reduced the carbon storage value from the 71 percent reported by Barlaz (1998) to 68 percent (as shown in Table 7-33).

Table 7-33: Moisture Content (%), Carbon Storage Factor, Initial Carbon Content (%), Proportion of Initial Carbon Sequestered (%), 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 carbon C stored	68%	72%	77%	16%
Initial Carbon Content (%)	45	42	49	51
Half-life (years)	5	20	20	5

Table 7-34: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	1990		1997	1998	1999	2000	2001	2002	2003	2004
Yard Trimmings	**161.3**		**189.7**	**191.9**	**193.7**	**195.3**	**196.9**	**198.5**	**200.3**	**202.0**
Grass	18.2		21.1	21.4	21.5	21.7	21.8	22.0	22.2	22.4
Leaves	72.8		85.5	86.5	87.3	88.0	88.7	89.4	90.2	90.9
Branches	70.3		83.0	84.0	84.9	85.6	86.4	87.1	87.9	88.7
Food Scraps	**20.3**		**24.7**	**25.5**	**26.3**	**27.2**	**28.1**	**28.9**	**29.8**	**30.5**
Total Carbon Stocks	**181.6**		**214.4**	**217.4**	**220.1**	**222.5**	**224.9**	**227.5**	**230.0**	**232.6**

Note: Totals may not sum due to independent rounding.

[14] The molar ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins as $C_{3.2}H_5ON_{0.86}$, the molar ratio is 1.65 CH_4 per 1.55 CO_2 (Barlaz et al. 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

Uncertainty

The estimation of carbon storage in landfills is directly related to the following yard trimming and food scrap data and factors: disposal in landfills per year (tons of carbon), initial carbon content, moisture content, decomposition rate (half-life), and proportion of carbon stored. The carbon storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are uncertainties associated with each of these factors.

The uncertainty ranges were assigned based on expert judgment and are assumed to be uniformly distributed around the inventory estimate (e.g., ±10 percent), except for the values for decomposition rate, proportion of carbon stored, and moisture content for branches.

The uncertainty ranges associated with the input variables for the proportion of grass and leaves in yard trimmings, as well as the initial carbon content and moisture content for grass, leaves, and food scraps (all expressed as percentages in the calculations for the inventory) were plus or minus 10 percent. For the moisture content of branches (where the inventory estimate is 10 percent), the uncertainty range was assumed to be 5 to 30 percent.

The uncertainty ranges associated with the disposal of grass, leaves, branches, and food scraps were bound at 50 percent to 150 percent times the inventory estimates. The half-life of grass and food scraps were assumed to range from 1 to 20 years, and the half-lives of leaves and branches were assumed to range from 5 to 30 years. Finally, the proportion of carbon stored in grass, leaves, branches, and food scraps was assumed to vary plus or minus 20 percent from the best estimate, with an upper bound of 100 percent and a lower bound of 0 percent.

A Monte Carlo (Tier 2) uncertainty analysis was then applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-35. Total yard trimmings and food scraps CO_2 flux in 2004 was estimated to be between -16.3 and -5.7 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 75 percent below to 39 percent above the 2004 flux estimate of -9.3 Tg CO_2 Eq.

Table 7-35: 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	2004 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	(9.3)	(16.3)	(5.7)	-75%	+39%

[a]Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net carbon sequestration.

The uncertainty of the landfilled carbon storage estimate arises from the disposal data and the factors applied to the following data.

Disposal per Year (tons of carbon)

A source of uncertainty affecting CO_2 sequestration is the estimate of the tonnage of yard trimmings and food scraps which are disposed of in landfills each year. Of all the individual inputs tested for sensitivity in the uncertainty analysis, net carbon storage in landfills is most sensitive to the estimate of the food scrap disposal rate. The estimates for yard trimming and food scrap disposal in landfills are determined using data from EPA (1999, 2002, 2003) estimates of materials generated, discarded, and combusted, which carry considerable uncertainty associated with the wastestream sampling methodology used to generate them.

Moisture Content and Initial Carbon Content

Moisture content, and to a lesser extent carbon content, vary widely. Moisture content for a given sample of waste can be affected by the precipitation conditions when the waste is placed at the curb for collection, as well as the status and condition of the landfill cover. Carbon content (on a dry weight basis) is a function of the specific waste constituents (e.g., oak leaves versus pine needles or banana peels versus bacon grease), which in turn vary temporally, geographically, and demographically (i.e., characteristics of households in the wasteshed).

Decomposition Rate

Although several investigators have made estimates of the decomposition rate of mixed solid waste in a landfill environment, there are no known studies of decomposition rates for individual materials in actual landfills, and thus the inventory estimate is based on assumed values. The uncertainty analysis indicates that the results are sensitive to decomposition rates, especially the food scraps half-life, and thus the decomposition rates introduce considerable uncertainty into the analysis.

Proportion of Carbon Stored

The estimate of the proportion of carbon stored is based on a set of experiments measuring the amount of carbon persisting in conditions promoting decomposition. Because these experiments have only used conditions conducive to decomposition, they are more likely to underestimate than to overestimate carbon storage. Nonetheless, measurement error may be the dominant source of uncertainty, and so the uncertainty analysis used symmetrical values (plus or minus 20 percent) as inputs.

Recalculations Discussion

The principal change this year is the addition of newly generated experimental results for leaves, provide by Barlaz (2005). This has the effect of reducing the overall estimate of landfill carbon storage, as the new results for leaves indicate more decomposition than the earlier values.

This year's inventory also reflects changes in the estimate for carbon storage from grass, reflecting the mass balance constraint described above in the methodology section. This mass balance constraint had not been applied in previous years.

Overall, the recalculations have the effect of reducing carbon stocks by about 4 percent in this year's inventory compared to those reported last year.

Planned Improvements

Future work may evaluate the potential contribution of inorganic carbon to landfill sequestration and to assure consistency between the estimates of carbon storage described in this chapter and the estimates of landfill CH_4 emissions described in the Waste chapter.

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. (in review)). With an average tree canopy cover of 27.1 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 72.1 Tg CO_2 Eq. (19.7 Tg C) over the period from 1990-2004. Total sequestration increased by 50 percent between 1990 and 2004 due to increases in urban land area. Data on carbon storage and urban tree coverage were collected throughout the 1990s, and have been applied to the entire time series in this report. Annual estimates of CO_2 flux were developed based on periodic U.S. Census data on urban area (Table 7-36).

Net carbon 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 carbon 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 carbon density than forested areas (Nowak and Crane 2002).

Table 7-36: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(58.7)	(16.0)
1998	(73.3)	(20.0)
1999	(77.0)	(21.0)
2000	(77.0)	(21.0)
2001	(80.7)	(22.0)
2002	(80.7)	(22.0)
2003	(84.3)	(23.0)
2004	(88.0)	(24.0)

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 the IPCC *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2003), although sufficient data are not yet available to determine interannual changes in carbon 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.

Nowak and Crane (2002) developed estimates of annual gross carbon sequestration from tree growth and annual gross carbon emissions from decomposition for ten U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Jersey City, NJ; New York, NY; Oakland, CA; Philadelphia, PA; Sacramento, CA; and Syracuse, NY. The gross carbon sequestration estimates were derived from field data that were collected in these ten cities during the period from 1989 through 1999, including tree measurements of stem diameter, tree height, crown height, and crown width, and information on location, species, and canopy condition. The field data were converted to annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition (forested, park-like, and open growth) by applying allometric equations, a root-to-shoot ratio, moisture contents, a carbon content of 50 percent (dry weight basis), an adjustment factor to account for smaller aboveground biomass volumes (given a particular diameter) in urban conditions compared to forests, an adjustment factor to account for tree condition (fair to excellent, poor, critical, dying, or dead), and annual diameter and height growth rates. The annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition were then scaled up to city estimates using tree population information. The field data from the 10 cities, some of which are unpublished, are described in Nowak and Crane (2002) and references cited therein. The allometric equations were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), and the adjustments to account for smaller volumes in urban conditions were 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). Adjustment factors to account for tree condition were based on percent crown dieback (Nowak and Crane 2002). Tree growth rates were also 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.

Annual gross carbon emission estimates were derived by applying estimates of annual mortality and condition, and

assumptions about whether dead trees were removed from the site, to carbon stock estimates. These values were derived as intermediate steps in the sequestration calculations, and different decomposition rates were applied to dead trees left standing compared with those removed from the site. The annual gross carbon emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Assumptions about whether dead trees would be removed from the site were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak and Crane 2002).

National annual net carbon sequestration by urban trees was estimated from estimates of gross and net sequestration from seven of the ten cities, and urban area and urban tree cover data for the United States. Annual net carbon sequestration estimates were derived for seven cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[15] The urban areas are based on 1990 and 2000 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent "urban places," which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the "urban places" category with a new category of urban land called an "urban cluster," which included areas with more than 500 people per square mile. Urban land area has increased by approximately 36 percent from 1990 to 2000; Nowak et al. (in review) 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). National urban tree cover area was estimated by Nowak et al. (2002) to be 27.1 percent of urban areas.

The gross and net carbon 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 (0.30 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 (0.70). The urban tree cover area estimates for each of the 10 cities and the United States were obtained from Dwyer et al. (2000) and Nowak et al. (in review).

Table 7-37: Carbon Stocks (Metric Tons C), Annual Carbon Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual Carbon Sequestration per Area of Tree Cover (kg C/m^2 cover-yr) for Ten 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
New York, NY	1,225,200	38,400	20,800	20.9	0.23	0.12
Atlanta, GA	1,220,200	42,100	32,200	36.7	0.34	0.26
Sacramento, CA	1,107,300	20,200	NA	13.0	0.66	NA
Chicago, IL	854,800	40,100	NA	11.0	0.61	NA
Baltimore, MD	528,700	14,800	10,800	25.2	0.28	0.20
Philadelphia, PA	481,000	14,600	10,700	15.7	0.27	0.20
Boston, MA	289,800	9,500	6,900	22.3	0.30	0.22
Syracuse, NY	148,300	4,700	3,500	24.4	0.30	0.22
Oakland, CA	145,800	NA	NA	21.0	NA	NA
Jersey City, NJ	19,300	800	600	11.5	0.18	0.13

NA = not analyzed

[15] Three cities did not have net estimates.

Uncertainty

The only quantifiable uncertainty associated with changes in C stocks in urban trees was sampling, as reported by Nowak and Crane (2002). The average standard deviation for urban tree carbon storage was 27 percent of the mean carbon storage on an area basis. Additionally, a 5 percent uncertainty was associated with national urban tree covered area. These estimates are based on field data collected in ten U.S. cities, and uncertainty in these estimates increases as they are scaled up to the national level.

There is additional uncertainty associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there may be some overlap between the urban tree carbon estimates and the forest tree carbon estimates. However, both the omission of urban soil carbon flux and the potential overlap with forest carbon are believed to be relatively minor (Nowak 2002). Because these are inestimable, they are not quantified as part of this analysis.

The results of the Tier 1 quantitative uncertainty analysis are summarized in Table 7-38. Net C flux from changes in C stocks in urban trees was estimated to be between -120.5 and -55.5 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 37 percent above and below the 2004 flux estimate of -88.0 Tg CO_2 Eq.

Table 7-38: Tier 1 Quantitative Uncertainty Estimates for Net C Flux from Changes in Carbon Stocks in Urban Trees (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Changes in C Stocks in Urban Trees	CO_2	(88.0)	(120.5)	(55.5)	-37%	+37%

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

The net carbon flux resulting from urban trees was calculated using estimates of gross and net carbon sequestration estimates 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 the 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 2002).

Recalculations Discussion

New estimates of urban area available in the 2000 U.S. Census have made it possible to develop estimates of net C flux in urban trees over the time series 1990 to 2004. Previous Inventory estimates relied solely on 1990 U.S. Census data, which were applied over the entire time series from 1990 to 2004. The new 2000 estimates were applied to the calculation of net C flux in that year. Additionally, 1990 and 2000 estimates were used as the basis for interpolating and extrapolating, respectively, estimates of urban area in the intervening years (1991 through 1999) and subsequent years (2001 through 2004). New 1990 estimates for urban area were also used in the current Inventory. Estimates used in previous Inventories did not include Alaska and Hawaii. Nowak et al. (in review) provide new 1990 estimates that include Alaska and Hawaii. Net C flux for the entire time series 1990 through 2004 was calculated based on these new estimates of urban area. These changes resulted in a change in emissions estimates for every year except 1990 and 1991. Estimates of net C flux from urban trees changed an average of 21 percent over the period from 1990 to 2003 relative to the previous report.

N_2O Fluxes from Soils (IPCC Source Category 5E1)

Of the fertilizers applied to soils in the United States, approximately 10 percent are applied to lawns, golf courses,

and other landscaping occurring within settled areas. Application rates are less 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 2004, N_2O emissions from this source were 6.4 Tg CO_2 Eq. (20.8 Gg). There was an overall increase of 15 percent over the period from 1990 through 2004 due to a general increase in the application of synthetic fertilizers. 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 7-39.

Table 7-39: N_2O Fluxes from Soils in Settlements Remaining Settlements (Tg CO_2 Eq. and Gg)

Settlements Remaining Settlements: N_2O Fluxes from Soils	1990	1998	1999	2000	2001	2002	2003	2004
Tg CO_2 Eq.	5.6	6.2	6.2	6.0	5.8	6.0	6.2	6.4
Gg	18	20	20	19	19	19	20	21

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 applied to turf grass annually through the application of synthetic commercial fertilizers and the amount of N in sewage sludge applied to non-agricultural land and in surface disposal of sewage sludge. Nitrogen applications to turf grass are assumed to be 10 percent of the total synthetic fertilizer used in the United States (Qian 2004). Total synthetic fertilizer applications were derived from fertilizer statistics (TVA 1991, 1992, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b, 2002, 2003, 2004, 2005) and a recent AAPFCO database (AAPFCO 2000a). Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and nitrogen content (see Annex 3.11 for further detail). The IPCC default volatilization factor for synthetic fertilizer N applied (10 percent) was used to calculate the amount of unvolatilized N applied to turf grass through synthetic fertilizers (IPCC/UNEP/OECD/IEA 1997). The IPCC default volatilization factor for N excreted by livestock (20 percent) was used to calculate the amount of unvolatilized N applied to non-agricultural land through sewage sludge applications and resulting from surface disposal of sewage sludge (IPCC/UNEP/OECD/IEA 1997).[16] The total amount of unvolatilized N resulting from these sources was multiplied by the IPCC default emission factor (1.25 percent) to estimate direct N_2O emissions. The volatilized and leached/runoff proportion, calculated with the IPCC default volatilization factors (10 or 20 percent, respectively, for synthetic or organic fertilizers) and leaching/runoff factor (30 percent), was included with the total N contributions to indirect emissions, as reported in the N_2O Emissions from Agricultural Soil Management source category of the Agriculture sector.

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 carbon availability, O_2 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 used here does not incorporate any of these variables and only accounts for variations in national fertilizer application rates. All settlement soils are treated equivalently under this methodology. Uncertainties exist in both the fertilizer application rates and the emission factors used to derive emission estimates.

The 95 percent confidence interval for the IPCC's default emission factor for synthetic fertilizer applied to soil

[16] Although the IPCC default factor of 20 percent is for the application of livestock manure, it is assumed to be a more accurate representation of volatilization for organic N additions when compared to the volatilization factor for synthetic N additions.

ranges from 0.25 to 6 percent, according to Chapter 4 of IPCC (2000). While a Tier 1 analysis should be generated from a symmetrical distribution of uncertainty around the emission factor, an asymmetrical distribution was imposed here to account for the fact that the emission factor used was not the mean of the range given by IPCC. Therefore, an upper bound of 480 percent and a lower bound of 80 percent were assigned to the emission factor. The uncertainty in the amount of synthetic fertilizer N applied to settlement soils was conservatively estimated to be 50 percent (Qian 2004). The results of the Tier 1 quantitative uncertainty analysis are summarized in Table 7-40. N_2O emissions from soils in *Settlements Remaining Settlements* in 2004 were estimated to be between 0.4 and 37.6 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 94 percent below to 483 percent above the 2004 emission estimate of 6.5 Tg CO_2 Eq.

Table 7-40: Tier 1 Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (Tg CO_2 Eq. and Percent)

Source	Gas	Year 2004 Emissions (Tg CO_2 Eq.)	Uncertainty Range Relative to 2004 Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	6.5	0.4	37.6	94%	483%

Recalculations Discussion

The 2003 data were updated from the AAPFCO *Commercial Fertilizers 2004* report (2005). This change resulted in a one percent decrease in the emissions estimates for that year. The inclusion of N in sewage sludge applied to non-agricultural land and surface disposal of sewage sludge is new to the current Inventory. These changes resulted in an average change of about 1 percent over the period from 1990 to 2003.

Planned Improvements

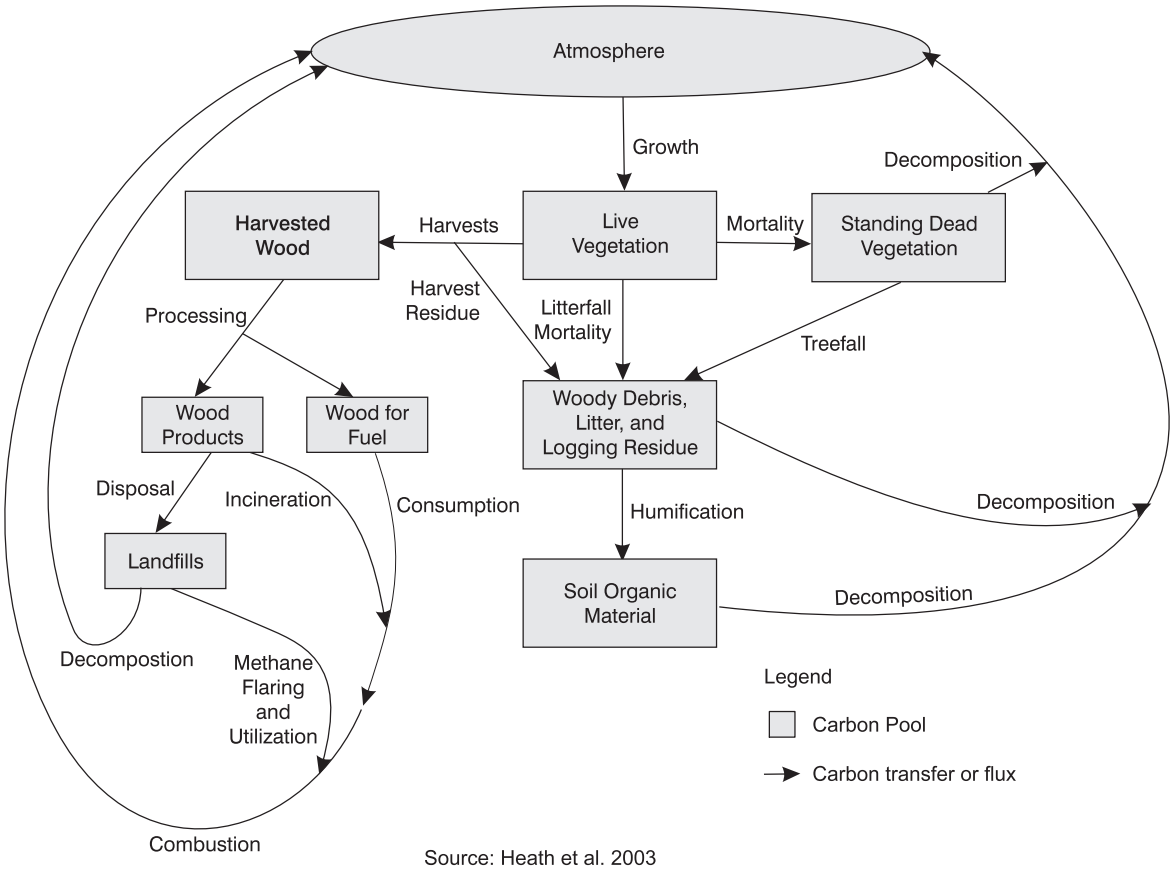
The indirect N_2O emissions from fertilization of settlements, which are currently reported in the Agriculture chapter, will be reported here. In addition, the process-based model DAYCENT, which was used to estimate N_2O emissions from cropped soils this year, could also be used to simulate direct emissions as well as volatilization and leaching/runoff from settlements. DAYCENT has been parameterized to simulate turf grass. State-level settlement area data is available from the National Resource Inventory.

7.8. 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.

Figure 7-1

Forest Sector Carbon Pools and Flows



Source: Heath et al. 2003

Note: Boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere.

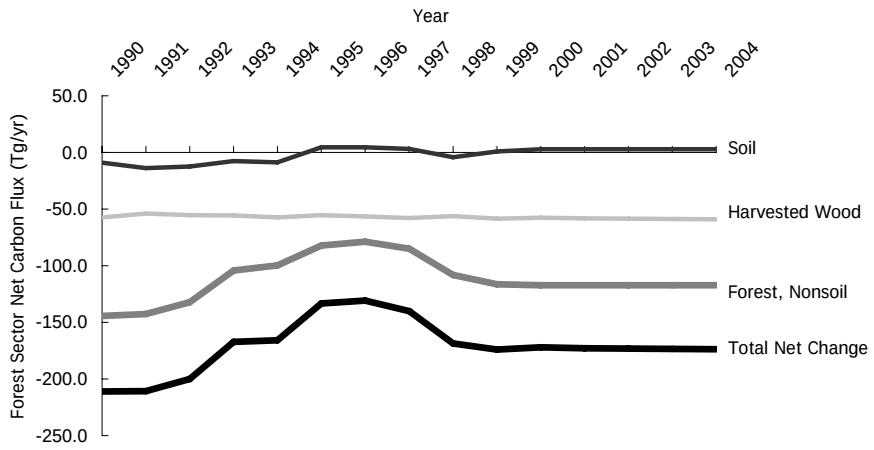
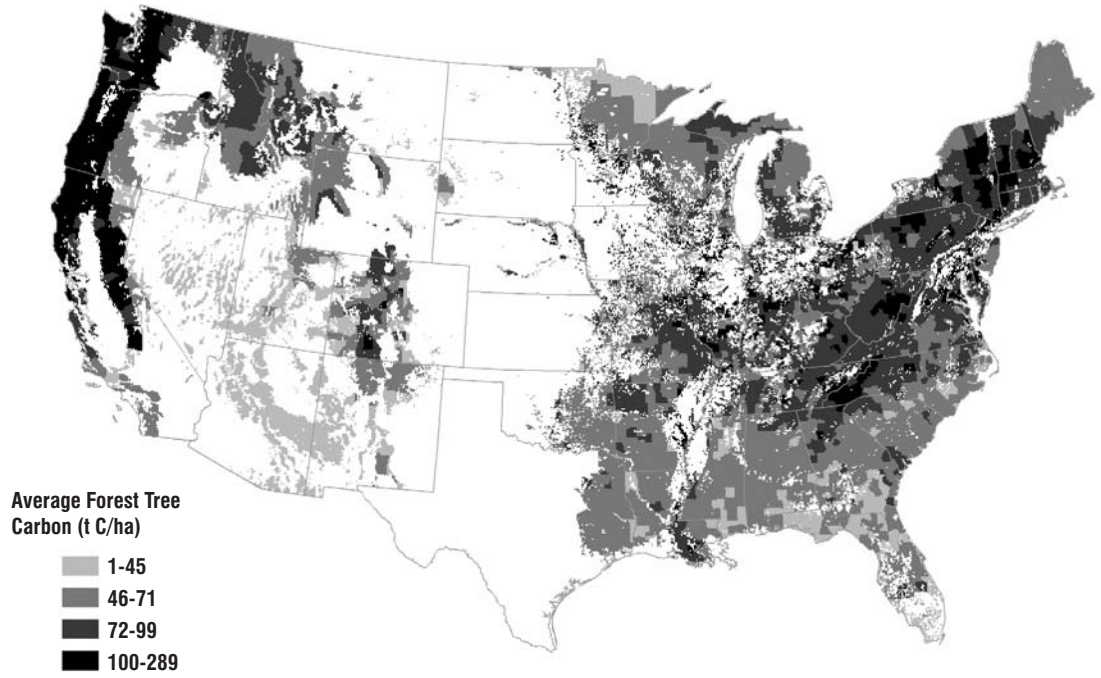


Figure 7-2: Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools

Figure 7-3

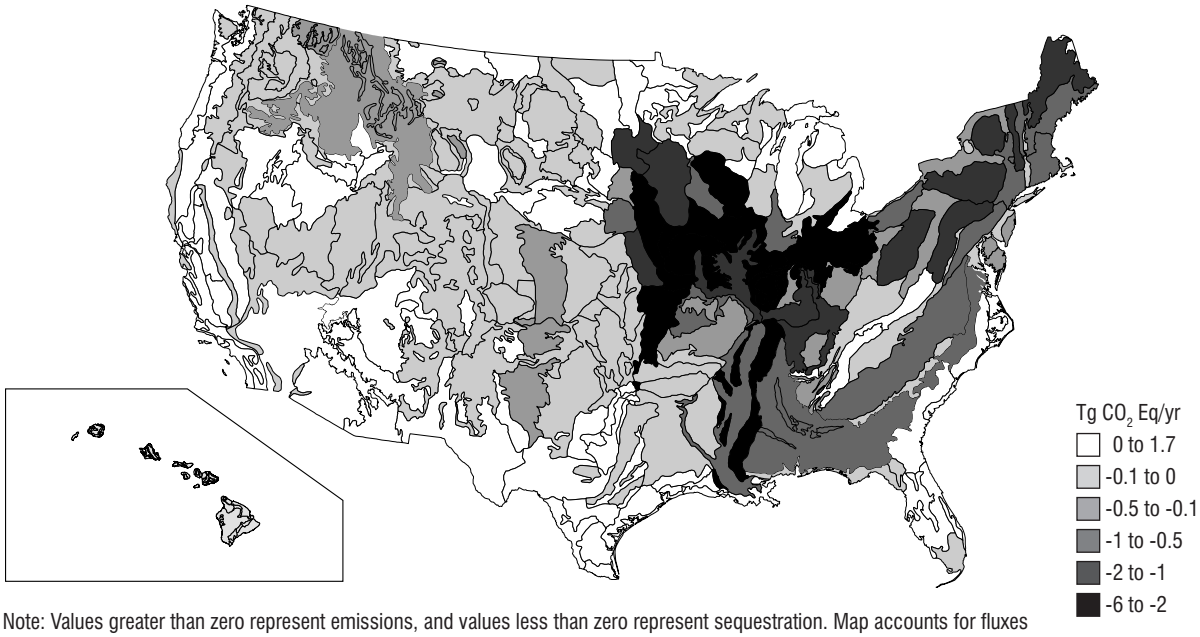
Average Carbon Density in the Forest Tree Pool in the Conterminous U.S. During 2005



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.

Figure 7-4

Net C Stock Change for Mineral Soils in Cropland Remaining Cropland, 1990-1992

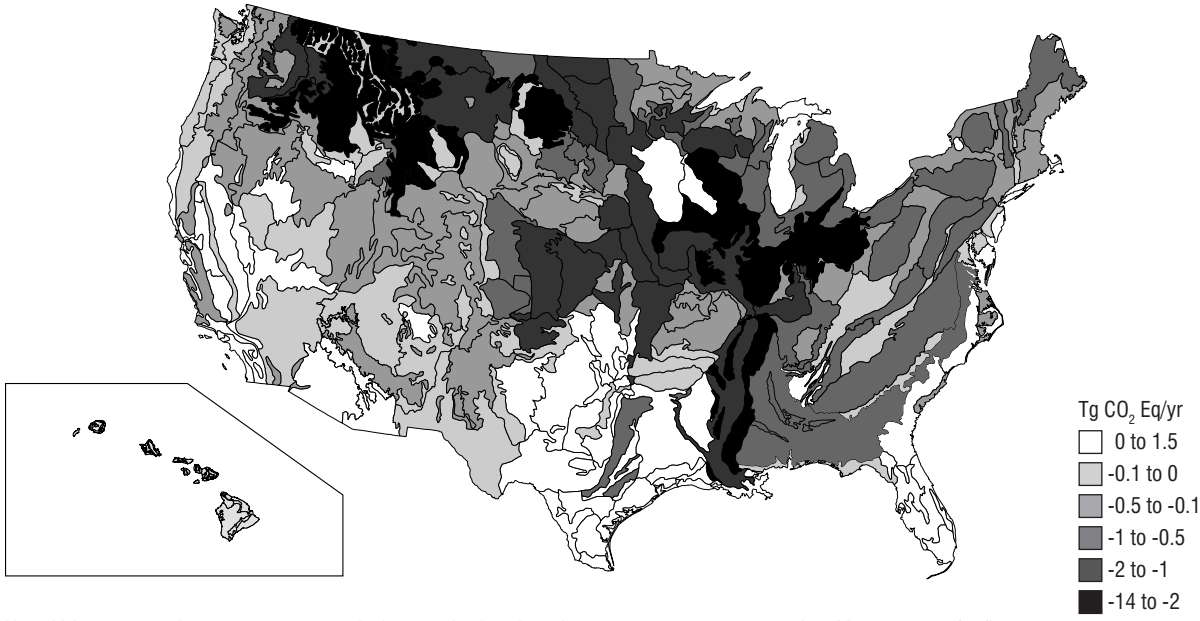


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations, but not the Tier 1 estimates. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-5

Net C Stock Change for Mineral Soils in Cropland Remaining Cropland, 1993-2004

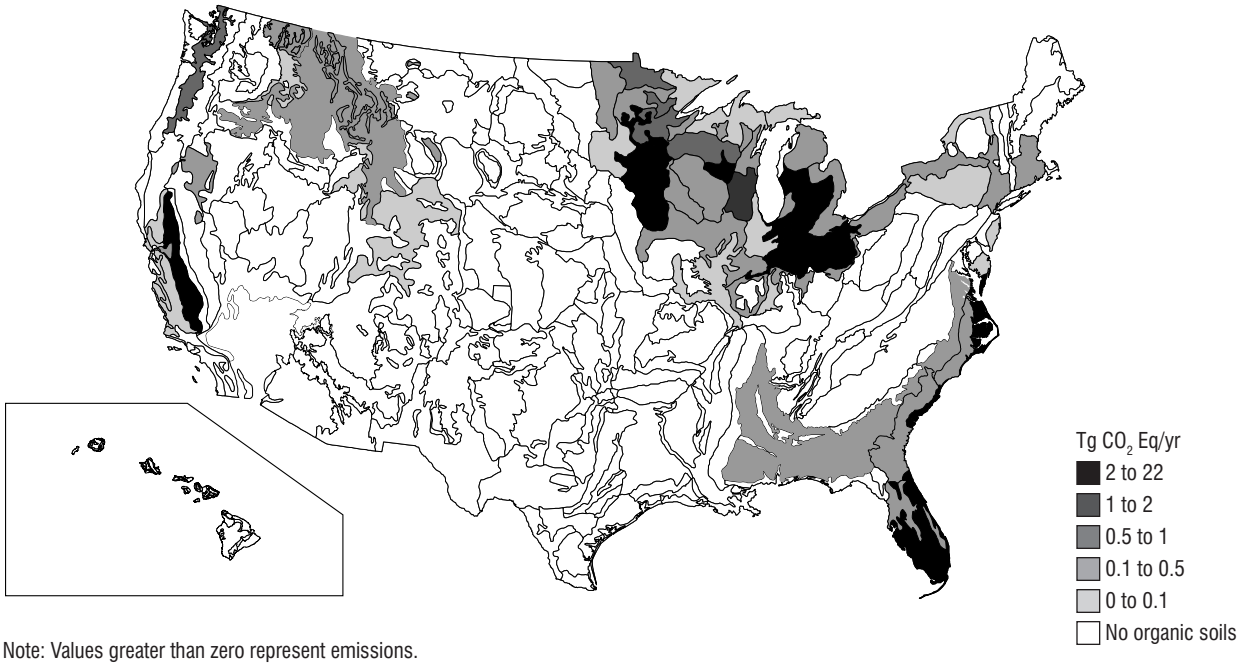


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations, but not the Tier 1 estimates. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-6

Net C Stock Change for Organic Soils in Cropland Remaining Cropland, 1990-1992

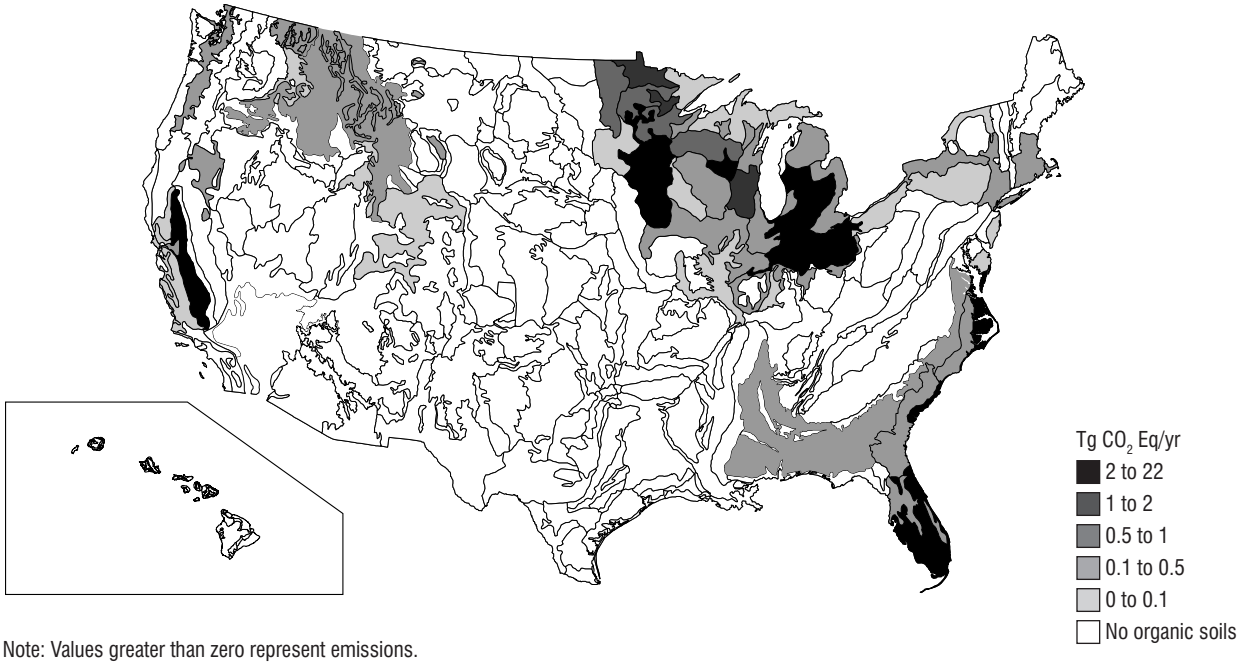


Note: Values greater than zero represent emissions.

This map shows the spatial variability in net carbon stock change for organic soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed organic soils in that polygon.

Figure 7-7

Net C Stock Change for Organic Soils in Cropland Remaining Cropland, 1993-2004

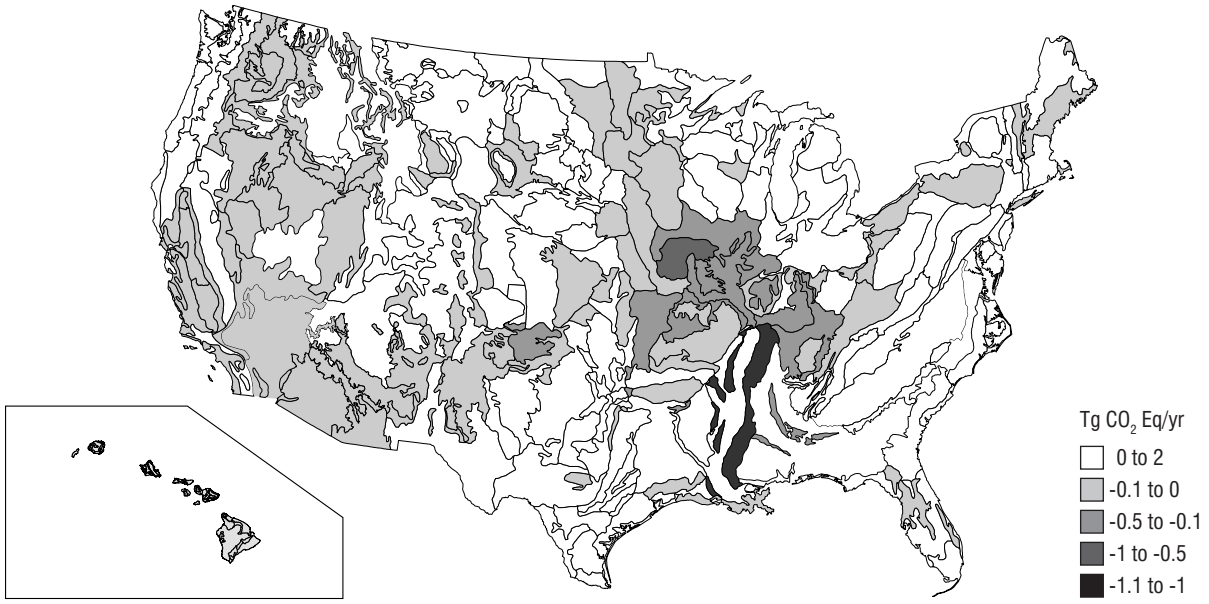


Note: Values greater than zero represent emissions.

This map shows the spatial variability in net carbon stock change for organic soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed organic soils in that polygon.

Figure 7-8

Net C Stock Change for Mineral Soils in Land Converted to Cropland, 1990-1992

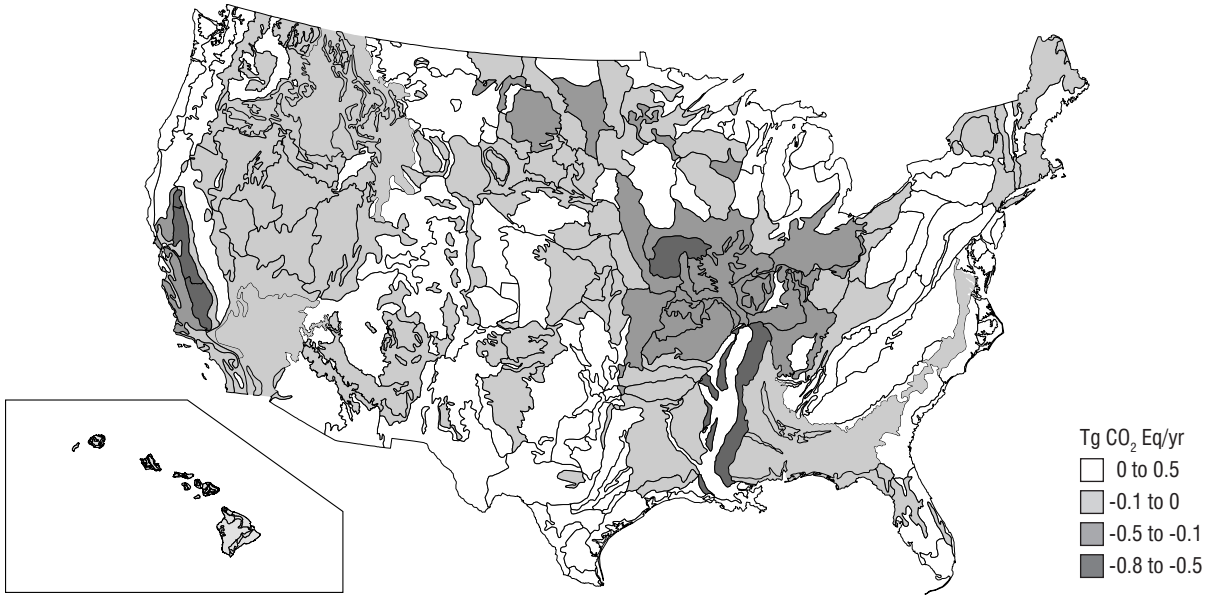


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 3 inventory computations. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-9

Net C Stock Change for Mineral Soils in Land Converted to Cropland, 1993-2004

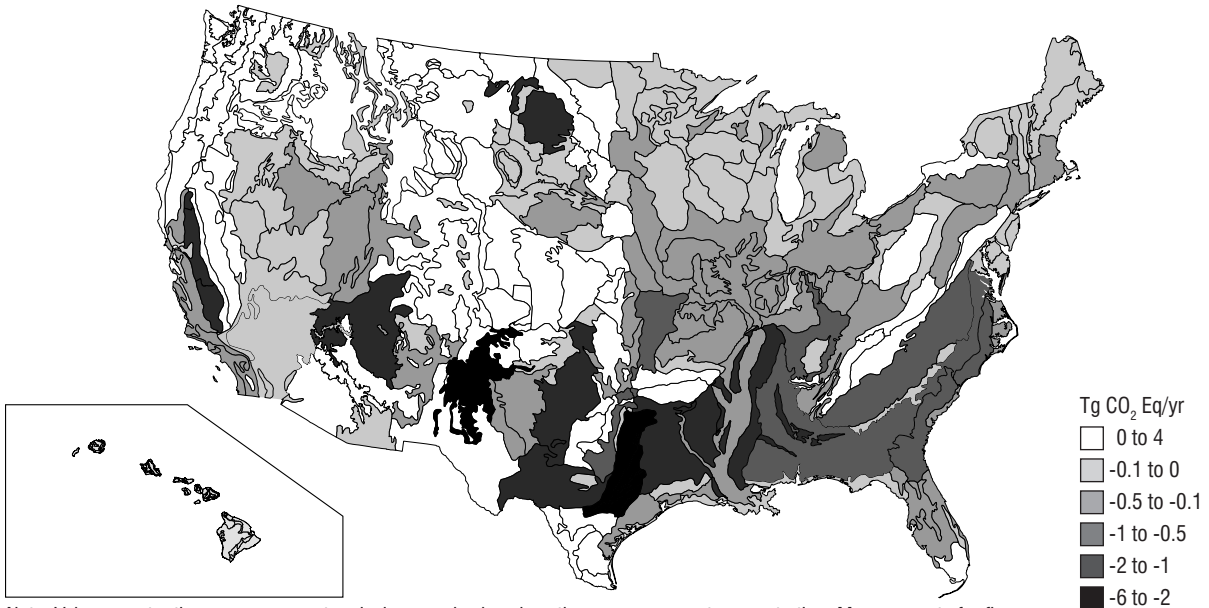


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 3 inventory computations. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-10

Net Soil C Stock Change for Mineral Soils in Grassland Remaining Grassland, 1990-1992

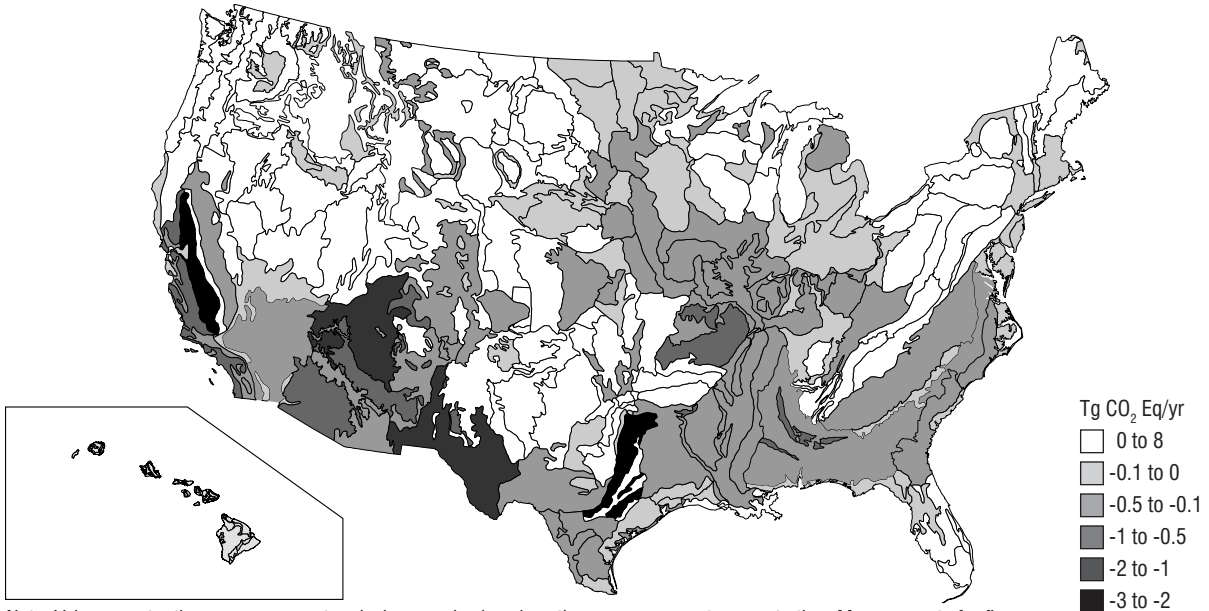


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 3 inventory computations, but not the Tier 1 estimates for sewage sludge additions. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-11

Net Soil C Stock Change for Mineral Soils in Grassland Remaining Grassland, 1993-2004

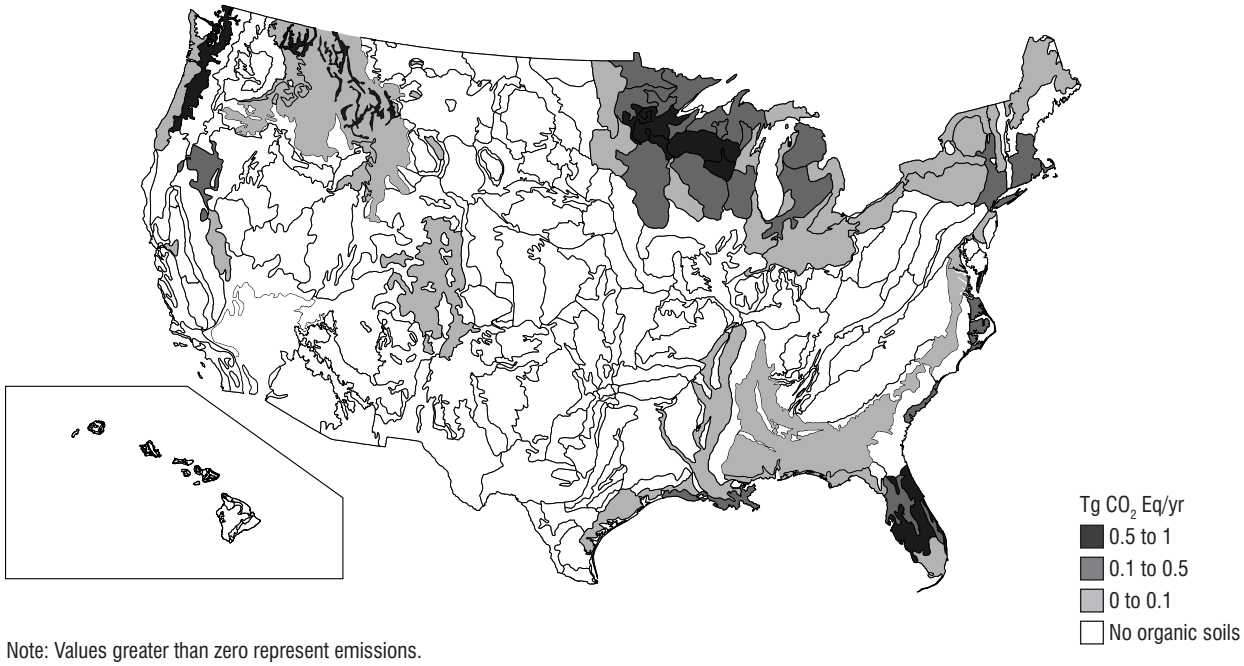


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 3 inventory computations, but not the Tier 1 estimates for sewage sludge additions. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-12

Net Soil C Stock Change for Organic Soils in Grassland Remaining Grassland, 1990-1992

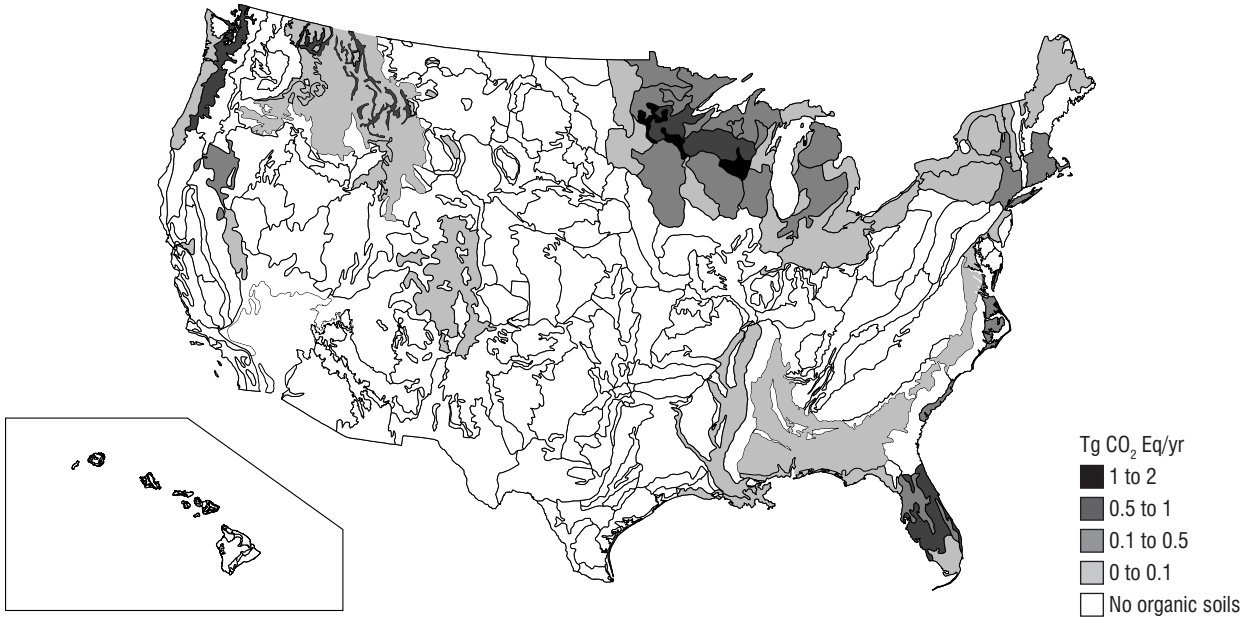


Note: Values greater than zero represent emissions.

This map shows the spatial variability in net carbon stock change for organic soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed organic soils in that polygon.

Figure 7-13

Net Soil C Stock Change for Organic Soils in Grassland Remaining Grassland, 1993-2004

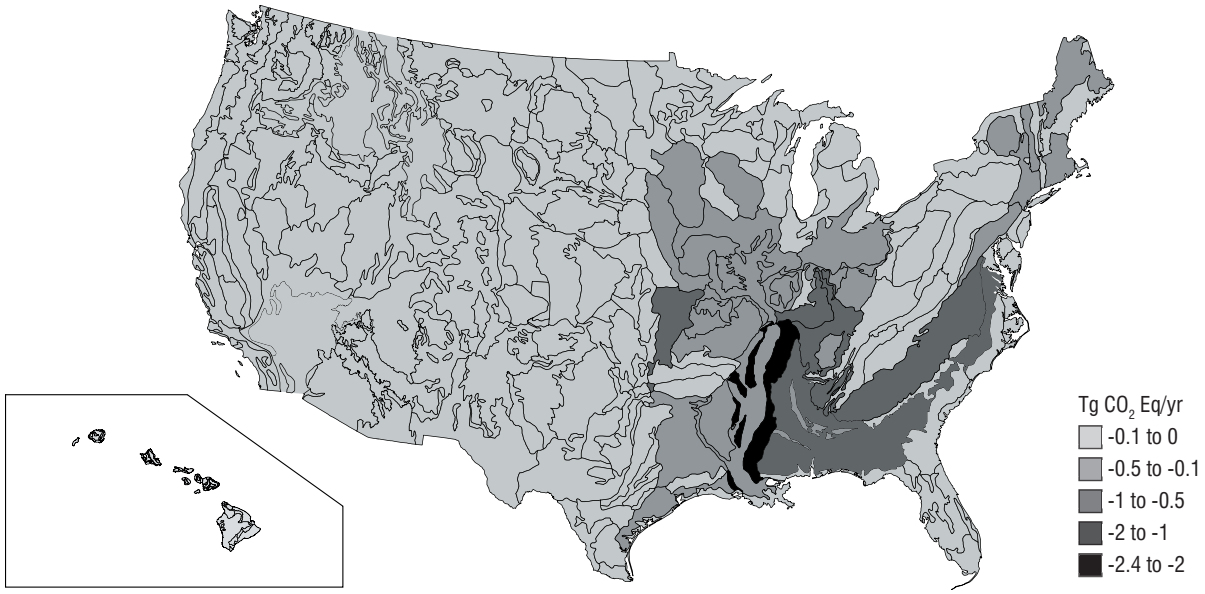


Note: Values greater than zero represent emissions.

This map shows the spatial variability in net carbon stock change for organic soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed organic soils in that polygon.

Figure 7-14

Net Soil C Stock Change for Mineral Soils in Land Converted to Grassland, 1990-1992

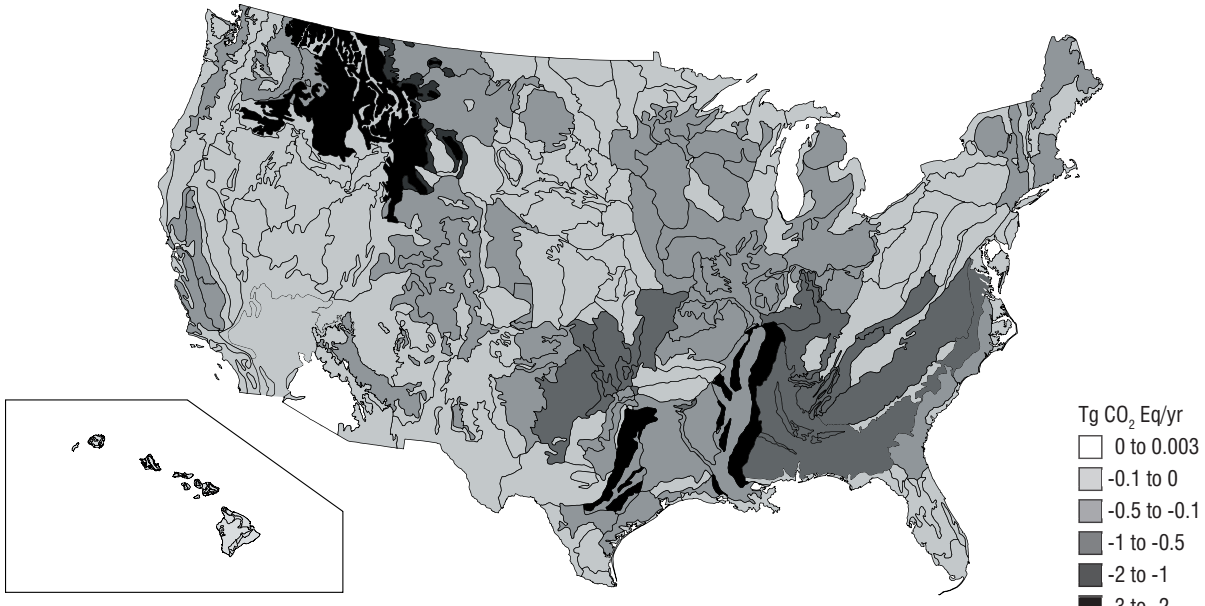


Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1990 through 1992. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Figure 7-15

Net Soil C Stock Change for Mineral Soils in Land Converted to Grassland, 1993-2004



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.

This map shows the spatial variability in net carbon stock change for mineral soils for the years 1993 through 2004. The color assigned to each polygon represents the total annual flux for the area of managed mineral soils in that polygon.

Descriptions of Figures: Land-Use Change and Forestry

Figure 7-1 illustrates forest sector carbon pools and flows. Forest carbon storage pools are represented by boxes, while flows between storage pools, and between storage pools and the atmosphere, are represented by arrows.

Figures 7-2 is a line graph indicating forest carbon flux for the years 1990 through 2004. Total net carbon flux is the bottom line that combines forest soils, harvested wood, and trees. Total net carbon flux increased from -210.9 Tg in 1990 to -17.8 Tg in 2004.

Figure 7-3 is a map of the Unites States that illustrates the average carbon density in forests, estimated for 2005. The states along both the east and west coasts are shaded darker, indicating a higher carbon density than central states.

Figures 7-4 through 7-15 are maps of the United States illustrating CO_2 flux from mineral and organic soils for the years 1990-2004. For a full description of figures 7-4 through 7-15, refer to the Inventory text found in Chapter 7.

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 25 percent of total U.S. CH_4 emissions.[1] Additionally, wastewater treatment accounts for 7 percent of U.S. CH_4 emissions. 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, using a simplified methodology. 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 and indirect greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Figure 8-1: 2004 Waste Chapter Greenhouse Gas Sources

Overall, in 2004, waste activities generated emissions of 193.8 Tg CO_2 Eq., or 3 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**197.1**		**176.9**	**175.3**	**173.3**	**170.8**	**175.6**	**179.0**	**177.8**
Landfills	172.3		144.4	141.6	139.0	136.2	139.8	142.4	140.9
Wastewater Treatment	24.8		32.6	33.6	34.3	34.7	35.8	36.6	36.9
N_2O	**12.9**		**14.9**	**15.4**	**15.5**	**15.6**	**15.6**	**15.8**	**16.0**
Human Sewage	12.9		14.9	15.4	15.5	15.6	15.6	15.8	16.0
Total	**210.0**		**191.8**	**190.7**	**188.8**	**186.4**	**191.3**	**194.8**	**193.8**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**9,385**		**8,425**	**8,346**	**8,254**	**8,135**	**8,364**	**8,524**	**8,467**
Landfills	8,206		6,874	6,743	6,619	6,484	6,659	6,782	6,709
Wastewater Treatment	1,180		1,550	1,602	1,635	1,651	1,705	1,742	1,758
N_2O	**42**		**48**	**50**	**50**	**50**	**50**	**51**	**52**
Human Sewage	42		48	50	50	50	50	51	52
NMVOCs	**673**		**161**	**140**	**119**	**122**	**133**	**134**	**134**
CO	**1**		**5**	**13**	**8**	**8**	**8**	**8**	**8**
NO_x	**+**		**3**	**3**	**2**	**2**	**2**	**2**	**2**

Note: Totals may not sum due to independent rounding.

8.1. Landfills (IPCC Source Category 6A1)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2004, landfill CH_4 emissions were approximately 140.9 Tg CO_2 Eq. (6,709 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately

[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 Change, and Forestry chapter.

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 2004).

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.

From 1990 to 2004, net CH_4 emissions from landfills decreased by approximately 18 percent (see Table 8-3 and Table 8-4), with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, 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 landfills are a function of several factors, including: (1) the total amount of municipal solid waste in landfills, which is related to total municipal solid 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 landfills increased from about 209 Tg in 1990 to 279 Tg in 2004, an increase of 33 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from landfills increased as well. In 1990, for example, approximately 930 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2004, the estimated quantity of CH_4 recovered and combusted increased to 5,343 Gg.

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 increase primarily 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), and the Landfill Methane Outreach Program (LMOP), an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
MSW Landfills	197.2	219.1	222.3	226.5	231.9	238.6	245.0	251.2
Industrial Landfills	13.8	15.3	15.6	15.9	16.2	16.7	17.2	17.6
Recovered								
Gas-to-Energy	(14.0)	(41.6)	(47.0)	(50.8)	(56.2)	(56.3)	(57.8)	(59.7)
Flared	(5.5)	(32.4)	(33.5)	(37.1)	(40.7)	(43.7)	(46.2)	(52.5)
Oxidized[a]	(19.1)	(16.0)	(15.7)	(15.4)	(15.1)	(15.5)	(15.8)	(15.7)
Total	**172.3**	**144.4**	**141.6**	**139.0**	**136.2**	**139.8**	**142.4**	**140.9**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at both municipal and industrial landfills.

[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 non-methane volatile organic compounds (NMVOCs).

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
MSW Landfills	9,391		10,435	10,588	10,785	11,045	11,364	11,669	11,960
Industrial Landfills	657		730	741	755	773	795	817	837
Recovered									
Gas-to-Energy	(667)		(1,982)	(2,239)	(2,419)	(2,676)	(2,679)	(2,751)	(2,841)
Flared	(263)		(1,545)	(1,597)	(1,767)	(1,938)	(2,082)	(2,199)	(2,502)
Oxidized[a]	(912)		(764)	(749)	(735)	(720)	(740)	(754)	(745)
Total	**8,206**		**6,874**	**6,743**	**6,619**	**6,484**	**6,659**	**6,782**	**6,709**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

Methodology

CH_4 emissions from landfills were estimated to equal the CH_4 produced from municipal solid waste landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere:

$$CH_{4,\text{Solid Waste}} = [(CH_{4,MSW} - R) + CH_{4,ind}] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$	= CH_4 emissions from solid waste
$CH_{4,MSW}$	= CH_4 generation from municipal solid waste landfills,
R	= CH_4 recovered and combusted,
$CH_{4,ind}$	= CH_4 generation from industrial landfills, 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 in the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance* (IPCC 2000) and in a background paper prepared by Jensen and Pipatti (2002). 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 1989 through 2004 were obtained from *BioCycle* (2004). 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 (2005) and national per capita solid waste generation from *BioCycle* (2004). 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.

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 EPA's Landfill Methane Outreach Program (LMOP) (EPA 2005a), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2005). 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

2004 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 359 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.

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (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 (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. Also, the approach used to estimate the contribution of industrial non-hazardous 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.

The 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. The total nitrogen (N) in sewage sludge increased from 189 to 261 Gg total N between 1990 and 2004, however; the quantity of sewage sludge applied to landfills decreased from 28 to 10 percent from 1990 to 2004.[3]

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2004 were estimated to be between 90.2 and 163.4 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of 36 percent below to 16 percent above the 2004 emission estimate of 140.9 Tg CO_2 Eq.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	140.9	90.2	163.4	-36%	+16%

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

[3] The methodology for estimating the quantity of N in sewage sludge disposed via incineration, land application, surface disposal, landfill, ocean dumping, and other is described in Annex 3.11 Methodology for Estimating N_2O Emissions From Agricultural Soil Management.

Recalculations Discussion

The primary recalculation was that associated with updating the EIA, LMOP, and flare vendor databases. The estimates of gas recovery at LFGTE projects decreased by 6.6 percent for the 2003 estimate, and most of this change is due to updating the EIA database. The EIA database for 2003 did not become available until late in 2004; consequently, the gas recovery rate for 2003 was estimated from the 2002 data. The 2004 update showed that LFGTE projects in the EIA 2002 database reported less gas recovery in 2003 than 2002, which decreased the estimate of CH_4 recovery. Another change affecting estimates of CH_4 recovery was due to additional projects reported in the EIA update that were previously included in the LMOP database. The recovery rates for these projects were changed to reflect the EIA estimate rather than the estimate of the LMOP database. A preference is given to the EIA database because those estimates are based on measured gas recovery rates, and they reflect changes in the recovery rate over time. Other changes affecting (decreasing) recovery rates over the time series resulted from identifying a few landfill projects that were inadvertently included in more than one of the three databases used to estimate gas recovery. There were also changes due to correcting and updating the LMOP database with changes in operational status and project start date. Overall, these changes resulted in an average annual decrease of 2.8 percent over the time series in CH_4 recovered by gas-to-energy projects.

Similar updates were made to the flare database and flares in the EIA database. The flare changes resulted in an average annual decrease of 8.4 percent in reductions due to flaring over the 1990 to 2003 time series. The primary factor causing this decrease was an adjustment made to the estimates for flaring when the flare vendor supplied information on the flare's maximum capacity. An analysis of flare capacity versus measured CH_4 flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the analysis was revised to estimate actual flow as 50 percent of capacity. Other factors contributing to the decrease were the update of the recovery by flares in the EIA database and removing flares inadvertently included in the flare database because they were reported in the EIA database. Average annual CH_4 emissions over the time series increased by 4 percent because of the decrease in estimates of CH_4 recovered for gas-to-energy projects and flaring.

The recovery of CH_4 for flaring increased by 14 percent from 2003 to 2004 (from 2,199 Gg to 2,502 Gg). This increase was due to 41 additional flares identified by flare vendors as becoming operational in 2004 and an additional 9 landfills with flares added to the EIA database. CH_4 recovery by LFGTE projects increased by 3 percent from 2003 to 2004 (from 2,751 Gg to 2,841 Gg). This increase was due to 22 new projects in the LMOP database becoming operational in 2004 and the addition of 4 new projects to the EIA database.

Planned Improvements

For future inventories, emerging guidance will be incorporated to help provide more accurate estimates of CH_4 generation by using the first order decay model and incorporating a delay time for CH_4 generation. The equation presented by Jensen and Pipatti (2002) and the 1996 IPCC guidance approximates the CH_4 generation rate using an estimate of the instantaneous rate at a point in time. This approximation simplifies estimating CH_4 generation using nationwide totals for waste disposal for each year. The revised guidance will improve the CH_4 generation estimate and incorporate a time lag to reflect the delay in CH_4 generation from the time the waste is disposed. The new guidance will result in a decrease of about 2 percent in the CH_4 generation rates presented here.

Additional efforts will be made to improve the estimates of CH_4 generation at industrial landfills and estimates of oxidation, especially for landfills with gas recovery systems. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares. The parameters for the first order decay model will be re-evaluated as more data become available.

[Begin Text Box]

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. However, 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.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products, yard trimmings, and food scraps resulted in net long-term storage of 9.3 Tg CO_2 Eq. in 2004, as described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003).

[End Box]

8.2. Wastewater Treatment (IPCC Source Category 6B)

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 off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems (EPA 1996). 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 organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), governs the CH_4 producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater.

In 2004, CH_4 emissions from domestic wastewater treatment were estimated to be 20.0 Tg CO_2 Eq. (953 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Also, the per capita organic wastewater loading has increased. In 2004, CH_4 emissions from industrial wastewater treatment were estimated to be 16.9 Tg CO_2 Eq. (805 Gg). Industrial emission sources include wastewater from the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.[4] Table 8-6 and Table 8-7 provide emission estimates from domestic and industrial wastewater treatment.

Table 8-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Domestic	11.4		16.4	17.1	17.8	18.5	19.1	19.8	20.0
Industrial*	13.4		16.1	16.5	16.5	16.2	16.7	16.7	16.9
Total	**24.8**		**32.6**	**33.6**	**34.3**	**34.7**	**35.8**	**36.6**	**36.9**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.

[4]Emissions associated with refinery wastewater are estimated in Annex 2.3 Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles, however emissions from these sectors are considered to be insignificant.

Note: Totals may not sum due to independent rounding.

Table 8-7: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Domestic	543		783	815	848	880	912	944	953
Industrial*	637		767	787	788	771	794	797	805
Total	**1,180**		**1,550**	**1,602**	**1,635**	**1,651**	**1,705**	**1,742**	**1,758**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology:

$$CH_4 \text{ (domestic wastewater)} = US_{POP} \times BOD_5 \times 365 \times 16.25\ \% \times EF$$

where,

CH_4 = Total CH_4 emissions from domestic wastewater (kg/year)
US_{POP} = U.S. population
BOD_5 = organic loading in wastewater (kg BOD_5/person.day) [5]
365 = days per year
16.25% = Percent of wastewater BOD_5 that is anaerobically digested
EF = Emission factor (0.6 kg CH_4/kg BOD_5)

National population data for 1990 to 2004, used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2005). For BOD_5 for domestic wastewater, two data points were available for 1991 and 2003 (Metcalf & Eddy 1990; Metcalf & Eddy 2003). The BOD loadings for intervening years were obtained by linear interpolation. The emission factor (0.6 kg CH_4/kg BOD_5) was taken from IPCC *Good Practice Guidance* (IPCC 2000). The percent of wastewater BOD_5 that was anaerobically digested was assumed to be 16.25 percent (ARCADIS 2001). This value also accounts for U.S. septic systems and is based on expert judgment and on septic system usage data from EPA (1996).

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	5,566
1998	280	8,032
1999	283	8,363
2000	286	8,695
2001	289	9,021
2002	292	9,351
2003	295	9,685
2004	297	9,774

Source: U.S. Census Bureau (2005); Metcalf & Eddy 1990; Metcalf & Eddy 2003.

CH_4 emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2000). 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.

[5] BOD_5 is the 5-day biochemical oxygen demand measurement (Metcalf and Eddy 2003).

The top three industries that meet these criteria are pulp and paper manufacturing, meat and poultry packing, and vegetables, fruits and juices processing.

CH_4 emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD or BOD) in the outflow, the percentage of organic loading assumed to degrade anaerobically, and the emission factor. For pulp and paper as well as meat and poultry wastewater, BOD was used. In developing estimates for the vegetables, fruits, and juices category, COD was used instead of BOD, because no accurate BOD numbers were available. The emission factor used for pulp and paper as well as meat and poultry wastewater is 0.6 kg CH_4/kg BOD_5, whereas the emission factor for vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000). The methodological equation is:

$$CH_4 \text{ (industrial wastewater)} = P \times W \times (\text{COD or BOD}) \times MCF \times EF$$

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 or BOD	= Organics loading in wastewater (kg /m^3)
MCF	= CH_4 correction factor, indicating the extent to which the organic COD or BOD degrades anaerobically
EF	= Emission factor (0.6 kg CH_4/kg BOD_5 for meat and poultry and pulp and paper; 0.25 kg CH_4/kg COD for vegetables, fruits and juices)

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. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur and, consequently, the primary lagoons are assumed to be 1.4 percent anaerobic (expert judgment). Approximately 42 percent of the BOD passes on to secondary treatment, which is less likely to be aerated (EPA 1993). Twenty-five percent of the BOD in secondary treatment lagoons was assumed to degrade anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Consequently, the overall percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent (i.e., 58% × 1.4% + 42% × 90% × 25%). A time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999).

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps and dissolved air flotation. Production data, in carcass weight for the meat and poultry industry, were obtained from the U.S. Census (2004). EPA (2002) provided estimates for wastewater flows into anaerobic lagoons: 7.9 and 16.6 m^3/metric ton for meat and poultry production, respectively. The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. Ninety percent of organic BOD is believed to degrade anaerobically in the lagoon (EPA 1997b).

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, 5 percent of these wastewater organics are assumed to degrade anaerobically. The USDA National Agricultural Statistics Service (USDA 2004) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m^3/metric ton was used. For the organics loading, a COD value of 5 g/liter was used (EPA 1997b).

Table 8-9: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Tg)

Year	Pulp and Paper	Meat (carcass weight)	Poultry (carcass weight)	Vegetables, Fruits and Juices
1990	128.9	17.6	10.6	29.8
1995	140.9	19.8	13.8	36.8
1996	140.3	19.8	14.5	36.4
1997	145.6	19.7	15.0	37.7
1998	144.0	20.5	15.1	36.5
1999	145.1	21.0	16.0	37.4
2000	142.8	21.0	16.4	38.9
2001	134.3	20.8	16.8	35.0
2002	137.5	21.5	17.3	36.5
2003	140.0	21.2	17.5	34.1
2004	140.0	21.5	17.7	36.6

Uncertainty

The overall uncertainty associated with the 2004 CH_4 emissions estimate from wastewater treatment was calculated using the IPCC *Good Practice Guidance* Tier 2 methodology. Uncertainty associated with the parameters used to estimate CH_4 emissions included that of numerous input variables used to model emissions from domestic wastewater, and wastewater from the pulp and paper industry, meat and poultry processing, as well as from fruits, vegetables and juices processing.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-10. CH_4 emissions from wastewater treatment were estimated to be between 24.9 and 51.2 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 33 percent below to 39 percent above the 2004 emissions estimate of 36.9 Tg CO_2 Eq.

Table 8-10: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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	36.9	24.9	51.2	-33%	+39%

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

Recalculations Discussion

The 2004 estimates did not include any methodological changes or refinements. However, the time series for domestic wastewater changed because population estimates for the United States and U.S. territories changed slightly. This change resulted in a less than one percent decrease in emission estimates over the time series.

Planned Improvements Discussion

The methodology to estimate emissions from domestic wastewater uses a factor of 16.25 percent for the overall quantity of organics (BOD) in wastewater that is anaerobically digested. This factor is based on the percentage of the population that uses septic systems and on the amount of BOD that degrades anaerobically in septic systems and in centralized treatment plants. Information may be available that will allow for refinement of this factor. Another area for improvement is characterization of pulp and paper wastewater treatment (organics loading, wastewater generation and anaerobic degradation percentage).

8.3. Human Sewage (Domestic Wastewater) (IPCC Source Category 6B)

Domestic human sewage is usually mixed with other household wastewater, which includes effluent from shower drains, sink drains, washing machines, etc., and is either discharged directly, or transported to an on-site or decentralized wastewater treatment system, or to a centralized wastewater treatment system. Decentralized wastewater treatment systems are septic systems and package plants. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized wastewater treatment systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent is discharged to a receiving water environment (e.g., river, lake, estuary, etc.), or applied to soils, or disposed of below the surface.

N_2O may be generated during both nitrification and denitrification of the nitrogen 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 United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes; and emissions from effluent that has been discharged into aquatic environments. The 2004 emissions of N_2O from wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 15.8 Tg CO_2 Eq. (51 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 16.0 Tg CO_2 Eq. (52 Gg) (see Table 8-11). Emissions from wastewater treatment processes have gradually increased as a result of increasing U.S. population and protein consumption.

Table 8-11: N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	12.9	42
1998	14.9	48
1999	15.4	50
2000	15.5	50
2001	15.6	50
2002	15.6	50
2003	15.8	51
2004	16.0	52

Methodology

The IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) assumes that nitrogen disposal, and thus N_2O emissions associated with land disposal, subsurface disposal, and domestic wastewater treatment are negligible and all nitrogen is discharged directly into aquatic environments. For the United States, N_2O emissions from domestic wastewater (human sewage) were estimated using the IPCC methodology with three modifications:

- In the United States, a certain amount of nitrogen is removed with sewage sludge, which is applied to land, incinerated or landfilled (N_{sludge}). The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.[6]
- The IPCC methodology uses annual, per capita protein consumption (kg protein/(person-year)). This number is

[6] The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11 Methodology for Estimating N_2O Emissions From Agricultural Soil Management.

likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. A factor of 1.4 is introduced to account for non-consumption nitrogen.[7] Furthermore, a significant quantity of industrial wastewater (nitrogen) is co-discharged with domestic wastewater. To account for this, a factor of 1.25 is introduced.[8] In summary, a factor of 1.75 (1.4 × 1.25) is used to account for the extra nitrogen discharge from kitchen, bath, and laundry wastes, as well as industrial wastewater that is co-discharged into sewers, based on Metcalf & Eddy (1991) and expert judgment.

- Process emissions from wastewater treatment plants are not accounted for in the current IPCC methodology. To estimate N_2O emissions from U.S. wastewater treatment plants, an overall emission factor (4 g N_2O/(person-year)) was introduced. This emission factor is based on a factor of 3.2 g N_2O/(person-year) (Czepiel et al. 1995) multiplied by the 1.25 factor mentioned above, which adjusts for co-discharged industrial nitrogen and is based on expert judgment. The nitrogen quantity associated with these emissions (NWWT) is calculated by multiplying the N_2O emitted by (2 × 14)/44 and is subtracted from the total quantity of nitrogen that is ultimately disposed into the aquatic environment.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {}^{44}/_{28}\}$$

where,

$N_2O(s)$	= N_2O emissions from domestic wastewater ("human sewage") [kg/year]
US_{POP}	= U.S. population
0.75	= Fraction of population using centralized wastewater treatment plants (as opposed to septic systems)
EF_1	= Emission factor (4 g N_2O/(person-year)) expressing emissions from the centralized wastewater treatment plants
Protein	= Annual per capita protein consumption [kg/(person-year)]
1.75	= Fraction of non-consumption protein in domestic wastewater
$Frac_{NPR}$	= Fraction of nitrogen in protein (i.e., 0.16 kg N/kg protein)
N_{WWT}	= Quantity of wastewater nitrogen removed by wastewater treatment processes [($US_{POP} \times 0.75 \times EF_1 \times 10^{-3}$) × ${}^{28}/_{44}$] (kg N/year)
N_{sludge}	= Quantity of sewage sludge N not entering aquatic environments (kg N/year)
EF_2	= Emission factor (kg N_2O-N/kg sewage-N produced)
(${}^{44}/_{28}$)	= Molecular weight ratio of N_2O to N_2

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[7] Metcalf & Eddy (1991) provides an indication of the nitrogen concentration of 40 mg Total Kjeldahl Nitrogen (TKN)/liter for average wastewater from residences, which includes bathwater, laundry, and the use of garbage disposals. According to the Needs Survey (1996), the total volume of wastewater generated in the United States in 1996 was 32,175 million gallons per day (MGD), serving 189,710,899 people (72 percent of population, not including the septic system users). In 1996, the per capita TKN loading was: 40 [mg/l] × 32,175 × 10^6 [gal/day] × 3.8 [l/gal] × 365 days/yr × 1/(189.7 × 10^6) × 10^{-6} = 9.4 [kg TKN/yr.person]. Average protein intake in 1996 was 41 kg protein /(person-year) (6.6 kg N/(person-year)), leading to a factor of 1.4 (9.4/6.6).

[8] The type, composition, and quantity of this co-discharged wastewater vary greatly between municipalities. Metcalf & Eddy (1991) provide an indicative nitrogen loading of 20 to 85 mg TKN/liter (average 55) for combined residential and industrial wastewater, while residential wastewater loading was roughly estimated at 40 mg TKN/liter (see previous footnote). Until better data become available, the amount of N in wastewater is increased by 10 mg/l to account for industrial co-discharge (factor of 1.25).

U.S. population data were taken from the U.S. Census Bureau International Database (2005) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is from the Needs Survey (EPA 1996). The emission factor (EF_1) to estimate emissions from wastewater treatment is based on Czepiel, et al. (1995). Data on annual per capita protein intake were provided by the United Nations Food and Agriculture Organization for the 1990 to 2002 time frame (FAO, 2002). Because data on protein intake were unavailable for 2003 and 2004, the value of per capita protein consumption was extrapolated from previous years. Table 8-12 presents the data for U.S. population and average protein intake. An emission factor to estimate emissions from effluent (EF_2) has not been specifically estimated for the United States, thus the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 8-12: U.S. Population (Millions) and Average Protein Intake [kg/(person-year)]

Year	Population	Protein
1990	254	39.2
1998	280	41.2
1999	283	42.0
2000	286	41.9
2001	289	41.8
2002	292	41.6
2003	295	41.8
2004	297	42.0

Source: U.S. Census Bureau 2005, FAO 2002, and extrapolation from FAO 2002.

Uncertainty

The overall uncertainty associated with the 2004 N_2O emissions estimate from human sewage was calculated using the IPCC *Good Practice Guidance* Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of nitrogen in protein, non-consumption nitrogen factor, emission factors for individuals and per mass of wastewater, and for the percentage of total population using centralized wastewater treatment plants. The activity data inputs and their associated uncertainties and distributions are summarized in Table 8-13.

Table 8-13: Sources of Uncertainty in N_2O Emissions from Human Sewage

			Uncertainty Range[a]		
Variable	Value	Distribution Type	Lower Bound	Upper Bound	Reference
Sewage Sludge Disposal (10^6 metric tons total N)	0.26	Triangular	-39%	+39%	Expert Judgment
U.S. and Territories Total Population (million persons)	297	Normal	-5%	+5%	Expert Judgment
Protein (kg/(person-yr))	42	Normal	-5%	+5%	Expert Judgment
Fraction of Nitrogen in Protein (kg N/kg protein)	0.16	Normal	-2%	+2%	Expert Judgment
Fraction of Non-Consumption Protein in Domestic WW	1.75	Normal	-25%	+25%	Expert Judgment
EF_2 (kg N_2O-N/kg sewage-N produced)	0.01	Normal	-80%	+80%	IPCC Guidelines
Population Using Centralized Wastewater Treatment Plants (%)	75%	Normal	-25%	+25%	Expert Judgment
EF_1 (g N_2O/(person-year))	4.0	Normal	-50%	+50%	Expert Judgment

[a] Parameters presented represent upper and lower bounds as a percentage of the mean, based on a 95 percent confidence interval.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-14. N_2O emissions from

human sewage were estimated to be between 4.1 and 30.3 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 75 percent below to 89 percent above the 2004 emissions estimate of 16.0 Tg CO_2 Eq.

Table 8-14: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Percent)

Source	Gas	2004 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
Human Sewage	N_2O	16.0	4.1	30.3	-75%	+89%

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

Planned Improvements

The default emission factor for N_2O from wastewater effluent has a high uncertainty. 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. Several parameters constituting this factor are based on references that have since been updated, including the Needs Survey (1996) and Metcalf & Eddy (1991). The uncertainty associated with this factor can likely be reduced by incorporating more recent data. Also, the fraction of the U.S. population using centralized wastewater treatment plants is currently set at 0.75. This fraction can likely be refined with recent data from the 2004 Needs Survey. The U.S. Environmental Protection Agency intends to conduct research to update the protein consumption data.

Recalculations Discussion

The 2004 estimates did not include any methodological changes or refinements. However, the time series for domestic wastewater changed because the amount of nitrogen that is removed with the sewage sludge (i.e., N_{sludge}) was adjusted to include N from surface disposal, ocean dumping, and other disposals of N, in addition to sewage sludge that is incinerated, applied to land, or landfilled. This change resulted in less than a one percent decrease in emission estimates over the time series relative to the previous report.

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 2004 are provided in Table 8-15.

Table 8-15: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990		1998	1999	2000	2001	2002	2003	2004
NO_x	**+**		**3**	**3**	**2**	**2**	**2**	**2**	**2**
Landfills	+		2	3	2	2	2	2	2
Wastewater Treatment	+		+	+	+	+	+	+	+
Miscellaneous[a]	+		1	+	+	+	+	+	+
CO	**1**		**5**	**13**	**8**	**8**	**8**	**8**	**8**
Landfills	1		5	12	7	7	7	7	7
Wastewater Treatment	+		+	1	1	1	1	1	1
Miscellaneous[a]	+		+	+	+	+	+	+	+
NMVOCs	**673**		**161**	**140**	**119**	**122**	**133**	**134**	**134**
Landfills	58		33	27	23	23	25	25	25
Wastewater Treatment	57		63	59	51	53	58	58	58
Miscellaneous[a]	558		65	54	46	46	51	51	51

[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.
+ Does not exceed 0.5 Gg.

Methodology and Data Sources

These emission estimates were obtained from preliminary data (EPA 2005), 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 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.

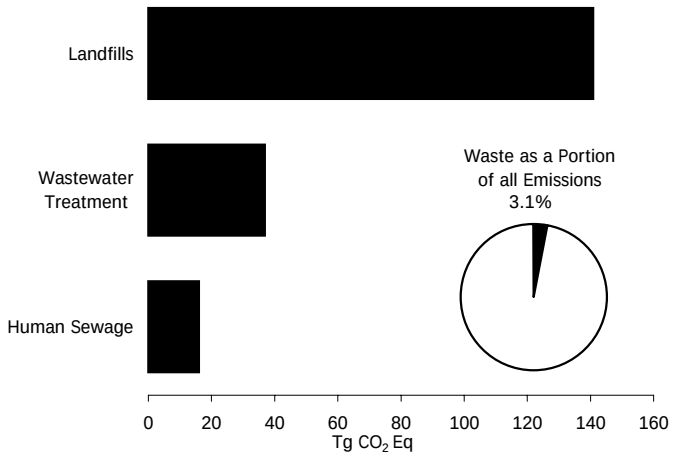


Figure 8-1: 2004 Waste Chapter Greenhouse Gas Sources

Descriptions of Figures: Waste

Figure 8-1 illustrates the data presented in Table 8-1, waste sources of greenhouse gases. Landfills are the greatest source, responsible for 140.9 Tg CO_2 Eq. In addition, there is a pie chart that indicates that waste made up 3.1 % of U.S. greenhouse gas emissions in 2004.

9. Other

The United States does not report any greenhouse gas emissions under the “other” Intergovernmental Panel on Climate Change (IPCC) 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 summarizes the quantitative effect on U.S. sinks, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2003 report). These tables present the magnitude of these changes in units of Tg CO_2 Eq. In addition to the changes summarized by the tables below, three new sources—silicon carbide consumption, lead production, and zinc production—have been added to the current Inventory.

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 2003) 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.

The following emission sources, which are listed in descending order of absolute average annual change in emissions from 1990 through 2003, 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.

- *Land Use, Land-Use Change, and Forestry*. The most influential of the changes in the Land Use, Land-Use Change, and Forestry sector occurred in calculations for forest carbon stocks. These changes included the use of survey data, utilizing all available state surveys in the FIADB with RPA data used as necessary. There were also changes in calculations for agricultural soil carbon stocks, the most significant being the implementation of the Tier 3 model-based approach for mineral soils. In addition, these recalculations reflect the inclusion of new categories to the LULUCF chapter (e.g. Grassland Remaining Grassland). Overall, these changes, in combination with adjustments in the other sources/sinks, resulted in an average annual increase in net flux of CO_2 to the atmosphere from the Land Use, Land-Use Change, and Forestry sector of 155.0 Tg CO_2 Eq. (17 percent) for the period 1990 through 2003.

- *Agricultural Soil Management*. Changes occurred as a result of minor adjustments in activity data and the use of an updated version of the DAYCENT model. The DAYCENT model was revised to more realistically represent the grain filling period and life span of crops. Additionally, this year a different soils database was used for model simulations. Overall, changes resulted in an average annual increase in N_2O emissions from agricultural soil management of 30.6 Tg CO_2 Eq. (12 percent) for the period 1990 through 2003.

- *Non-Energy Use of Fuels.* There were several refinements to the methodology for calculating emissions and storage for petrochemical feedstocks. There was a thorough review of system boundaries on the mass balance, which involved reconciling disparities in data for production and consumption, and making corresponding revisions to the import/export calculations. Three additional NEU fates were incorporated into the calculations—antifreeze and deicers, food additives, and silicone rubber—and refinery wastewaters was removed from the mass balance. There were also revisions to the data used to calculate storage factors. Overall, changes resulted in an average annual increase in CO_2 emissions from non-energy use of fuels of 15.2 Tg CO_2 Eq. (13 percent) for the period 1990 through 2003.

- *Petroleum Systems*. There was one major change to this source with respect to previous inventories.

Previously, offshore petroleum production emissions were calculated as eight separate sources. New analysis of the 2000 GOADS report (MMS 2005c) yields comprehensive shallow and deep water sources and related emissions factors, which account for all offshore emissions. The sources from the GOADS analysis have replaced the eight sources from previous inventories. Overall, changes resulted in an average annual increase in CH_4 emissions from petroleum systems of 11.8 Tg CO_2 Eq. (63 percent) for the period 1990 through 2003.

- *CO_2 from Fossil Fuel Combustion*. The most important change affecting historical estimates for fossil fuel combustion was the correction of overestimated emissions from the industrial sector. Previously, a portion of industrial sector fuels that are exported as petrochemical feedstocks or used in industrial processes were not subtracted from fuels consumed for energy purposes. Overall, this change, along with several other alterations, resulted in an average annual decrease of 5.6 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2003.

- *Landfills*. Changes to historical data were a result of updating the EIA, LMOP, and flare vendor databases. Average annual emissions increased over the time series because of a decrease in estimates of CH_4 recovered for gas-to-energy projects and flaring. Overall, changes resulted in an average annual increase in CH_4 emissions from landfills of 4.7 Tg CO_2 Eq. (4 percent) for the period 1990 through 2003.

- *Natural Gas Systems*. The most significant changes to this source resulted from methodological revisions in calculating offshore natural gas production emissions. Previously, these emissions were calculated as five separate sources. New analysis of the 2000 GOADS report (MMS 2005c) yields comprehensive shallow and deep water sources and related emissions factors, which account for all offshore emissions. The sources from the GOADS report have replaced the five sources from previous inventories. Overall, changes resulted in an average annual decrease in CH_4 emissions from natural gas systems of 4.5 Tg CO_2 Eq. (3 percent) for the period 1990 through 2003.

- *Biomass Combustion.* The historical data for wood biomass consumption was adjusted, which resulted in an average annual decrease in emissions from wood biomass and ethanol consumption of 2.0 Tg CO_2 Eq. (0.9 percent) from 1990 through 2003.

- *Substitution of Ozone Depleting Substances.* Assumptions to the Vintaging Model were updated based on changes in chemical substitution trends, market sizes, growth rates, and charge sizes. Overall, changes resulted in an average annual decrease in HFC and PFC emissions from the substitution of ozone depleting substances of 2.0 Tg CO_2 Eq. (3 percent) for the period 1990 through 2003.

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990		1998	1999	2000	2001	2002	2003
CO_2	**(4.3)**		**13.0**	**17.1**	**6.3**	**50.4**	**19.1**	**36.2**
Fossil Fuel Combustion	(15.2)		(6.9)	(3.5)	(11.4)	38.9	0.3	19.5
Non-Energy Use of Fuels	9.2		17.4	19.0	16.0	10.9	17.6	15.5
Natural Gas Flaring	NC		NC	NC	NC	NC	+	0.1
Cement Manufacture	NC		NC	NC	NC	NC	NC	0.1
Lime Manufacture	+		+	+	+	+	+	+
Limestone and Dolomite Use	NC		NC	NC	+	NC	NC	NC
Soda Ash Manufacture and Consumption	NC		NC	NC	NC	NC	NC	+
CO_2 Consumption	+		+	+	+	+	+	+
Waste Combustion	NC		NC	NC	(0.1)	(0.1)	0.1	0.6
Titanium Dioxide Production	NC		NC	NC	NC	NC	NC	+
Aluminum Production	0.7		0.6	0.6	0.5	0.4	0.4	0.4
Iron and Steel Production	(0.4)		0.3	(0.6)	(0.4)	(1.1)	(0.5)	(0.4)
Ferroalloy Production	NC		NC	NC	NC	NC	NC	(0.2)
Ammonia Manufacture & Urea Application	NC		NC	NC	+	+	(0.1)	(0.3)
Petrochemical Production	NC		NC	NC	NC	NC	NC	NC
Phosphoric Acid Production	NC		NC	NC	NC	NC	NC	NC
Silicon Carbide Consumption[a]	0.1		0.2	0.1	0.1	0.1	0.1	0.1
Lead Production[a]	0.3		0.3	0.3	0.3	0.3	0.3	0.3

Zinc Production[a]	0.9	1.1	1.1	1.1	1.0	0.9	0.5
Net CO_2 Flux From Land Use, Land-Use Change, and Forestry	*131.7*	*137.0*	*60.4*	*62.9*	*58.9*	*57.8*	*53.2*
International Bunker Fuels	*NC*	*NC*	*(0.1)*	*+*	*(0.1)*	*NC*	*(0.1)*
Biomass Combustion	*+*	*NC*	*NC*	*NC*	*NC*	*(12.9)*	*(14.7)*
CH_4	**12.7**	**10.4**	**11.7**	**12.8**	**13.4**	**17.3**	**19.4**
Stationary Sources	+	(0.1)	(0.1)	(0.1)	+	(0.2)	(0.2)
Mobile Sources	(0.1)	(0.1)	+	0.1	0.2	0.3	0.3
Coal Mining	NC	+	0.1	+	(0.1)	0.1	1.0
Abandoned Coal Mines	+	(0.3)	(0.4)	(0.5)	(0.4)	(0.3)	(0.6)
Natural Gas Systems	(1.6)	(6.4)	(5.7)	(5.4)	(6.2)	(5.3)	(1.2)
Petroleum Systems	14.5	11.2	10.7	10.3	9.9	9.7	8.8
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	NC	+	+	+	0.1	0.1	0.1
Manure Management	+	+	(0.6)	+	(0.1)	+	+
Rice Cultivation	NC	NC	NC	+	NC	NC	NC
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Landfills	0.1	5.9	7.6	8.3	10.0	13.0	11.3
Wastewater Treatment	(0.1)	+	+	+	+	+	(0.2)
International Bunker Fuels	NC	NC	+	+	+	NC	+
N_2O	**12.9**	**32.9**	**37.2**	**14.3**	**27.0**	**26.9**	**9.3**
Stationary Sources	+	+	+	(0.1)	+	(0.3)	(0.3)
Mobile Sources	(0.3)	(0.5)	(0.6)	+	1.0	1.9	2.7
Adipic Acid	NC	NC	NC	NC	NC	NC	0.2
Nitric Acid	NC	NC	NC	NC	NC	NC	0.9
Manure Management	+	+	+	+	+	+	+
Agricultural Soil Management	13.1	33.4	37.8	14.3	25.8	25.2	5.7
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Human Sewage	(0.1)	(0.1)	(0.1)	+	+	(0.1)	(0.1)
N_2O Product Usage	NC	NC	NC	NC	NC	NC	NC
Waste Combustion	0.1	+	+	+	0.1	0.1	0.1
Settlements Remaining Settlements	0.1	+	+	+	+	+	0.2
Forest Land Remaining Forest Land	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels	NC	NC	+	+	+	NC	+
HFCs, PFCs, and SF_6	**(0.5)**	**(2.3)**	**(3.3)**	**(4.2)**	**(4.6)**	**(5.6)**	**(6.0)**
Substitution of Ozone Depleting Substances	NC	(2.1)	(3.0)	(3.8)	(4.6)	(5.3)	(6.0)
Aluminum Production	0.1	+	+	+	NC	+	+
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Electrical Transmission and Distribution	(0.6)	(0.3)	(0.3)	(0.4)	(0.1)	(0.2)	(0.1)
Magnesium Production and Processing	+	+	+	+	+	(0.1)	+
Net Change in Total Emissions[b]	**20.9**	**53.9**	**62.7**	**29.1**	**86.2**	**57.7**	**58.9**
Percent Change	**0.3%**	**0.8%**	**0.9%**	**0.4%**	**1.3%**	**0.8%**	**0.9%**

+ 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] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from international bunker fuels and biomass combustion.
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	1990	1998	1999	2000	2001	2002	2003
Forest Land Remaining Forest Land	175.9	186.7	113.9	116.9	116.9	116.9	116.9
Cropland Remaining Cropland	(25.0)	(20.3)	(20.3)	(20.5)	(20.7)	(21.3)	(22.0)
Land Converted to Cropland[a]	1.5	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Grassland Remaining Grassland[a]	(4.5)	7.5	7.5	7.4	7.4	7.4	7.3
Land Converted to Grassland[a]	(17.6)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Settlements Remaining Settlements	1.5	(13.0)	(16.7)	(17.0)	(20.8)	(21.1)	(25.0)
Net Change in Total Flux	**131.7**	**137.0**	**60.4**	**62.9**	**58.9**	**57.8**	**53.2**
Percent Change	**12.6%**	**15.5%**	**7.3%**	**7.6%**	**7.1%**	**7.0%**	**6.4%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)
[a] Estimates for this category was reported in Cropland Remaining Cropland in the previous inventory.
Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere, or an increase in net sequestration.
Note: Totals may not sum due to independent rounding.

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