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

1990 – 2003

APRIL 15, 2005

U.S. Environmental Protection Agency

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U.S.A.

[Inside Front Cover]

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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.

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

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

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Executive Summary

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…is to achieve…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 2003. 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 IPCC methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

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

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

[2] Article 2 of the 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>.

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

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 other greenhouse gases, including tropospheric and stratospheric ozone. These gases include carbon monoxide (CO), oxides of nitrogen (NO_x), and non-methane 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. Since the pre-industrial era (i.e., ending about 1750), concentrations of these greenhouse gases have increased by 31, 150, and 16 percent, respectively (IPCC 2001).

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) 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 ODSs 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).

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 relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

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

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 2003 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

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[6] Albedo is a measure of the Earth's reflectivity; see the Glossary (Annex 6.8) for definition.

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

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

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

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

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

In 2003, total U.S. greenhouse gas emissions were 6,900.2 Tg CO_2 Eq. Overall, total U.S. emissions have risen by 13 percent from 1990 to 2003, while the U.S. gross domestic product has increased by 46 percent over the same period (BEA 2004). Emissions rose slightly from 2002 to 2003, increasing by 0.6 percent (42.2 Tg CO_2 Eq.). The following factors were primary contributors to this increase: 1) moderate economic growth in 2003, leading to increased demand for electricity and fossil fuels, 2) increased natural gas prices, causing some electric power producers to switch to burning coal, and 3) a colder winter, which caused an increase in the use of heating fuels, primarily in the residential end-use sector.

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 2003.

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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**5,009.6**	**5,580.0**	**5,607.2**	**5,678.0**	**5,858.2**	**5,744.8**	**5,796.8**	**5,841.5**
Fossil Fuel Combustion	4,711.7	5,263.2	5,278.7	5,345.9	5,545.1	5,448.0	5,501.4	5,551.6
Non-Energy Use of Fuels	108.0	120.3	135.4	141.6	124.7	120.1	118.8	118.0
Iron and Steel Production	85.4	71.9	67.4	64.4	65.7	58.9	55.1	53.8
Cement Manufacture	33.3	38.3	39.2	40.0	41.2	41.4	42.9	43.0
Waste Combustion	10.9	17.8	17.1	17.6	18.0	18.8	18.8	18.8
Ammonia Production and Urea Application	19.3	20.7	21.9	20.6	19.6	16.7	18.6	15.6
Lime Manufacture	11.2	13.7	13.9	13.5	13.3	12.8	12.3	13.0
Natural Gas Flaring	5.8	7.9	6.6	6.9	5.8	6.1	6.2	6.0
Limestone and Dolomite Use	5.5	7.2	7.4	8.1	6.0	5.7	5.9	4.7
Aluminum Production	6.3	5.6	5.8	5.9	5.7	4.1	4.2	4.2
Soda Ash Manufacture and Consumption	4.1	4.4	4.3	4.2	4.2	4.1	4.1	4.1
Petrochemical Production	2.2	2.9	3.0	3.1	3.0	2.8	2.9	2.8
Titanium Dioxide Production	1.3	1.8	1.8	1.9	1.9	1.9	2.0	2.0
Phosphoric Acid Production	1.5	1.5	1.6	1.5	1.4	1.3	1.3	1.4
Ferroalloys	2.0	2.0	2.0	2.0	1.7	1.3	1.2	1.4
Carbon Dioxide Consumption	0.9	0.8	0.9	0.8	1.0	0.8	1.0	1.3
Land-Use Change and Forestry (Sinks)[a]	*(1,042.0)*	*(930.0)*	*(881.0)*	*(826.1)*	*(822.4)*	*(826.9)*	*(826.5)*	*(828.0)*
International Bunker Fuels[b]	*113.5*	*109.9*	*114.6*	*105.3*	*101.4*	*97.9*	*89.5*	*84.2*
Biomass Combustion[b]	*216.7*	*233.2*	*217.2*	*222.3*	*226.8*	*200.5*	*207.2*	*216.8*
CH_4	**605.3**	**579.5**	**569.1**	**557.3**	**554.2**	**546.8**	**542.5**	**545.0**
Landfills	172.2	147.4	138.5	134.0	130.7	126.2	126.8	131.2
Natural Gas Systems	128.3	133.6	131.8	127.4	132.1	131.8	130.6	125.9
Enteric Fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Coal Mining	81.9	62.6	62.8	58.9	56.2	55.6	52.4	53.8
Manure Management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Wastewater Treatment	24.8	31.7	32.6	33.6	34.3	34.7	35.8	36.8
Petroleum Systems	20.0	18.8	18.5	17.8	17.6	17.4	17.1	17.1
Rice Cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Stationary Sources	7.8	7.4	6.9	7.1	7.3	6.7	6.4	6.7
Abandoned Coal Mines	6.1	8.1	7.2	7.3	7.7	6.9	6.4	6.4
Mobile Sources	4.8	4.0	3.9	3.6	3.4	3.1	2.9	2.7
Petrochemical Production	1.2	1.6	1.7	1.7	1.7	1.4	1.5	1.5
Iron and Steel Production	1.3	1.3	1.2	1.2	1.2	1.1	1.0	1.0
Agricultural Residue Burning	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**382.0**	**396.3**	**407.8**	**382.1**	**401.9**	**385.8**	**380.5**	**376.7**
Agricultural Soil Management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Mobile Sources	43.7	55.2	55.3	54.6	53.2	49.0	45.6	42.1
Manure Management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Human Sewage	13.0	14.7	15.0	15.4	15.6	15.6	15.7	15.9
Nitric Acid	17.8	21.2	20.9	20.1	19.6	15.9	17.2	15.8
Stationary Sources	12.3	13.5	13.4	13.5	14.0	13.5	13.5	13.8
Settlements Remaining Settlements	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0
Adipic Acid	15.2	10.3	6.0	5.5	6.0	4.9	5.9	6.0
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Waste Combustion	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
Agricultural Residue Burning	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4

Forest Land Remaining Forest Land	0.1	0.3	0.4	0.5	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*
HFCs, PFCs, and SF_6	**91.2**	**121.7**	**135.7**	**134.8**	**138.9**	**129.5**	**138.3**	**137.0**
Substitution of Ozone Depleting Substances	0.4	46.5	56.6	65.8	75.0	83.3	91.5	99.5
Electrical Transmission and Distribution	29.2	21.7	17.1	16.4	15.6	15.4	14.7	14.1
HCFC-22 Production	35.0	30.0	40.1	30.4	29.8	19.8	19.8	12.3
Semiconductor Manufacture	2.9	6.3	7.1	7.2	6.3	4.5	4.4	4.3
Aluminum Production	18.3	11.0	9.1	9.0	9.0	4.0	5.2	3.8
Magnesium Production and Processing	5.4	6.3	5.8	6.0	3.2	2.6	2.6	3.0
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. 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.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2003. 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. Methane 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: 2003 Greenhouse Gas Emissions by Gas

Overall, from 1990 to 2003, total emissions of CO_2 increased by 832.0 Tg CO_2 Eq. (17 percent), while CH_4 and N_2O emissions decreased by 60.4 Tg CO_2 Eq. (10 percent) and 5.2 Tg CO_2 Eq. (1 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 45.8 Tg CO_2 Eq. (50 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 12 percent of total emissions in 2003. 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, atmospheric concentrations of CO_2 have risen about 31 percent (IPCC 2001), principally due to the combustion of fossil fuels. Within the United States, fuel combustion accounted for 95 percent of CO_2 emissions in 2003. Globally, approximately 24,240 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2000, 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: 2003 Sources of CO_2

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for a nearly constant 80 percent of GWP weighted emissions since 1990. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 2003. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 13 years, and (2) significant growth in emissions from transportation activities and electricity generation. Between 1990 and 2003, CO_2 emissions from fossil fuel combustion increased from 4,711.7 Tg CO_2 Eq. to 5,551.6 Tg CO_2 Eq.—an 18 percent total increase over the thirteen-year period. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

From 2002 to 2003, these emissions increased by 50.2 Tg CO_2 Eq. (1 percent). A number of factors played a major role in the magnitude of this increase. The U.S. economy experienced moderate growth from 2002, causing an increase in the demand for fuels. The price of natural gas escalated dramatically, causing some electric power producers to switch to coal, which remained at relatively stable prices. Colder winter conditions brought on more demand for heating fuels, primarily in the residential sector. Though a cooler summer partially offset demand for electricity as the use of air-conditioners decreased, electricity consumption continued to increase in 2003. The primary drivers behind this trend were the growing economy and the increase in U.S. housing stock. Use of nuclear and renewable fuels remained relatively stable. Nuclear capacity decreased slightly, for the first time since 1997. Use of renewable fuels rose slightly due to increases in the use of hydroelectric power and biofuels.

Figure ES-6: 2003 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure ES-7: 2003 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. In reality, sources of electricity vary widely in carbon intensity. By assuming the same carbon intensity for each end-use sector's electricity consumption, for example, emissions attributed to the residential end-use sector may be underestimated, while emissions attributed to the industrial end-use sector may be overestimated. 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.

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

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

End-Use Sector	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Transportation	**1,449.8**	**1,606.4**	**1,636.5**	**1,693.9**	**1,741.0**	**1,723.1**	**1,755.4**	**1,770.4**
Combustion	1,446.8	1,603.3	1,633.4	1,690.8	1,737.7	1,719.7	1,752.3	1,767.2
Electricity	3.0	3.1	3.1	3.2	3.4	3.4	3.2	3.2
Industrial	**1,553.9**	**1,703.0**	**1,668.5**	**1,651.2**	**1,684.4**	**1,587.4**	**1,579.0**	**1,572.9**
Combustion	882.8	963.8	911.6	888.1	905.0	878.2	876.6	858.6
Electricity	671.1	739.2	757.0	763.1	779.4	709.3	702.4	714.3
Residential	**924.8**	**1,040.7**	**1,044.4**	**1,063.5**	**1,124.2**	**1,116.2**	**1,145.0**	**1,168.9**
Combustion	339.6	370.6	338.6	359.3	379.1	367.0	371.4	385.1
Electricity	585.3	670.2	705.8	704.2	745.0	749.2	773.6	783.8
Commercial	**755.1**	**876.7**	**892.9**	**901.2**	**959.5**	**972.7**	**973.9**	**983.1**
Combustion	224.2	237.2	219.7	222.3	235.2	226.7	230.0	234.0
Electricity	530.9	639.5	673.2	678.9	724.3	745.9	743.9	749.2
U.S. Territories	**28.0**	**36.4**	**36.3**	**36.2**	**35.9**	**48.6**	**48.1**	**56.2**
Total	**4,711.7**	**5,263.2**	**5,278.7**	**5,345.9**	**5,545.1**	**5,448.0**	**5,501.4**	**5,551.6**
Electricity Generation	**1,790.3**	**2,051.9**	**2,139.0**	**2,149.3**	**2,252.1**	**2,207.8**	**2,223.0**	**2,250.5**

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 32 percent of CO_2 emissions from fossil fuel combustion in 2003.[10] 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 2003. 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 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2003. Both sectors relied heavily on electricity for meeting energy demands, with 67 and 76 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 35 percent of U.S. energy from fossil fuels and emitted 41 percent of the CO_2 from fossil fuel combustion in 2003. 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 93 percent of all coal consumed for energy in the United States in 2003. 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:

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[10] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 33 percent of U.S. emissions from fossil fuel combustion in 2003.

- Carbon dioxide emissions from iron and steel production decreased to 53.8 Tg CO_2 Eq. in 2003, and have declined by 31.7 Tg CO_2 Eq. (37 percent) from 1990 through 2003, due to reduced domestic production of pig iron, sinter, and coal coke.
- Carbon dioxide emissions from waste combustion (18.8 Tg CO_2 Eq. in 2003) increased by 7.9 Tg CO_2 Eq. (72 percent) from 1990 through 2003, 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 214.0 Tg CO_2 Eq. (21 percent) from 1990 through 2003. This decline was primarily attributable to forest soils, a result of the slowed rate of forest area increases after 1997.

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 150 percent (IPCC 2001). Experts believe that over half of this atmospheric increase was due to emissions from 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: 2003 U.S. Sources of CH_4

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

- Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2003, landfill CH_4 emissions were 131.2 Tg CO_2 Eq. (approximately 24 percent of total CH_4 emissions), which represents a decline of 41.1 Tg CO_2 Eq., or 24 percent, since 1990.
- Methane emissions from coal mining declined by 28.1 Tg CO_2 Eq. (34 percent) from 1990 to 2003, as a result of the mining of less gassy coal from underground mines and the increased use of methane collected from degasification systems.

Nitrous Oxide Emissions

Nitrous oxide 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 atmospheric concentration of N_2O has risen by approximately 16 percent (IPCC 2001). 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: 2003 U.S. Sources of N_2O

Some significant trends in U.S. emissions of N_2O included 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 67 percent (253.5 Tg CO_2 Eq.).
- In 2003, N_2O emissions from mobile combustion were 42.1 Tg CO_2 Eq. (approximately 11 percent of U.S. N_2O emissions). From 1990 to 2003, N_2O emissions from mobile combustion decreased by 4 percent.

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: 2003 U.S. Sources of HFCs, PFCs, and SF_6

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

- Emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) have been increasing from small amounts in 1990 to 99.5 Tg CO_2 Eq. in 2003. Emissions from substitutes for ozone depleting substances are both the largest and the fastest growing source of HFC, PFC and SF_6 emissions.
- 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 79 percent (14.5 Tg CO_2 Eq.) from 1990 to 2003, due to both industry emission reduction efforts and lower domestic aluminum production. Emissions from the production of HCFC-22 decreased by 65 percent (22.6 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 (15.1 Tg CO_2 Eq.) from 1990 to 2003, 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), this Inventory of U.S. Greenhouse Gas Emissions and Sinks 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Energy	5,141.7	5,712.8	5,737.7	5,802.6	5,985.3	5,877.3	5,920.7	5,963.4
Industrial Processes	299.9	327.1	334.9	329.2	332.1	304.7	315.4	308.6
Solvent and Other Product Use	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Agriculture	426.5	432.8	449.8	425.9	444.1	437.5	432.4	433.3
Land-Use Change and Forestry (Emissions)	5.6	6.4	6.5	6.6	6.3	6.2	6.4	6.4
Waste	210.1	193.7	186.0	183.1	180.6	176.5	178.3	183.8
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Land-Use Change and Forestry (Sinks)	(1042.0)	(930.0)	(881.0)	(826.1)	(822.4)	(826.9)	(826.5)	(828.0)
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

* Sinks are only included in net emissions total, and are based partially on projected activity data.
Note: Totals may not sum due to independent rounding.
Note: 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 2003. In 2003, 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, respectively). Overall, emission sources in the Energy chapter account for a combined 87 percent of total U.S. greenhouse gas emissions in 2003.

Figure ES-12: 2003 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, 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 2003.

Solvent and Other Product Use

The Solvent and Other Product Use chapter contains emissions 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 less than 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2003.

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. Methane and N_2O were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented about 21 percent and 7 percent of total CH_4 emissions from anthropogenic activities, respectively in 2003. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2003, accounting for 67 percent. In 2003, emission sources accounted for in the Agricultural chapters were responsible for 6.3 percent of total U.S. greenhouse gas emissions.

Land-Use Change and Forestry

The 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 91 percent of total 2003 sequestration, urban trees accounted for 7 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 1 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2003. 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 approximately one and a third 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 2003 resulted in a net carbon sequestration of 828.0 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 14 percent of total U.S. CO_2 emissions, or 12 percent of total gross greenhouse gas emissions in 2003. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 21 percent between 1990 and 2003. 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, as did annual carbon accumulation in agricultural soils. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for 1990 through 1999).

Land use, land-use change, and forestry activities in 2003 also resulted in emissions of N_2O (6.4 Tg CO_2 Eq.). Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 14 percent between 1990 and 2003.

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

Sink Category	1990	1997	1998	1999	2000	2001	2002	2003
Forest Land Remaining Forest Land	**(949.3)**	**(851.0)**	**(805.5)**	**(751.7)**	**(747.9)**	**(750.9)**	**(751.5)**	**(752.7)**
Changes in Forest Carbon Stocks	(949.3)	(851.0)	(805.5)	(751.7)	(747.9)	(750.9)	(751.5)	(752.7)
Cropland Remaining Cropland	**(8.1)**	**(7.4)**	**(4.3)**	**(4.3)**	**(5.7)**	**(7.1)**	**(6.2)**	**(6.6)**
Changes in Agricultural Soil Carbon Stocks	(8.1)	(7.4)	(4.3)	(4.3)	(5.7)	(7.1)	(6.2)	(6.6)
Settlements Remaining Settlements	**(84.7)**	**(71.6)**	**(71.2)**	**(70.0)**	**(68.9)**	**(68.9)**	**(68.8)**	**(68.7)**
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Landfilled Yard Trimmings and Food Scraps	(26.0)	(12.9)	(12.5)	(11.4)	(10.2)	(10.3)	(10.2)	(10.1)
Total	**(1,042.0)**	**(930.0)**	**(881.0)**	**(826.1)**	**(822.4)**	**(826.9)**	**(826.5)**	**(828.0)**

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

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 24 percent of total U.S. CH_4 emissions.[11] Wastewater treatment systems are a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a

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[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 Change and Forestry chapter.

simplified methodology. Overall, in 2003, 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 this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy, Industrial Processes, Solvent Use, Agriculture, 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 2003.

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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Electric Power Industry	1,841.8	2,104.6	2,186.8	2,197.3	2,299.0	2,254.9	2,269.7	2,296.2
Transportation	1,506.8	1,693.0	1,728.7	1,790.0	1,839.6	1,819.8	1,851.6	1,864.4
Industry	1,446.1	1,509.1	1,470.6	1,427.9	1,431.8	1,371.0	1,365.7	1,331.4
Agriculture	473.3	492.0	508.4	486.9	495.3	488.6	485.6	486.4
Commercial	435.4	445.2	424.2	426.8	440.7	431.4	440.2	453.5
Residential	350.9	391.0	358.4	379.5	399.7	387.1	391.6	406.1
U.S. Territories	33.8	42.7	42.7	43.9	47.0	54.1	53.6	62.3
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Land-Use Change and Forestry Sinks	(1,042.0)	(930.0)	(881.0)	(826.1)	(822.4)	(826.9)	(826.5)	(828.0)
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

Note: Totals may not sum. Emissions include CO_2, CH_4, 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 2003. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2003. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing based to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. The remaining 21 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial economic sectors, plus emissions from U.S. Territories. Residences 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; these emissions were dominated by N_2O emissions from agricultural soils instead of CO_2 from fossil fuel combustion. The commercial sector accounted for about 7 percent of emissions, while U.S. territories accounted for 1 percent.

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

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 2003. Emissions from the residential and commercial sectors also increase substantially due to their relatively large share of electricity consumption (e.g., lighting, appliances, etc.). Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, CO_2 accounts for more than 75 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 2003.

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

Economic Sector	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Industry	2,075.7	2,247.3	2,223.2	2,190.1	2,207.7	2,074.0	2,062.9	2,040.1
Transportation	1,509.9	1,696.1	1,731.8	1,793.2	1,843.0	1,823.2	1,854.8	1,867.6
Commercial	981.6	1,083.8	1,093.5	1,104.9	1,161.8	1,170.6	1,178.5	1,196.8
Residential	953.0	1,060.3	1,060.0	1,082.9	1,141.4	1,129.6	1,159.5	1,183.7
Agriculture	534.1	547.4	568.6	537.3	552.3	555.5	548.8	549.8
U.S. Territories	33.8	42.7	42.7	43.9	47.0	54.1	53.6	62.3
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Land-Use Change and Forestry Sinks	(1,042.0)	(930.0)	(881.0)	(826.1)	(822.4)	(826.9)	(826.5)	(828.0)
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

See Table 2-16 for more detailed data.

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

[BEGIN BOX]

Box ES-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 2003; 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 1.0 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

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[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.

concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.5 percent per year.

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

Variable	**1991**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**Growth Rate**[f]
Greenhouse Gas Emissions[a]	99	110	110	111	114	112	113	113	**1.0%**
Energy Consumption[b]	100	112	113	114	117	114	116	116	**1.2%**
Fossil Fuel Consumption[b]	99	112	113	114	117	115	116	116	**1.2%**
Electricity Consumption[b]	102	117	121	124	128	125	129	130	**2.1%**
GDP[c]	100	122	127	133	138	139	142	146	**3.0%**
Population[d]	101	109	110	112	113	114	115	116	**1.1%**
Atmospheric CO_2 Concentration[e]	100	103	104	104	104	105	105	106	**0.5%**

[a] GWP weighted values
[b] Energy content weighted values (EIA 2004)
[c] Gross Domestic Product in chained 2000 dollars (BEA 2004)
[d] (U.S. Census Bureau 2004)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2004)
[f] Average annual growth rate

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

[END BOX]

Ambient Air Pollutant Emissions

In the United States, CO, NO_x, NMVOCs, SO_2 are referred to as "ambient air pollutants," and are regulated under the Clean Air Act in an effort to protect human health and the environment. These pollutants 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 pollutants 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 ambient air pollutants (EPA 2004).[13] Table ES-9 shows that fuel combustion accounts for the majority of emissions of these 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
NO_x	**22,860**	**22,284**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**18,573**
Stationary Fossil Fuel Combustion	9,884	9,578	9,419	8,344	8,002	7,667	7,523	7,222
Mobile Fossil Fuel Combustion	12,134	11,768	11,592	11,300	11,395	10,823	10,389	10,418
Oil and Gas Activities	139	130	130	109	111	113	135	124
Waste Combustion	82	140	145	143	114	114	134	121

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

Industrial Processes	591	629	637	595	626	656	630	648
Solvent Use	1	3	3	3	3	3	5	4
Agricultural Burning	28	34	35	34	35	35	33	33
Waste	0	3	3	3	2	2	2	2
CO	**130,580**	**101,138**	**98,984**	**94,361**	**92,895**	**89,329**	**87,451**	**85,077**
Stationary Fossil Fuel Combustion	4,999	3,927	3,927	5,024	4,340	4,377	4,020	4,454
Mobile Fossil Fuel Combustion	119,482	90,284	87,940	83,484	83,680	79,972	78,574	75,526
Oil and Gas Activities	302	333	332	145	146	147	116	125
Waste Combustion	978	2,668	2,826	2,725	1,670	1,672	1,672	1,674
Industrial Processes	4,124	3,153	3,163	2,156	2,217	2,339	2,308	2,431
Solvent Use	4	1	1	46	46	45	46	65
Agricultural Burning	689	767	789	767	790	770	707	794
Waste	1	5	5	13	8	8	8	8
NMVOCs	**20,937**	**16,994**	**16,403**	**15,869**	**15,228**	**15,048**	**14,222**	**13,939**
Stationary Fossil Fuel Combustion	912	1,016	1,016	1,045	1,077	1,080	926	1,007
Mobile Fossil Fuel Combustion	10,933	7,928	7,742	7,586	7,230	6,872	6,560	6,351
Oil and Gas Activities	555	442	440	414	389	400	340	345
Waste Combustion	222	313	326	302	257	258	281	263
Industrial Processes	2,426	2,038	2,047	1,813	1,773	1,769	1,725	1,711
Solvent Use	5,217	5,100	4,671	4,569	4,384	4,547	4,256	4,138
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	673	157	161	140	119	122	133	125
SO_2	**20,936**	**17,091**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,463**
Stationary Fossil Fuel Combustion	18,407	15,104	15,191	13,915	12,848	12,461	11,946	12,477
Mobile Fossil Fuel Combustion	793	659	665	704	632	624	631	634
Oil and Gas Activities	390	312	310	283	286	289	315	293
Waste Combustion	39	29	30	30	29	30	24	28
Industrial Processes	1,306	985	991	984	1,031	1,047	1,009	1,029
Solvent Use	0	1	1	1	1	1	2	2
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	0	1	1	1	1	1	1	1

Source: (EPA 2004) 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.

Figure ES-16: 2003 Key Sources – 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 Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (hereafter referred to as the *IPCC Good Practice Guidance*) and require that countries provide single point estimates of uncertainty for many 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.

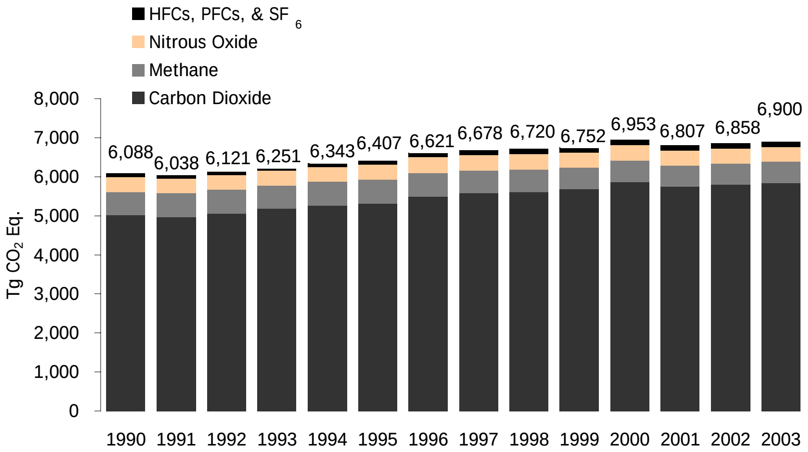

Figure ES-1: U.S. GHG Emissions by Gas

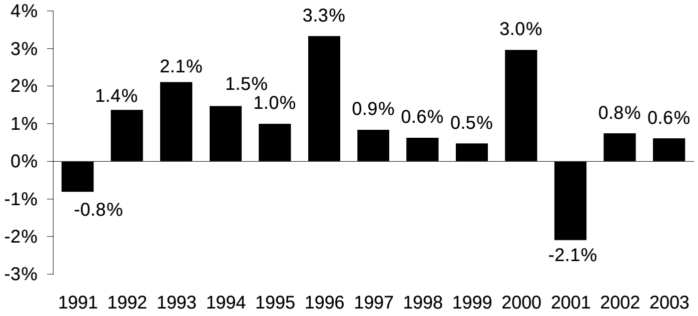

Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

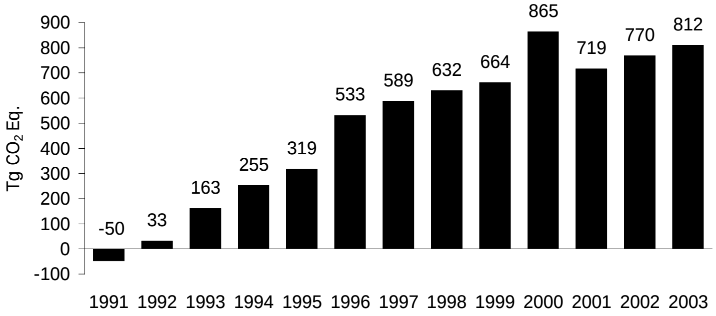

Figure ES-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

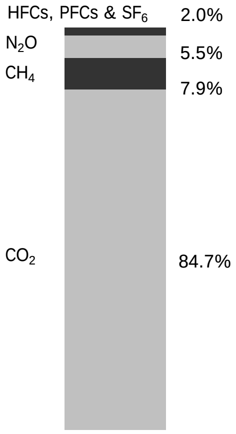

Figure ES-4: 2003 Greenhouse Gas Emissions by Gas

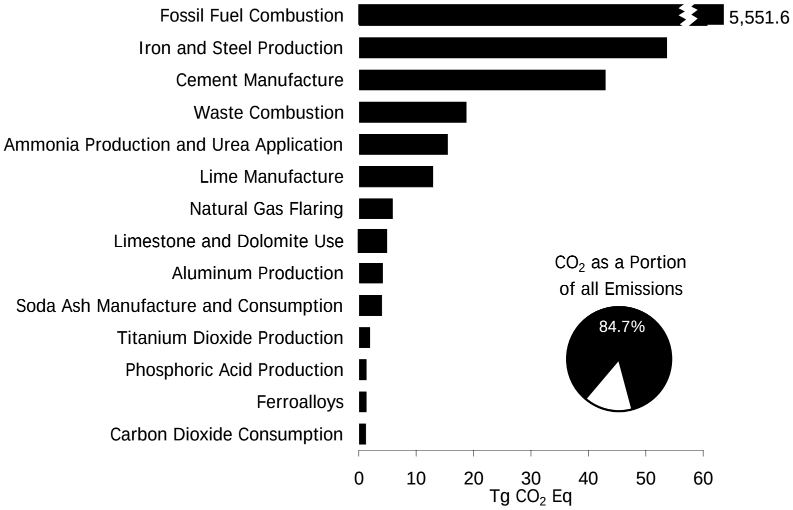

Figure ES-5: 2003 Sources of CO$_2$

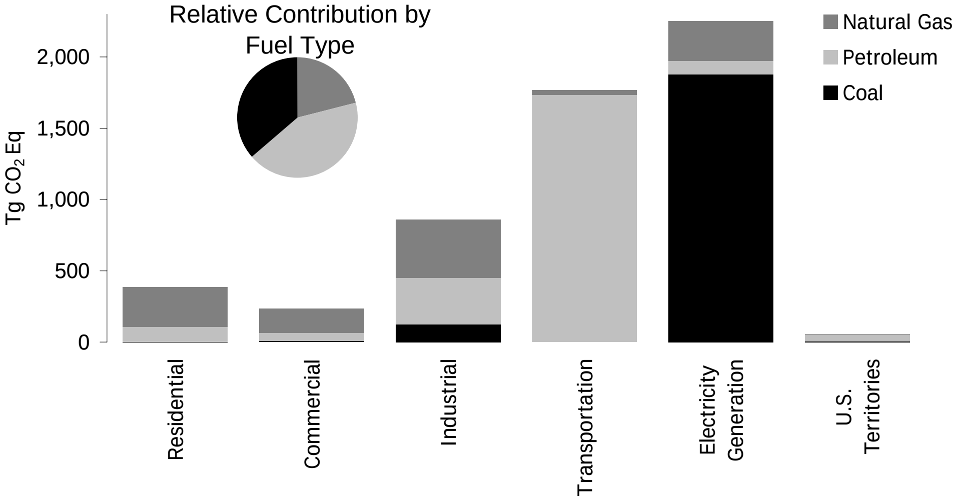

Figure ES-6: 2003 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricity generation.

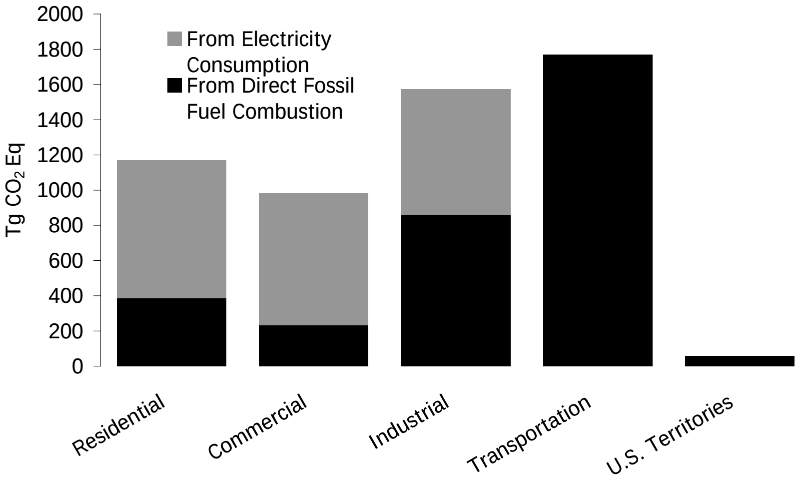

Figure ES-7: 2003 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

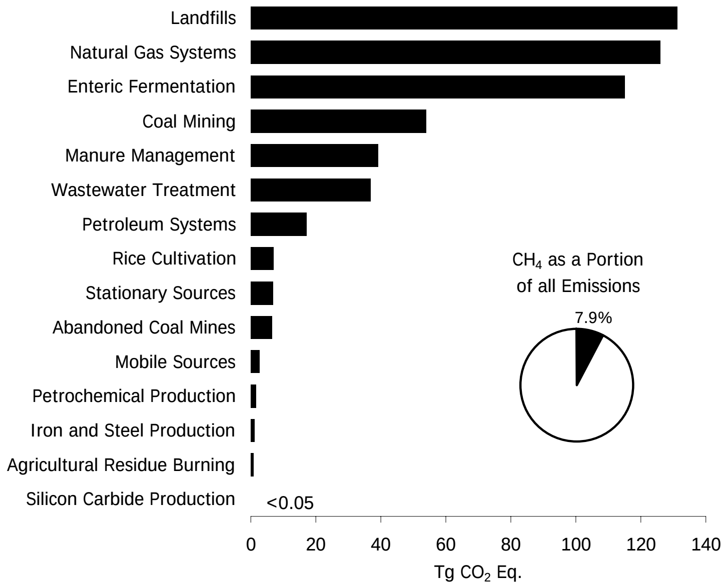

Figure ES-8: 2003 Sources of CH_4

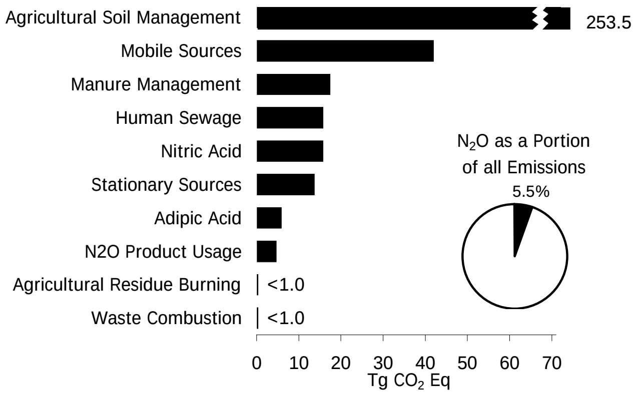

Figure ES-9: 2003 Sources of N_2O

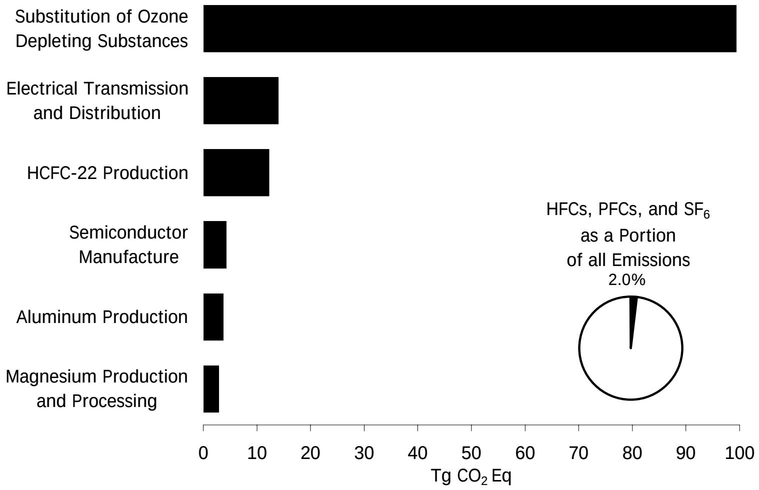

Figure ES-10: 2003 Sources of HFCs, PFCs, and SF_6

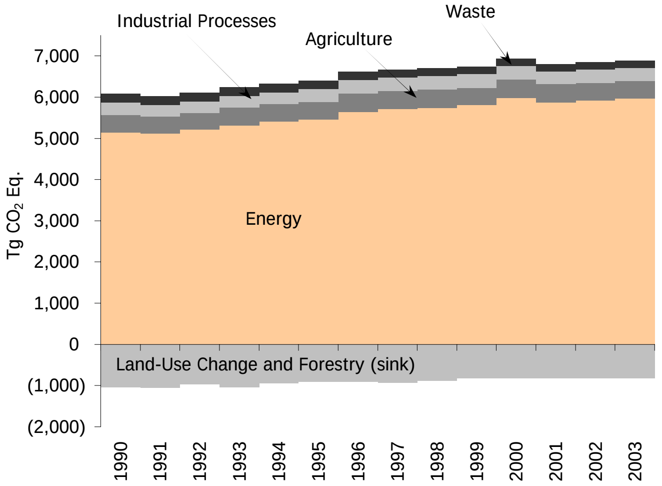

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

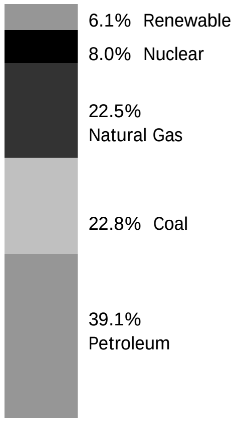

Figure ES-12: 2003 U.S. Energy Consumption by Energy Source

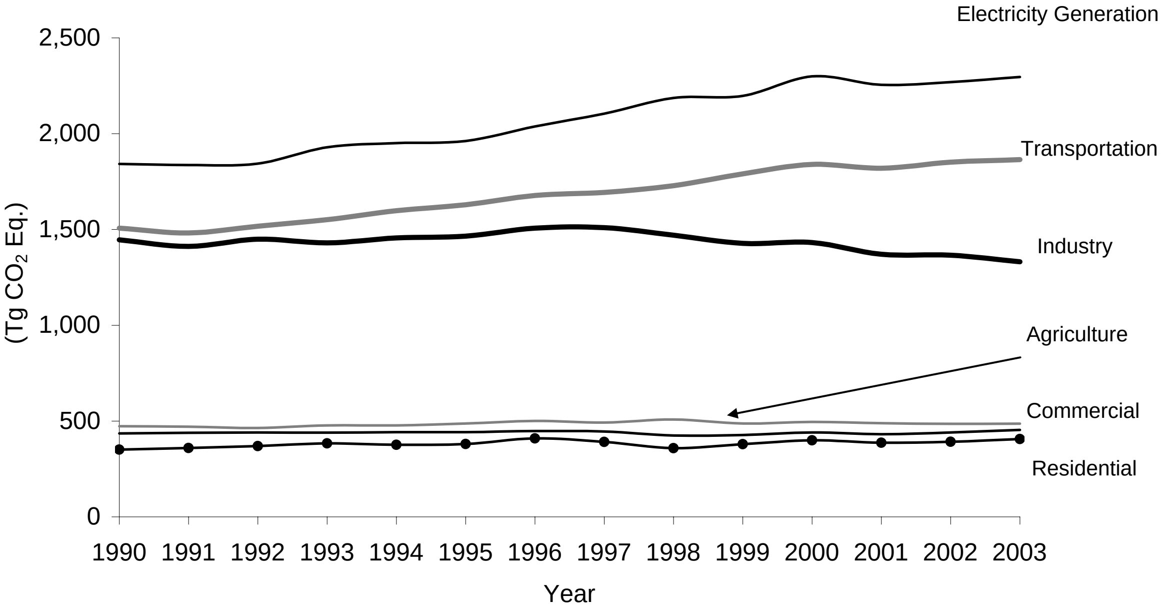

Figure ES-13: Emissions Allocated to Economic Sectors
Note: Does not include U.S. territories.

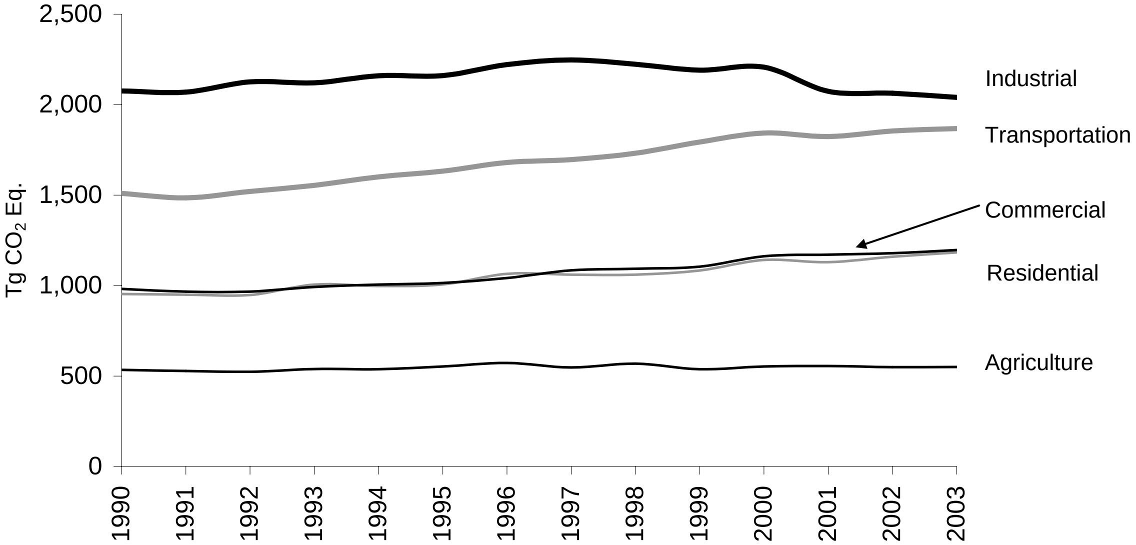

Figure ES-14: Emissions with Electricity Distributed to Economic Sectors
Note: Does not include U.S. territories.

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

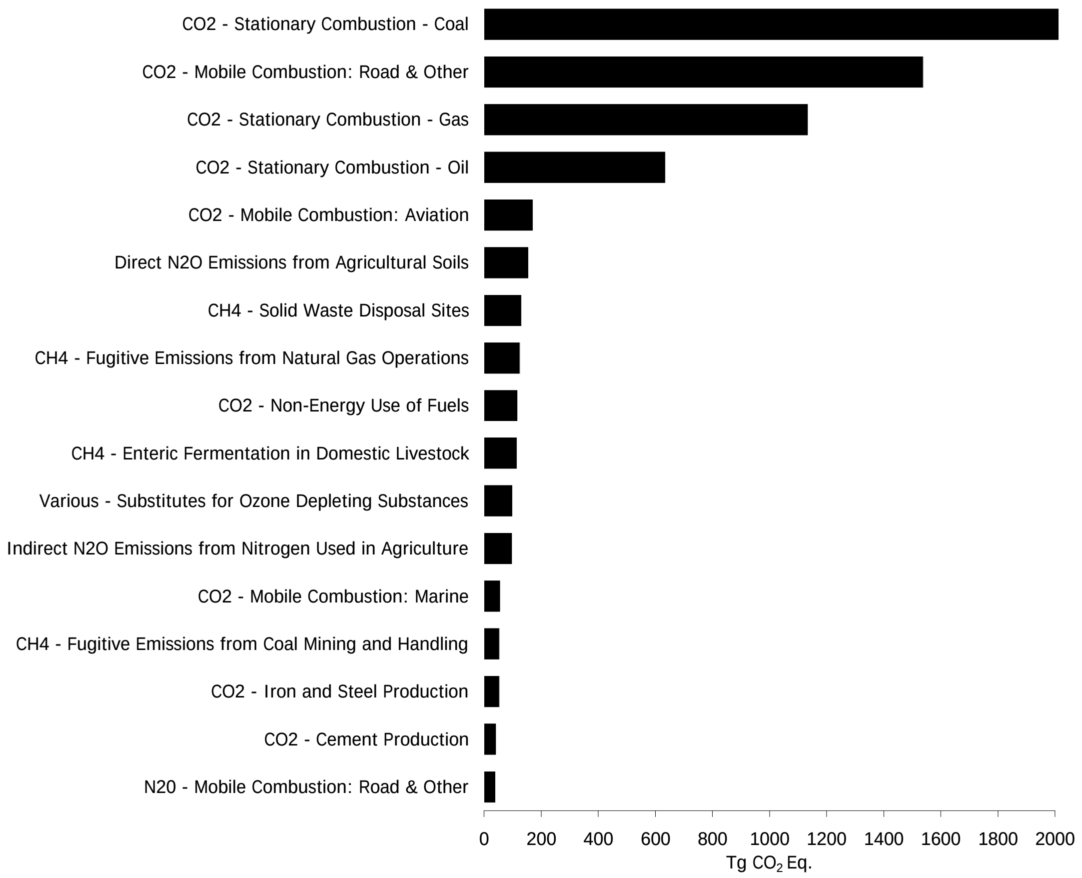

Figure ES-16: 2003 Key Sources - Tier 1 Level Assessment

Note: For a complete discussion of the key source analysis see Annex 1.

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 2003. 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 the UNFCCC is to achieve…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 charter of the IPCC is to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies (IPCC 1996). 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, 11-13 September 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 1996). 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 simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). 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).

Carbon dioxide, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems.

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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.

Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global atmospheric concentration (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]	372.3	1.729-1.843[c]	0.317-0.318[c]	4.7-4.8	80
Rate of concentration change[d]	1.5[e]	0.007[e]	0.0008	0.24	1.0
Atmospheric Lifetime	50-200[f]	12[g]	114[g]	3,200	>50,000

Source: Current atmospheric concentrations for CO_2, CH_4, N_2O, and SF_6 are from Blasing and Jones (2003). All other data is from IPCC (2001).

[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.

[b] Concentration for SF_6 was measured in 2001; concentration for CF_4 was measured in 2000. Concentrations for all other gases were measured in 2002.

[c] The low and high endpoints of the range represent concentrations from Tasmania, a mid-latitude Southern-Hemisphere site, and Ireland, a mid-latitude Northern-Hemisphere site, respectively.

[d] Rate is calculated over the period 1990 to 1999.

[e] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH_4 over the period 1990 to 1999.

[f] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

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

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

Water Vapor (H_2O). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to affect directly the average global concentration of water vapor, but, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. While a warmer atmosphere has an increased water holding capacity, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide. In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 372.3 ppmv in 2001, a 33 percent increase (IPCC 2001 and Blasing and Jones 2004).[7,8] The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2.

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

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

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

Methane. Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 150 percent since pre-industrial times, 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).

Methane is removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that may increase the atmospheric lifetime of CH_4 (IPCC 2001).

Nitrous Oxide. Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of N_2O has increased by 17 percent since 1750, from a pre-industrial value of about 270 ppb to 314 ppb in 1998, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 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. Ozone, CO, SO_2, nitrogen dioxide (NO_2) and particulate matter are included in the category referred to as "ambient air pollutants" in the United States under the Clean Air Act[11] and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

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

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

[11] [42 U.S.C § 7408, CAA § 108]

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 importation of HCFCs by non-Article 5[12] 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 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.[13] 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). Nonmethane 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

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[12] 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.

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

and biomass burning. Aerosols affect radiative forcing differently than greenhouse gases, and their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols is typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect 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[14] 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.[15] 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 GWP 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.)[16] 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,

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

[15] 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).

[16] Carbon comprises 12/44$^{\text{ths}}$ of carbon dioxide by weight.

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

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±35 percent. The parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon although other time horizon values are available.

> *Greenhouse gas emissions and removals should be presented on a gas-by-gas basis in units of mass... In addition, consistent with decision 2/CP.3, Parties should report aggregate emissions and removals of greenhouse gases, expressed in CO_2 equivalent terms at summary inventory level, using GWP values provided by the IPCC in its Second Assessment Report... based on the effects of greenhouse gases over a 100-year time horizon.*[17]

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.

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[17] 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)

[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 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[18] 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 2003 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. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table 1-4. All estimates provided throughout this report are also presented in unweighted units.

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

Table 1-4: Effects on U.S. Greenhouse Gas Emission Trends Using IPCC SAR and TAR GWP Values (Tg CO_2 Eq.)

	Change from 1990 to 2003		**Revisions to Annual Estimates**	
Gas	**SAR**	**TAR**	**1990**	**2003**
CO_2	832.0	832.0	0	0
CH_4	(60.4)	(66.1)	57.7	51.9
N_2O	(5.2)	(5.0)	(17.3)	(17.0)
HFCs, PFCs, and SF_6	45.8	45.5	(2.7)	(2.9)
Total	**812.1**	**806.3**	**37.7**	**31.9**
Percent Change	**13.3%**	**13.2%**	**0.6%**	**0.5%**

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

Table 1-5 below shows a comparison of total emission estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (8.3 percent in 2003), due the predominance of CH_4 emissions in this sector. Emissions from all other sectors were comprised of mainly CO_2 or a mix of gases, which moderated the effect of the changes.

Table 1-5: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg CO_2 Eq.)

Sector	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Energy								
SAR GWP (Used In Inventory)	5,141.7	5,712.8	5,737.3	5,802.6	5,985.3	5,877.3	5,920.7	5,963.4
TAR GWP	5,162.9	5,732.0	5,756.6	5,820.7	6,003.7	5,895.6	5,938.6	5,981.1
Difference (%)	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Industrial Processes								
SAR GWP (Used In Inventory)	299.9	327.1	334.9	329.2	332.1	304.7	315.4	308.6
TAR GWP	296.0	323.3	332.0	325.7	328.4	301.2	311.8	304.9
Difference (%)	(1.3%)	(1.1%)	(0.9%)	(1.1%)	(1.1%)	(1.1%)	(1.1%)	(1.2%)
Solvent and Other Product Use								
SAR GWP (Used In Inventory)	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
TAR GWP	4.1	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Difference (%)	(4.5%)	(4.5%)	(4.5%)	(4.5%)	(4.5%)	(4.5%)	(4.5%)	(4.5%)
Agriculture								
SAR GWP (Used In Inventory)	426.5	432.8	449.8	425.9	444.1	437.5	432.4	433.3
TAR GWP	429.2	436.1	452.6	429.7	446.8	440.4	435.6	436.4
Difference (%)	0.6%	0.8%	0.6%	0.9%	0.6%	0.7%	0.7%	0.7%
Land-Use Change and Forestry								
SAR GWP (Used In Inventory)	(1,036.5)	(923.6)	(874.5)	(819.5)	(816.1)	(820.7)	(820.1)	(821.6)
TAR GWP	(1,036.7)	(923.9)	(874.8)	(819.8)	(816.4)	(821.0)	(820.4)	(821.9)
Difference (%)	+	+	+	+	+	+	+	+
Waste								
SAR GWP (Used In Inventory)	210.1	193.7	186.0	183.1	180.6	176.5	178.3	183.8
TAR GWP	228.3	210.1	201.6	198.4	195.6	191.1	193.1	199.1
Difference (%)	8.7%	8.5%	8.4%	8.3%	8.3%	8.3%	8.3%	8.3%
Net Emissions (Sources and Sinks)								
SAR GWP (Used In Inventory)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**
TAR GWP	**5,083.8**	**5,782.2**	**5,872.6**	**5,959.2**	**6,162.6**	**6,012.0**	**6,063.2**	**6,104.1**
Difference (%)	**0.7%**	**0.6%**	**0.6%**	**0.6%**	**0.5%**	**0.5%**	**0.5%**	**0.5%**

NC (No change)

+ Less than 0.05%.

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

[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.

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 is 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 source 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 general 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). 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 Text Box]

Box 1-2: IPCC Good Practice Guidance

In response to a request by Parties in 1998 to the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) prepared and published a report on inventory good practice. The report, entitled *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC Good Practice Guidance),* was developed with extensive participation of experts from the United States and many other countries.[19] It focuses on providing direction to countries to produce emission estimates that are as accurate and transparent as possible, with the least possible uncertainty. In addition, the *IPCC Good Practice Guidance* was designed as a tool to complement the methodologies suggested in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines).*

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[19] See <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

In order to obtain these goals, *IPCC Good Practice Guidance* gives specific guidance in the following areas:

- Selection of the most appropriate estimation method, within the context of the IPCC Guidelines
- Implementation of quality control and quality assurance measures
- Proper assessment and documentation of data and information
- Quantification of uncertainties for most source categories

By providing such direction, the IPCC hopes to help countries provide inventories that are transparent, documented, and comparable.

In addition, the IPCC accepted the *Land Use, Land-Use Change, and Forestry (LULUCF) Good Practice Guidance* report in 2003, and the United States has implemented the new guidance in this Inventory submission.

[End Box]

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). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

1.5. Key Sources

The IPCC's *Good Practice Guidance* (IPCC 2000) defines a key source category as a "[source 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."[20] By definition, key source 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 source categories must also account for the influence of trends of individual source categories. Therefore, a trend assessment is conducted to identify source categories for which significant uncertainty in the estimate would have considerable effects on overall emission trends. This analysis culls out source categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key source 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 source categories for the United States. Using this approach, a number of key source categories were identified based on an assessment of their absolute emission level and/or trend in emissions.

Due to the relative quantity of CO_2 emissions from fossil fuel combustion—particularly from mobile combustion in road vehicles and stationary combustion of coal, gas, and oil—these sources contributed most to this year's level assessment. Additionally, the following sources were identified as key sources based on the level assessments for each year (listed in descending order of their 2003 emissions):

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

- CO_2 emissions from mobile combustion in the aviation sector;
- Direct N_2O from agricultural soils;
- CH_4 from solid waste disposal sites;
- Fugitive emissions from natural gas operations;
- CO_2 from non-energy use of fuel;
- CH_4 from enteric fermentation in domestic livestock;
- Indirect N_2O emissions from nitrogen used in agriculture;
- Fugitive emissions from coal mining;
- CO_2 emissions from iron and steel production;
- CO_2 emissions from cement production; and
- N_2O emissions from mobile combustion in road vehicles.

The remaining key sources identified under the level assessment varied by year. The following five source categories were determined to be key using the level assessment for only part of the complete time series (listed in descending order of their 2003 emissions):

- HFC and PFC emissions from substitutes for ozone depleting substances (1996-2003);
- CO_2 emissions from mobile combustion in the marine sector (1990-1997, 1999-2003);
- CH_4 emissions from manure management (1990-2000);
- CH_4 emissions from wastewater handling (1995 and 1997); and
- HFC-23 emissions from HCFC-22 manufacture (1990-1996, 1998).

Although other sources have fluctuated by greater percentages since 1990, by virtue of their size, CO_2 emissions from mobile combustion from road vehicles and stationary combustion of coal are the greatest contributors to the overall trend for 2003. The third largest contributor to the overall trend in 2003 is emissions from substitutes for ozone depleting substances (ODSs). These emissions have grown quickly with the phase out of ODSs under the Montreal Protocol.

Two additional source categories with trends of note are fugitive emissions from coal mining and PFC emissions from aluminum manufacturing, which decreased from 1990 through 2003 by approximately 34 and 79 percent, respectively. Reductions in emissions from coal mining are primarily due to EPA's voluntary coalbed methane capture program and the mining of less gassy coal than in previous years. PFC emissions have decreased primarily as a result of emission reduction activities by the aluminum industry.

The remaining source categories that were identified as key sources based solely on a trend assessment are listed below (listed in descending order of their 2003 emissions).

- CO_2 emissions from waste incineration;
- Fugitive emissions from oil operations;
- CO_2 emissions from ammonia production and urea application;
- SF_6 emissions from electrical equipment; and
- N_2O emissions from adipic acid production.

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 sources that were not identified by either quantitative method. One additional key source was identified using this qualitative assessment. A brief discussion of the reasoning for the qualitative designation is provided below.

- 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 source 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 1-6 presents the key source categories for the United States based on the Tier 1 approach using emissions data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2003. The table also indicates the criteria used in identifying these source categories (i.e., level, trend, and/or qualitative assessments). Please see Annex 1 for additional information regarding the key source categories in the United States and the methodologies used to identify them.

Table 1-6: Key Source Categories for the United States (1990-2003) Based on Tier 1 Approach

IPCC Source Categories	**Gas**	**Level**	**Trend**	**Qual**[a]	**2003 Emissions (Tg CO_2 Eq.)**
Energy					
CO_2 Emissions from Stationary Combustion - Coal	CO_2	✓	✓		2,013.8
Mobile Combustion: Road & Other	CO_2	✓	✓		1,538.5
CO_2 Emissions from Stationary Combustion - Gas	CO_2	✓	✓		1,134.9
CO_2 Emissions from Stationary Combustion - Oil	CO_2	✓	✓		635.3
Mobile Combustion: Aviation	CO_2	✓	✓		171.3
Fugitive Emissions from Natural Gas Operations	CH_4	✓	✓		125.9
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	✓			118.0
International Bunker Fuels[b]	Several			✓	85.1
Mobile Combustion: Marine	CO_2	✓			57.5
Fugitive Emissions from Coal Mining and Handling	CH_4	✓	✓		53.8
Mobile Combustion: Road & Other	N_2O	✓	✓		39.9
Fugitive Emissions from Oil Operations	CH_4		✓		17.1
Industrial Processes					
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓		99.5
CO_2 Emissions from Iron and Steel Production	CO_2	✓	✓		53.8
CO_2 Emissions from Cement Production	CO_2	✓	✓		43.0
CO_2 Emissions from Ammonia Production and Urea Application	CO_2		✓		15.6
SF_6 Emissions from Electrical Equipment	SF_6		✓		14.1
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	✓	✓		12.3
N_2O Emissions from Adipic Acid Production	N_2O		✓		6.0
PFC Emissions from Aluminum Production	PFCs		✓		3.8
Agriculture					
Direct N_2O Emissions from Agricultural Soils	N_2O	✓			155.3
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	✓	✓		115.0
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	✓	✓		98.2
CH_4 Emissions from Manure Management	CH_4	✓			39.1
Waste					
CH_4 Emissions from Solid Waste Disposal Sites	CH_4	✓	✓		131.2
CH_4 Emissions from Wastewater Handling	CH_4	✓	✓		36.8

CO_2 Emissions from Waste Incineration	CO_2	✓	18.8
Subtotal of Key Source Emissions			**6,833.5**
Total Emissions			**6,900.2**
Percent of Total			**99.0%**

[a] Qualitative criteria.

[b] Emissions from these sources not included in totals.

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis. The Tier 1 approach for identifying key source categories does not directly include an assessment of uncertainty in emission estimates.

1.6. Quality Assurance and Quality Control

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 what 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. For example, the availability of new information or additional detail on techniques or procedures for checking the quality of data inputs or emission calculations could necessitate revising the procedures in the Procedures Manual or preparing a background paper expanding on procedures to be used.

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.

In addition, based on the national QA/QC plan for the Inventory, source-specific QA/QC plans have been developed for a limited 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.

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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (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 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 IPCC provides good practice guidance on two approaches—Tier 1 and Tier 2—to estimating uncertainty for individual source categories. The Tier 1 method is a spreadsheet-based analysis that estimates uncertainties by using the error propagation equation. The spreadsheet employs uncertainty ranges for activity data and emission factors consistent with the sectoral good practice guidance. The Tier 2 uncertainty estimation methodology employs the Monte Carlo Stochastic Simulation technique. The principle of Monte Carlo analysis is to select random values of emission factor and activity data from within their individual probability density functions, and to calculate the corresponding emission values. Tier 2 uncertainty analysis was applied wherever data and resources permitted. Consistent with the 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 quantitative estimates of uncertainty where none currently exist. See Annex 7, Uncertainty, 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.

While there are two types of estimation uncertainty, parameter uncertainty and model uncertainty, the Tier 1 and Tier 2 approaches were applied only to estimate parameter uncertainty of emission estimates. Parameter uncertainty refers to the uncertainty associated with quantifying the parameters used as inputs (e.g., activity data and emission factors) to the emission estimation models. Model uncertainty refers to the uncertainty associated with developing mathematical equations or models to characterize the emission and/or removal processes. Model uncertainties can be evaluated by comparing the model results with the results of other models that are developed to characterize the same emission generation process and through sensitivity analysis. Model uncertainties for some sources are identified, but not evaluated.

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.

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 2003. 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.

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 1-7. 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 1-7: 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 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 necessitating 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 relative to other sources 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 1-8.

Table 1-8: List of Annexes

ANNEX 1 Key Source 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 Stored in Products 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 Ambient Air Pollutants from Stationary Combustion
3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants 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 Carbon Stocks
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

2. Trends in Greenhouse Gas Emissions

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

In 2003, total U.S. greenhouse gas emissions were 6,900.2 teragrams of carbon dioxide equivalent (Tg CO_2 Eq.)[1] (13.3 percent above 1990 emissions). Emissions rose slightly from 2002 to 2003, increasing by 0.6 percent (42.2 Tg CO_2 Eq.). The following factors were primary contributors to this increase: 1) moderate economic growth in 2003, leading to increased demand for electricity and fossil fuels, 2) increased natural gas prices, causing some electric power producers to switch to burning coal, and 3) a colder winter, which caused an increase in the use of heating fuels, primarily in the residential sector. (See the following section for an analysis of emission trends by general economic sectors.) 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 a nearly constant 80 percent of global warming potential (GWP) weighted emissions since 1990. Emissions from this source category grew by 17.8 percent (839.8 Tg CO_2 Eq.) from 1990 to 2003 and were responsible for most of the increase in national emissions during this period. From 2002 to 2003, these emissions increased by 50.2 Tg CO_2 Eq. (0.9 percent), the same rate as the source's average annual growth rate of 1.3 percent from 1990 through 2003. 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.)

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 six 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**	**1999 to 2000**		**2000 to 2001**		**2001 to 2002**		**2002 to 2003**	
Electricity Generation	Coal	87.6	5%	-62.6	-3%	22.2	1%	36.6	2%
Electricity Generation	Natural Gas	20.8	8%	8.4	3%	16.5	6%	-28.0	-9%
Electricity Generation	Petroleum	-5.6	-6%	9.8	11%	-23.5	-23%	18.9	24%
Transportation[a]	Petroleum	47.0	3%	-16.4	-1%	29.4	2%	16.6	1%
Residential	Natural Gas	13.9	5%	-10.7	-4%	6.2	2%	11.5	4%
Commercial	Natural Gas	7.1	4%	-7.9	-5%	4.2	3%	2.0	1%
Industrial	Coal	1.1	1%	-4.4	-3%	-7.9	-6%	0.8	1%
Industrial	Natural Gas	8.2	2%	-38.5	-8%	9.5	2%	-27.6	-6%
All Sectors[b]	**All Fuels[b]**	**199.2**	**4%**	**-97.1**	**-2%**	**53.5**	**1%**	**50.2**	**1%**

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

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, residential and commercial heating fuel demand partially recovered as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal.[2] These increases were offset, in part, by a decline in emissions from electric power producers due primarily to: 1) an increase in net generation of electricity by nuclear plants which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year—thereby reducing electricity demand for air conditioning.

Emissions from fuel combustion increased considerably in 2000, due to several factors. The primary reason for the increase was the robust U.S. economy, which produced a high demand for fuels—especially for petroleum in the transportation sector—despite increases in the price of both natural gas and petroleum. Colder winter conditions relative to the previous year triggered a rise in residential and commercial demand for heating. Additionally, electricity generation became more carbon intensive as coal and natural gas consumption offset reduced hydropower output.

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

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[2] Normals are based on data from 1971 through 2000. Source: EIA (2004b)

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.

Other significant trends in emissions from additional source categories over the fourteen-year period from 1990 through 2003 included the following:

- Carbon dioxide emissions from waste combustion increased by 7.9 Tg CO_2 Eq. (72 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 214.0 Tg CO_2 Eq. (21 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 28.1 Tg CO_2 Eq. (34 percent) from 1990 to 2003, as a result of the mining of less gassy coal from underground mines and the increased use of methane collected from degasification systems.
- 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 79 percent (14.5 Tg CO_2 Eq.) from 1990 to 2003, due to both industry emission reduction efforts and lower domestic aluminum production. Emissions from the production of HCFC-22 decreased by 65 percent (22.6 Tg CO_2 Eq.) from 1990 to 2003, 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 (15.1 Tg CO_2 Eq.) from 1990 to 2003, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

Overall, from 1990 to 2003, total emissions of CO_2 increased by 832.0 Tg CO_2 Eq. (17 percent), while CH_4 and N_2O emissions decreased by 60.4 Tg CO_2 Eq. (10 percent) and 5.2 Tg CO_2 Eq. (just over 1 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 45.8 Tg CO_2 Eq. (50 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 12 percent of total emissions in 2003.

[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 2003; 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 1.0 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 0.5 percent per year.

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

Variable	**1991**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**Growth Rate**[f]
Greenhouse Gas Emissions[a]	99	110	110	111	114	112	113	113	**1.0%**
Energy Consumption[b]	100	112	113	114	117	114	116	116	**1.2%**
Fossil Fuel Consumption[b]	99	112	113	114	117	115	116	116	**1.2%**
Electricity Consumption[b]	102	117	121	124	128	125	129	130	**2.1%**
GDP[c]	100	122	127	133	138	139	142	146	**3.0%**
Population[d]	101	109	110	112	113	114	115	116	**1.1%**
Atmospheric CO_2 Concentration[e]	100	103	104	104	104	105	105	106	**0.5%**

[a] GWP weighted values
[b] Energy content weighted values (EIA 2004a)
[c] Gross Domestic Product in chained 2000 dollars (BEA 2004)
[d] (U.S. Census Bureau 2004)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 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 (2004), U.S. Census Bureau (2004), and emission estimates in this report.

[END BOX]

As an alternative, emissions of all gases can be totaled for each of the IPCC sectors. Over the thirteen year period of 1990 to 2003, total emissions in the Energy, Industrial Processes, Agriculture, and Solvent and Other Product Use sectors climbed by 821.6Tg CO_2 Eq. (16 percent), 8.7 Tg CO_2 Eq. (3 percent), 6.8 Tg CO_2 Eq. (2 percent), and 0.5 Tg CO_2 Eq. (11 percent), respectively, while emissions from the Waste sector decreased 26.3 Tg CO_2 Eq. (13 percent). Over the same period, estimates of net carbon sequestration in the Land-Use Change and Forestry sector declined by 214.8 Tg CO_2 Eq. (21 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 Table 2-4. Alternatively, emissions and sinks are aggregated by 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**5,009.6**	**5,580.0**	**5,607.2**	**5,678.0**	**5,858.2**	**5,744.8**	**5,796.8**	**5,841.5**
Fossil Fuel Combustion	4,711.7	5,263.2	5,278.7	5,345.9	5,545.1	5,448.0	5,501.4	5,551.6
Non-Energy Use of Fuels	108.0	120.3	135.4	141.6	124.7	120.1	118.8	118.0
Iron and Steel Production	85.4	71.9	67.4	64.4	65.7	58.9	55.1	53.8
Cement Manufacture	33.3	38.3	39.2	40.0	41.2	41.4	42.9	43.0

Waste Combustion	10.9	17.8	17.1	17.6	18.0	18.8	18.8	18.8
Ammonia Production and Urea Application	19.3	20.7	21.9	20.6	19.6	16.7	18.6	15.6
Lime Manufacture	11.2	13.7	13.9	13.5	13.3	12.8	12.3	13.0
Natural Gas Flaring	5.8	7.9	6.6	6.9	5.8	6.1	6.2	6.0
Limestone and Dolomite Use	5.5	7.2	7.4	8.1	6.0	5.7	5.9	4.7
Aluminum Production	6.3	5.6	5.8	5.9	5.7	4.1	4.2	4.2
Soda Ash Manufacture and Consumption	4.1	4.4	4.3	4.2	4.2	4.1	4.1	4.1
Petrochemical Production	2.2	2.9	3.0	3.1	3.0	2.8	2.9	2.8
Titanium Dioxide Production	1.3	1.8	1.8	1.9	1.9	1.9	2.0	2.0
Phosphoric Acid Production	1.5	1.5	1.6	1.5	1.4	1.3	1.3	1.4
Ferroalloys	2.0	2.0	2.0	2.0	1.7	1.3	1.2	1.4
Carbon Dioxide Consumption	0.9	0.8	0.9	0.8	1.0	0.8	1.0	1.3
Land-Use Change and Forestry (Sinks)[a]	*(1,042.0)*	*(930.0)*	*(881.0)*	*(826.1)*	*(822.4)*	*(826.9)*	*(826.5)*	*(828.0)*
International Bunker Fuels[b]	*113.5*	*109.9*	*114.6*	*105.3*	*101.4*	*97.9*	*89.5*	*84.2*
Biomass Combustion[b]	*216.7*	*233.2*	*217.2*	*222.3*	*226.8*	*200.5*	*207.2*	*216.8*
CH_4	**605.3**	**579.5**	**569.1**	**557.3**	**554.2**	**546.8**	**542.5**	**545.0**
Landfills	172.2	147.4	138.5	134.0	130.7	126.2	126.8	131.2
Natural Gas Systems	128.3	133.6	131.8	127.4	132.1	131.8	130.6	125.9
Enteric Fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Coal Mining	81.9	62.6	62.8	58.9	56.2	55.6	52.4	53.8
Manure Management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Wastewater Treatment	24.8	31.7	32.6	33.6	34.3	34.7	35.8	36.8
Petroleum Systems	20.0	18.8	18.5	17.8	17.6	17.4	17.1	17.1
Rice Cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Stationary Sources	7.8	7.4	6.9	7.1	7.3	6.7	6.4	6.7
Abandoned Coal Mines	6.1	8.1	7.2	7.3	7.7	6.9	6.4	6.4
Mobile Sources	4.8	4.0	3.9	3.6	3.4	3.1	2.9	2.7
Petrochemical Production	1.2	1.6	1.7	1.7	1.7	1.4	1.5	1.5
Iron and Steel Production	1.3	1.3	1.2	1.2	1.2	1.1	1.0	1.0
Agricultural Residue Burning	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**382.0**	**396.3**	**407.8**	**382.1**	**401.9**	**385.8**	**380.5**	**376.7**
Agricultural Soil Management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Mobile Sources	43.7	55.2	55.3	54.6	53.2	49.0	45.6	42.1
Manure Management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Human Sewage	13.0	14.7	15.0	15.4	15.6	15.6	15.7	15.9
Nitric Acid	17.8	21.2	20.9	20.1	19.6	15.9	17.2	15.8
Stationary Sources	12.3	13.5	13.4	13.5	14.0	13.5	13.5	13.8
Settlements Remaining Settlements	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0
Adipic Acid	15.2	10.3	6.0	5.5	6.0	4.9	5.9	6.0
N_2O Product Usage	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Waste Combustion	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
Agricultural Residue Burning	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4
Forest Land Remaining Forest Land	0.1	0.3	0.4	0.5	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*
HFCs, PFCs, and SF_6	**91.2**	**121.7**	**135.7**	**134.8**	**138.9**	**129.5**	**138.3**	**137.0**
Substitution of Ozone Depleting Substances	0.4	46.5	56.6	65.8	75.0	83.3	91.5	99.5

Electrical Transmission and Distribution	29.2	21.7	17.1	16.4	15.6	15.4	14.7	14.1
HCFC-22 Production	35.0	30.0	40.1	30.4	29.8	19.8	19.8	12.3
Semiconductor Manufacture	2.9	6.3	7.1	7.2	6.3	4.5	4.4	4.3
Aluminum Production	18.3	11.0	9.1	9.0	9.0	4.0	5.2	3.8
Magnesium Production and Processing	5.4	6.3	5.8	6.0	3.2	2.6	2.6	3.0
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**5,009,552**	**5,579,984**	**5,607,159**	**5,677,970**	**5,858,201**	**5,744,782**	**5,796,757**	**5,841,504**
Fossil Fuel Combustion	4,711,741	5,263,164	5,278,721	5,345,904	5,545,083	5,447,969	5,501,427	5,551,580
Non-Energy Use of Fuels	107,965	120,301	135,352	141,583	124,714	120,104	118,811	118,001
Iron and Steel Production	85,413	71,863	67,428	64,376	65,693	58,887	55,082	53,763
Cement Manufacture	33,278	38,323	39,218	39,991	41,190	41,357	42,898	43,030
Waste Combustion	10,919	17,761	17,094	17,632	17,979	18,781	18,781	18,781
Ammonia Production and Urea Application	19,306	20,650	21,934	20,615	19,616	16,719	18,571	15,560
Lime Manufacture	11,238	13,685	13,914	13,466	13,315	12,823	12,304	12,983
Natural Gas Flaring	5,805	7,874	6,566	6,943	5,769	6,094	6,233	5,970
Limestone and Dolomite Use	5,533	7,242	7,449	8,057	5,959	5,733	5,885	4,720
Aluminum Production	6,315	5,621	5,792	5,895	5,723	4,114	4,220	4,219
Soda Ash Manufacture and Consumption	4,141	4,354	4,325	4,217	4,181	4,147	4,139	4,082
Petrochemical Production	2,221	2,919	3,015	3,054	3,004	2,787	2,857	2,777
Titanium Dioxide Production	1,308	1,836	1,819	1,853	1,918	1,857	1,997	2,013
Phosphoric Acid Production	1,529	1,544	1,593	1,539	1,382	1,264	1,338	1,382
Ferroalloys	1,980	2,038	2,027	1,996	1,719	1,329	1,237	1,374
Carbon Dioxide Consumption	860	808	912	849	957	818	978	1,267
Land-Use Change and Forestry (Sinks)[a]	*(1,042,050)*	*(930,011)*	*(880,995)*	*(826,106)*	*(822,409)*	*(826,879)*	*(826,483)*	*(828,046)*
International Bunker Fuels[b]	*113,503*	*109,858*	*114,557*	*105,294*	*101,404*	*97,865*	*89,489*	*84,193*
Biomass Combustion	*216,702*	*233,243*	*217,201*	*222,340*	*226,765*	*200,477*	*207,249*	*216,813*
CH_4	**28,826**	**27,595**	**27,100**	**26,537**	**26,389**	**26,039**	**25,832**	**25,950**
Landfills	8,202	7,017	6,595	6,382	6,223	6,010	6,039	6,246
Natural Gas Systems	6,112	6,363	6,276	6,066	6,289	6,277	6,221	5,998
Enteric Fermentation	5,612	5,634	5,557	5,561	5,505	5,454	5,458	5,475
Coal Mining	3,900	2,983	2,989	2,805	2,677	2,647	2,497	2,561
Manure Management	1,485	1,733	1,850	1,846	1,813	1,853	1,873	1,864

Wastewater Treatment	1,183	1,509	1,550	1,602	1,635	1,651	1,705	1,751
Petroleum Systems	951	895	879	848	836	831	815	815
Rice Cultivation	339	356	376	395	357	364	325	328
Stationary Sources	373	351	328	338	349	318	305	319
Abandoned Coal Mines	288	385	341	349	369	331	303	306
Mobile Sources	228	193	185	172	161	147	138	128
Petrochemical Production	56	78	80	81	80	68	72	72
Iron and Steel Production	63	60	57	56	57	51	48	49
Field Burning of Agricultural Residues	33	37	38	37	38	37	34	38
Silicon Carbide Production	1	1	1	1	1	+	+	+
International Bunker Fuels[b]	*8*	*7*	*7*	*6*	*6*	*5*	*4*	*4*
N_2O	**1,232**	**1,278**	**1,315**	**1,233**	**1,297**	**1,245**	**1,228**	**1,215**
Agricultural Soil Management	816	813	864	785	851	829	815	818
Mobile Sources	141	178	179	176	171	158	147	136
Manure Management	52	56	56	56	57	58	58	57
Human Sewage	42	47	48	50	50	50	51	51
Nitric Acid	58	68	67	65	63	51	56	51
Stationary Sources	40	44	43	43	45	43	44	45
Settlements Remaining Settlements	18	20	20	20	19	19	19	19
Adipic Acid	49	33	19	18	19	16	19	19
N_2O Product Usage	14	15	15	15	15	15	15	15
Waste Combustion	1	1	1	1	1	1	1	1
Field Burning of Agricultural Residues	1	1	1	1	1	1	1	1
Forest Land Remaining Forest Land	+	1	1	2	1	1	1	1
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*2*
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
Electrical Transmission and Distribution[d]	1	1	1	1	1	1	1	1
HCFC-22 Production[c]	3	3	3	3	3	2	2	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**	**17,091**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,463**
NO_x	**22,860**	**22,284**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**18,573**
CO	**130,580**	**101,138**	**98,984**	**94,361**	**92,895**	**89,329**	**87,451**	**85,077**
NMVOCs	**20,937**	**16,994**	**16,403**	**15,869**	**15,228**	**15,048**	**14,222**	**13,939**

+ 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Energy	5,141.7	5,712.8	5,737.7	5,802.6	5,985.3	5,877.3	5,920.7	5,963.4
Industrial Processes	299.9	327.1	334.9	329.2	332.1	304.7	315.4	308.6
Solvent and Other Product Use	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Agriculture	426.5	432.8	449.8	425.9	444.1	437.5	432.4	433.3
Land-Use Change and Forestry (Emissions)	5.6	6.4	6.5	6.6	6.3	6.2	6.4	6.4
Waste	210.1	193.7	186.0	183.1	180.6	176.5	178.3	183.8
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**
Land-Use Change and Forestry (Sinks)	(1042.0)	(930.0)	(881.0)	(826.1)	(822.4)	(826.9)	(826.5)	(828.0)
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**

* Sinks are only included in net emissions total, and are based partially on projected activity data.

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 2003. In 2003, 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, respectively). Table 2-6 presents greenhouse gas emissions from the Energy sector, by source and gas.

Figure 2-6: 2003 Energy Sector Greenhouse Gas Sources

Figure 2-7: 2003 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

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

Gas/Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**4,836.4**	**5,409.1**	**5,437.7**	**5,512.1**	**5,693.5**	**5,592.9**	**5,645.3**	**5,694.3**
Fossil Fuel Combustion	4,711.7	5,263.2	5,278.7	5,345.9	5,545.1	5,448.0	5,501.4	5,551.6
Non-Energy Use of Fuels	108.0	120.3	135.4	141.6	124.7	120.1	118.8	118.0
Waste Combustion	10.9	17.8	17.1	17.6	18.0	18.8	18.8	18.8
Natural Gas Flaring	5.8	7.9	6.6	6.9	5.8	6.1	6.2	6.0
*Biomass-Wood**	*212.5*	*226.3*	*209.5*	*214.3*	*217.6*	*190.8*	*195.8*	*201.0*
*International Bunker Fuels**	*113.5*	*109.9*	*114.6*	*105.3*	*101.4*	*97.9*	*89.5*	*84.2*
*Biomass-Ethanol**	*4.2*	*7.0*	*7.7*	*8.0*	*9.2*	*9.7*	*11.5*	*15.8*
CH_4	**248.9**	**234.6**	**230.9**	**222.1**	**224.3**	**221.6**	**215.8**	**212.7**
Natural Gas Systems	128.3	133.6	131.8	127.4	132.1	131.8	130.6	125.9
Coal Mining	81.9	62.6	62.8	58.9	56.2	55.6	52.4	53.8
Petroleum Systems	20.0	18.8	18.5	17.8	17.6	17.4	17.1	17.1

Stationary Sources	7.8	7.4	6.9	7.1	7.3	6.7	6.4	6.7
Abandoned Coal Mines	6.1	8.1	7.2	7.3	7.7	6.9	6.4	6.4
Mobile Sources	4.8	4.0	3.9	3.6	3.4	3.1	2.9	2.7
*International Bunker Fuels**	*0.2*	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.4**	**69.1**	**69.1**	**68.4**	**67.5**	**62.8**	**59.6**	**56.4**
Mobile Sources	43.7	55.2	55.3	54.6	53.2	49.0	45.6	42.1
Stationary Sources	12.3	13.5	13.4	13.5	14.0	13.5	13.5	13.8
Waste Combustion	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
*International Bunker Fuels**	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*
Total	**5,141.7**	**5,712.8**	**5,737.7**	**5,802.6**	**5,985.3**	**5,877.3**	**5,920.7**	**5,963.4**

* 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 (5,551.6 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 2003, 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 2003. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 13 years, and (2) significant growth in emissions from transportation activities and electricity generation. Between 1990 and 2003, CO_2 emissions from fossil fuel combustion increased from 4,711.7 Tg CO_2 Eq. to 5,551.6 Tg CO_2 Eq.—an 18 percent total increase over the thirteen-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. In reality, sources of electricity vary widely in carbon intensity. By assuming the same carbon intensity for each end-use sector's electricity consumption, for example, emissions attributed to the residential end-use sector may be underestimated, while emissions attributed to the industrial end-use sector may be overestimated. 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	1997	1998	1999	2000	2001	2002	2003
Transportation	**1,449.8**	**1,606.4**	**1,636.5**	**1,693.9**	**1,741.0**	**1,723.1**	**1,755.4**	**1,770.4**
Combustion	1,446.8	1,603.3	1,633.4	1,690.8	1,737.7	1,719.7	1,752.3	1,767.2
Electricity	3.0	3.1	3.1	3.2	3.4	3.4	3.2	3.2
Industrial	**1,553.9**	**1,703.0**	**1,668.5**	**1,651.2**	**1,684.4**	**1,587.4**	**1,579.0**	**1,572.9**
Combustion	882.8	963.8	911.6	888.1	905.0	878.2	876.6	858.6
Electricity	671.1	739.2	757.0	763.1	779.4	709.3	702.4	714.3
Residential	**924.8**	**1,040.7**	**1,044.4**	**1,063.5**	**1,124.2**	**1,116.2**	**1,145.0**	**1,168.9**

Combustion	339.6		370.6	338.6	359.3	379.1	367.0	371.4	385.1
Electricity	585.3		670.2	705.8	704.2	745.0	749.2	773.6	783.8
Commercial	**755.1**		**876.7**	**892.9**	**901.2**	**959.5**	**972.7**	**973.9**	**983.1**
Combustion	224.2		237.2	219.7	222.3	235.2	226.7	230.0	234.0
Electricity	530.9		639.5	673.2	678.9	724.3	745.9	743.9	749.2
U.S. Territories	**28.0**		**36.4**	**36.3**	**36.2**	**35.9**	**48.6**	**48.1**	**56.2**
Total	**4,711.7**		**5,263.2**	**5,278.7**	**5,345.9**	**5,545.1**	**5,448.0**	**5,501.4**	**5,551.6**
Electricity Generation	**1,790.3**		**2,051.9**	**2,139.0**	**2,149.3**	**2,252.1**	**2,207.8**	**2,223.0**	**2,250.5**

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: 2003 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure 2-9: 2003 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 32 percent of CO_2 emissions from fossil fuel combustion in 2003.[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 2003. 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 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2003. Both sectors relied heavily on electricity for meeting energy demands, with 67 and 76 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 35 percent of U.S. energy from fossil fuels and emitted 41 percent of the CO_2 from fossil fuel combustion in 2003. 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 93 percent of all coal consumed for energy in the United States in 2003. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

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[3] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 33 percent of U.S. emissions from fossil fuel combustion in 2003.

Non-Energy Use of Fossil Fuels (118.0 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. Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Where appropriate data and methodologies are available, NEUs of fossil fuels used for industrial processes are reported in the Industrial Processes sector. Emissions in 2003 for non-energy uses of fossil fuels were 118.0 Tg CO_2 Eq., which constituted 2 percent of overall fossil fuel CO_2 emissions and 2 percent of total national CO_2 emissions, approximately the same proportion as in 1990.

Waste Combustion (19.2 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. Carbon dioxide and N_2O emissions arise from the organic materials found in these wastes. Within municipal solid waste, many products contain carbon of biogenic origin (e.g., paper, yard trimmings), and the CO_2 emissions from their combustion are accounted for under the Land Use Change and Forestry chapter. 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 2003, CO_2 emissions from waste combustion amounted to 18.8 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 2003, flaring accounted for approximately 0.1 percent of U.S. CO_2 emissions.

Natural Gas Systems (125.9 Tg CO_2 Eq.)

Methane 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 2003, CH_4 emissions from U.S. natural gas systems accounted for approximately 23 percent of U.S. CH_4 emissions.

Coal Mining (53.8 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.

Methane 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 methane, typically to the atmosphere. At some mines, CH_4-recovery systems may supplement these ventilation systems. Recovery of CH_4 in the United States has increased in recent years. During 2003, coal mining activities emitted 10 percent of U.S. CH_4 emissions. From 1990 to 2003, emissions from this source decreased by 34 percent due to increased use of the CH_4 collected by mine degasification systems and a general shift toward surface mining.

Petroleum Systems (17.1 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 methane. 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. Methane emissions from the components of petroleum systems generally occur as a result of system leaks, disruptions, and routine maintenance. In 2003, emissions from petroleum systems were just over 3 percent of U.S. CH_4 emissions.

Mobile Combustion (44.8 Tg CO_2 Eq.)

Mobile combustion results in N_2O and CH_4 emissions. Nitrous oxide 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 2003, N_2O emissions from mobile combustion were 42.1 Tg CO_2 Eq. (11 percent of U.S. N_2O emissions). From 1990 to 2003, N_2O emissions from mobile combustion decreased by about 4 percent.

In 2003, CH_4 emissions were estimated to be 2.7 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 (20.5 Tg CO_2 Eq.)

Stationary combustion results in N_2O and CH_4 emissions. In 2003, N_2O emissions from stationary combustion accounted for 13.8 Tg CO_2 Eq. (4 percent of U.S. N_2O emissions). From 1990 to 2003, N_2O emissions from stationary combustion increased by 13 percent, due to increased fuel consumption. In 2003, CH_4 emissions were 6.7 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 (6.4 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 2003, the emissions from abandoned coal mines constituted 1 percent of U.S. CH_4 emissions.

CO_2 from Biomass Combustion (216.8 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 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.

The consumption of wood biomass in the industrial, residential, electric power, and commercial end-use sectors accounted for 66, 17, 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 7 percent.

International Bunker Fuels (85.1 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 84.2, 0.1, and 0.8 Tg CO_2 Eq. in 2003, 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, aluminum production, petrochemical production, silicon carbide production, nitric acid production, and adipic acid 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: 2003 Industrial Processes Chapter Greenhouse Gas Sources

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

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**173.1**	**170.9**	**169.4**	**165.9**	**164.7**	**151.8**	**151.5**	**147.2**
Iron and Steel Production	85.4	71.9	67.4	64.4	65.7	58.9	55.1	53.8
Cement Manufacture	33.3	38.3	39.2	40.0	41.2	41.4	42.9	43.0
Ammonia Manufacture & Urea Application	19.3	20.7	21.9	20.6	19.6	16.7	18.6	15.6
Lime Manufacture	11.2	13.7	13.9	13.5	13.3	12.8	12.3	13.0
Limestone and Dolomite Use	5.5	7.2	7.4	8.1	6.0	5.7	5.9	4.7
Aluminum Production	6.3	5.6	5.8	5.9	5.7	4.1	4.2	4.2
Soda Ash Manufacture and Consumption	4.1	4.4	4.3	4.2	4.2	4.1	4.1	4.1
Petrochemical Production	2.2	2.9	3.0	3.1	3.0	2.8	2.9	2.8
Titanium Dioxide Production	1.3	1.8	1.8	1.9	1.9	1.9	2.0	2.0
Phosphoric Acid Production	1.5	1.5	1.6	1.5	1.4	1.3	1.3	1.4
Ferroalloy Production	2.0	2.0	2.0	2.0	1.7	1.3	1.2	1.4
Carbon Dioxide Consumption	0.9	0.8	0.9	0.8	1.0	0.8	1.0	1.3
CH_4	**2.5**	**2.9**	**2.9**	**2.9**	**2.9**	**2.5**	**2.5**	**2.5**
Petrochemical Production	1.2	1.6	1.7	1.7	1.7	1.4	1.5	1.5
Iron and Steel Production	1.3	1.3	1.2	1.2	1.2	1.1	1.0	1.0
Silicon Carbide Production	+	+	+	+	+	+	+	+
N_2O	**33.0**	**31.5**	**26.9**	**25.6**	**25.6**	**20.8**	**23.1**	**21.8**
Nitric Acid Production	17.8	21.2	20.9	20.1	19.6	15.9	17.2	15.8

Adipic Acid Production	15.2		10.3	6.0	5.5	6.0	4.9	5.9	6.0
HFCs, PFCs, and SF_6	**91.2**		**121.7**	**135.7**	**134.8**	**138.9**	**129.5**	**138.3**	**137.0**
Substitution of Ozone Depleting Substances	0.4		46.5	56.6	65.8	75.0	83.3	91.5	99.5
Electrical Transmission and Distribution	29.2		21.7	17.1	16.4	15.6	15.4	14.7	14.1
HCFC-22 Production	35.0		30.0	40.1	30.4	29.8	19.8	19.8	12.3
Aluminum Production	18.3		11.0	9.1	9.0	9.0	4.0	5.2	3.8
Semiconductor Manufacture	2.9		6.3	7.1	7.2	6.3	4.5	4.4	4.3
Magnesium Production and Processing	5.4		6.3	5.8	6.0	3.2	2.6	2.6	3.0
Total	**299.9**		**327.1**	**334.9**	**329.2**	**332.1**	**304.7**	**315.4**	**308.6**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Iron and Steel Production (54.8 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 2003, 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 53.8 Tg CO_2 Eq. in 2003. From 1990 to 2003, emissions from this source decreased by 37 percent.

Cement Manufacture (43.0 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 2003, emissions from this source increased by 29 percent.

Ammonia Manufacture and Urea Application (15.6 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 (13.0 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 (4.7 Tg CO_2 Eq.)

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)$) 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 (8.0 Tg CO_2 Eq.)

Aluminum production results in emissions of CO_2, CF_4 and C_2F_6. Carbon dioxide 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 2003, CO_2 emissions from aluminum production amounted to 4.2 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 79 percent between 1990 and 2003 due to emission reduction efforts by the industry and falling domestic aluminum production. In 2003, CF_4 and C_2F_6 emissions from aluminum production amounted to 3.8 Tg CO_2 Eq.

Soda Ash Manufacture and Consumption (4.1 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 (4.3 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 2.8 Tg CO_2 Eq. of CO_2 and 1.5 Tg CO_2 Eq. of CH_4 in 2003.

Titanium Dioxide Production (2.0 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. Carbon dioxide 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 (1.4 Tg CO_2 Eq.)

Carbon dioxide 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 (1.3 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. Carbon dioxide 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.

Silicon Carbide Production (0.01 Tg CO_2 Eq.)

Small amounts of CH_4 are released during the production of silicon carbide, a material used as an industrial abrasive. Silicon carbide (SiC) is made through a reaction of quartz (SiO_2) and carbon (in the form of petroleum coke). Methane is produced during this reaction from volatile compounds in the petroleum coke. Methane emissions from silicon carbide production have declined significantly due a 67 percent decrease in silicon carbide production since 1990. In 2003, only two companies produced silicon carbide in the United States (one company produced abrasive-grade silicon carbide and the other produced a small quantity for heat-resistant products).

Nitric Acid Production (15.8 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 2003, N_2O emissions from nitric acid production accounted for 4 percent of U.S. N_2O emissions. From 1990 to 2003, emissions from this source category decreased by11 percent with the trend in the time series closely tracking the changes in production.

Adipic Acid Production (6.0 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. Nitrous oxide is emitted as a by-product of the chemical synthesis of adipic acid.

In 2003, U.S. adipic acid plants emitted 2 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 60 percent since 1990.

Substitution of Ozone Depleting Substances (99.5 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 73 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 (12.3 Tg CO_2 Eq.)

HFC-23 is a by-product of the production of HCFC-22. Emissions from this source have decreased by 65 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 (14.1 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 (4.3 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 49 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 2003. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

Magnesium Production (3.0 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 45 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. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2003 (see Table 2-9).

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

Gas/Source	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
N_2O	**4.3**		**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**
Nitrous Oxide 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.)

Nitrous oxide 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 2003, N_2O emissions from product usage constituted approximately 1 percent of U.S. N_2O emissions. From 1990 to 2003, 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 2003, agricultural activities were responsible for emissions of 433.3 Tg CO_2 Eq., or 6 percent of total U.S. greenhouse gas emissions. Methane and N_2O were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented about 21 percent and 7 percent of total CH_4 emissions from anthropogenic activities, respectively in 2003. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2003, accounting for 67 percent. Table 2-10 presents emission estimates for the Agriculture sector.

Figure 2-11: 2003 Agriculture Chapter Greenhouse Gas Sources

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

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**156.9**	**163.0**	**164.2**	**164.6**	**162.0**	**161.9**	**161.5**	**161.8**
Enteric Fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Manure Management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Rice Cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
N_2O	**269.6**	**269.8**	**285.6**	**261.3**	**282.1**	**275.6**	**270.9**	**271.5**
Agricultural Soil Management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Manure Management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4
Total	**426.5**	**432.8**	**449.8**	**425.9**	**444.1**	**437.5**	**432.4**	**433.3**

Note: Totals may not sum due to independent rounding.

Enteric Fermentation (115.0 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 2003, enteric fermentation was the source of about 21 percent of U.S. CH_4 emissions, and more than 71 percent of the CH_4 emissions from agriculture. From 1990 to 2003, emissions from this source decreased by 2 percent. Emissions from enteric fermentation have decreasing significantly since 1995, primarily due to declining dairy cow and beef cattle populations as a result of improved efficiency in milk and beef production.

Manure Management (56.7 Tg CO_2 Eq.)

Both CH_4 and N_2O resulted 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 39.1 Tg CO_2 Eq., or about 7 percent of U.S. CH_4 emissions in 2003 and 24 percent of the CH_4 emissions from the agriculture sector. From 1990 to 2003, 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.

Nitrous oxide 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 2003 accounted for 17.5 Tg CO_2 Eq., or 5 percent of U.S. N_2O emissions. From 1990 to 2003, emissions from this source category increased by 8 percent, primarily due to increases in swine and poultry populations over the same time period.

Rice Cultivation (6.9 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 2003, rice cultivation was the source of 1 percent of U.S. CH_4 emissions, and about 4 percent of U.S. CH_4 emissions from agriculture. Emission estimates from this source have decreased about 3 percent since 1990.

Field Burning of Agricultural Residues (1.2 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 0.1 percent of U.S. CH_4 (0.8 Tg CO_2 Eq.) and N_2O (0.4 Tg CO_2 Eq.) emissions in 2003.

Agricultural Soil Management (253.5 Tg CO_2 Eq.)

Nitrous oxide is produced naturally in soils through microbial processes of nitrification and denitrification. 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 2003, agricultural soil management accounted for 67 percent of U.S. N_2O emissions. From 1990 to 2003, emissions from this source increased 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 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 12 percent of total U.S. gross CO_2 emissions in 2003. Forests (including vegetation, soils, and harvested wood) accounted for approximately 91 percent of total 2003 sequestration, urban trees accounted for 7 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 1 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2003. 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 approximately one and a third 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 2003 resulted in a net carbon sequestration of 828.0 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 14 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 21 percent between 1990 and 2003. 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, as did annual carbon accumulation in agricultural soils. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for 1990 through 1999).

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

Sink Category	1990		1997	1998	1999	2000	2001	2002	2003
Forest Land Remaining Forest Land	**(949.3)**		**(851.0)**	**(805.5)**	**(751.7)**	**(747.9)**	**(750.9)**	**(751.5)**	**(752.7)**
Changes in Forest Carbon Stocks	(949.3)		(851.0)	(805.5)	(751.7)	(747.9)	(750.9)	(751.5)	(752.7)
Cropland Remaining Cropland	**(8.1)**		**(7.4)**	**(4.3)**	**(4.3)**	**(5.7)**	**(7.1)**	**(6.2)**	**(6.6)**
Changes in Agricultural Soil Carbon	(8.1)		(7.4)	(4.3)	(4.3)	(5.7)	(7.1)	(6.2)	(6.6)

Stocks								
Settlements Remaining Settlements	**(84.7)**	**(71.6)**	**(71.2)**	**(70.0)**	**(68.9)**	**(68.9)**	**(68.8)**	**(68.7)**
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Landfilled Yard Trimmings and Food Scraps	(26.0)	(12.9)	(12.5)	(11.4)	(10.2)	(10.3)	(10.2)	(10.1)
Total	**(1,042.0)**	**(930.0)**	**(881.0)**	**(826.1)**	**(822.4)**	**(826.9)**	**(826.5)**	**(828.0)**

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

Land use, land-use change, and forestry activities in 2003 also resulted in emissions of N_2O (6.4 Tg CO_2 Eq., Table 2-12). Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 14 percent between 1990 and 2003.

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

Sink Category	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest Land Remaining Forest Land	**0.1**	**0.3**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
N_2O Fluxes from Soils	0.1	0.3	0.4	0.5	0.4	0.4	0.4	0.4
Settlements Remaining Settlements	**5.5**	**6.1**	**6.1**	**6.2**	**6.0**	**5.8**	**6.0**	**6.0**
N_2O Fluxes from Soils	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0
Total	**5.6**	**6.4**	**6.5**	**6.6**	**6.3**	**6.2**	**6.4**	**6.4**

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. This 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 2003 were almost 7 times higher than in 1990, primarily the result of an increase in 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 (6.0 Tg CO_2 Eq.)

Of the fertilizers applied to soils in the U.S., approximately 10 percent are applied to lawns, golf courses, and other landscaping within settled areas. In 2003, N_2O emissions from settlement soils constituted approximately 1.6 percent of total U.S N_2O emissions. There has been an overall increase in emissions of 9 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 methane (CH_4) emissions, accounting for 24 percent of total U.S. CH_4 emissions.[4] Wastewater treatment systems are a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide 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-methane volatile organic compounds (NMVOCs) are also emitted by waste activities. A summary of greenhouse gas and ambient air pollutant emissions from the Waste sector is presented in Table 2-13.

Figure 2-12: 2003 Waste Sector Greenhouse Gas Sources

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

Overall, in 2003, waste activities generated emissions of 183.8 Tg CO_2 Eq., or 3 percent of total U.S. greenhouse gas emissions.

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

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**197.1**	**179.0**	**171.0**	**167.7**	**165.0**	**160.9**	**162.6**	**167.9**
Landfills	172.2	147.4	138.5	134.0	130.7	126.2	126.8	131.2
Wastewater Treatment	24.8	31.7	32.6	33.6	34.3	34.7	35.8	36.8
N_2O	**13.0**	**14.7**	**15.0**	**15.4**	**15.6**	**15.6**	**15.7**	**15.9**
Human Sewage	13.0	14.7	15.0	15.4	15.6	15.6	15.7	15.9
Total	**210.1**	**193.7**	**186.0**	**183.1**	**180.6**	**176.5**	**178.3**	**183.8**

Note: Totals may not sum due to independent rounding.

Landfills (131.2 Tg CO_2 Eq.)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States, accounting for approximately 24 percent of total CH_4 emissions in 2003. 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 methane generation.

From 1990 to 2003, net CH_4 emissions from landfills decreased by approximately 24 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.

Wastewater Treatment (36.8 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 2003, wastewater treatment was the source of approximately 7 percent of U.S. CH_4 emissions.

Human Sewage (Domestic Wastewater) (15.9 Tg CO_2 Eq.)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc., and transported by a collection system to either a direct discharge, an on-site or 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. Nitrous oxide 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 2003. From 1990 to 2003, emissions from this source category increased by 22 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 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 2003. Transportation activities, in aggregate, accounted for the second largest portion (27 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 2003. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. 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.

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

Table 2-14 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 2003.

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 2003)

Sector/Source	1990	1997	1998	1999	2000	2001	2002	2003	Percent[a]
Electricity Generation	**1,841.8**	**2,104.6**	**2,186.8**	**2,197.3**	**2,299.0**	**2,254.9**	**2,269.7**	**2,296.2**	**33.3%**
CO_2 from Fossil Fuel Combustion	1,790.3	2,051.9	2,139.0	2,149.3	2,252.1	2,207.8	2,223.0	2,250.5	32.6%
Stationary Combustion[d]	8.1	9.3	9.5	9.5	10.0	9.7	9.8	10.0	0.1%
Electrical Transmission and Distribution[c]	29.2	21.7	17.1	16.4	15.6	15.4	14.7	14.1	0.2%
Waste Combustion[b]	11.3	18.1	17.4	18.0	18.3	19.2	19.2	19.2	0.3%
Limestone and Dolomite Use	2.8	3.6	3.7	4.0	3.0	2.9	2.9	2.4	+
Transportation	**1,506.8**	**1,693.0**	**1,728.7**	**1,790.0**	**1,839.6**	**1,819.8**	**1,851.6**	**1,864.4**	**27.0%**
CO_2 from Fossil Fuel Combustion	1,446.8	1,603.3	1,633.4	1,690.8	1,737.7	1,719.7	1,752.3	1,767.2	25.6%
Mobile Combustion[d]	48.1	58.7	58.7	57.7	56.1	51.6	48.1	44.3	0.6%
Substitution of ODS[e]	+	19.4	24.4	29.3	33.8	37.4	40.4	42.7	0.6%
Non-Energy Use of Fuels	11.9	11.6	12.1	12.3	12.1	11.1	10.9	10.2	0.1%
Industry	**1,446.1**	**1,509.1**	**1,470.6**	**1,427.9**	**1,431.8**	**1,371.0**	**1,365.7**	**1,331.4**	**19.3%**
CO_2 from Fossil Fuel Combustion	836.5	905.4	853.9	828.0	854.6	827.9	824.3	806.3	11.7%
Non-Energy Use of Fuels	90.4	102.6	117.0	121.8	101.7	103.7	102.6	101.9	1.5%
Stationary Combustion	5.3	5.9	5.5	5.5	5.6	5.2	5.3	5.3	0.1%

Coal Mining	81.9	62.6	62.8	58.9	56.2	55.6	52.4	53.8	0.8%
Abandoned Coal Mines	6.1	8.1	7.2	7.3	7.7	6.9	6.4	6.4	0.1%
Natural Gas Systems	128.3	133.6	131.8	127.4	132.1	131.8	130.6	125.9	1.8%
Petroleum Systems	20.0	18.8	18.5	17.8	17.6	17.4	17.1	17.1	0.2%
Natural Gas Flaring	5.8	7.9	6.6	6.9	5.8	6.1	6.2	6.0	0.1%
Titanium Dioxide Production	1.3	1.8	1.8	1.9	1.9	1.9	2.0	2.0	+
Aluminum Production[h]	24.7	16.6	14.8	14.9	14.7	8.1	9.5	8.0	0.1%
Iron and Steel Production[f]	86.7	73.1	68.6	65.5	66.9	60.0	56.1	54.8	0.8%
Ferroalloys	2.0	2.0	2.0	2.0	1.7	1.3	1.2	1.4	+
Ammonia Manufacture	19.3	20.7	21.9	20.6	19.6	16.7	18.6	15.6	0.2%
Cement Manufacture	33.3	38.3	39.2	40.0	41.2	41.4	42.9	43.0	0.6%
Lime Manufacture	11.2	13.7	13.9	13.5	13.3	12.8	12.3	13.0	0.2%
Limestone and Dolomite Use	2.8	3.6	3.7	4.0	3.0	2.9	2.9	2.4	+
Soda Ash Manufacture and Consumption	4.1	4.4	4.3	4.2	4.2	4.1	4.1	4.1	0.1%
Carbon Dioxide Consumption	0.9	0.8	0.9	0.8	1.0	0.8	1.0	1.3	+
Petrochemical Production	3.4	4.6	4.7	4.8	4.7	4.2	4.4	4.3	0.1%
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
Phosphoric Acid Production	1.5	1.5	1.6	1.5	1.4	1.3	1.3	1.4	+
Adipic Acid	15.2	10.3	6.0	5.5	6.0	4.9	5.9	6.0	0.1%
Nitric Acid	17.8	21.2	20.9	20.1	19.6	15.9	17.2	15.8	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	30.0	40.1	30.4	29.8	19.8	19.8	12.3	0.2%
Semiconductor Manufacture[e]	2.9	6.3	7.1	7.2	6.3	4.5	4.4	4.3	0.1%
Magnesium Production and Processing[c]	5.4	6.3	5.8	6.0	3.2	2.6	2.6	3.0	+
Substitution of ODS[e]	0.1	4.1	5.1	6.4	7.4	8.4	9.7	11.2	0.2%
Agriculture	**473.3**	**492.0**	**508.4**	**486.9**	**495.3**	**488.6**	**485.6**	**486.4**	**7.0%**
CO_2 from Fossil Fuel Combustion	46.3	58.4	57.6	60.0	50.4	50.3	52.3	52.2	0.8%
Stationary Combustion[d]	+	+	+	+	+	+	+	+	+
Mobile Combustion[d]	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5	+
Enteric Fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0	1.7%
Manure Management[d]	47.4	53.7	56.2	56.2	55.9	56.9	57.3	56.7	0.8%
Rice Cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9	0.1%
Agricultural Residue Burning[d]	1.1	1.2	1.2	1.2	1.2	1.2	1.1	1.2	+
Agricultural Soil Management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5	3.7%
Forest Soil Fertilization	0.1	0.3	0.4	0.5	0.4	0.4	0.4	0.4	+
Commercial	**435.4**	**445.2**	**424.2**	**426.8**	**440.7**	**431.4**	**440.2**	**453.5**	**7.0%**
CO_2 from Fossil Fuel Combustion	224.2	237.2	219.7	222.3	235.2	226.7	230.0	234.0	3.4%
Stationary Combustion[d]	1.1	1.1	1.1	1.1	1.2	1.0	1.1	1.1	+
Substitution of ODS[d]	+	13.1	17.4	20.3	23.8	27.1	30.8	34.7	0.5%
Landfills	172.2	147.4	138.5	134.0	130.7	126.2	126.8	131.2	1.9%
Human Sewage	13.0	14.7	15.0	15.4	15.6	15.6	15.7	15.9	0.2%
Wastewater Treatment	24.8	31.7	32.6	33.6	34.3	34.7	35.8	36.8	0.5%
Residential	**350.9**	**391.0**	**358.4**	**379.5**	**399.7**	**387.1**	**391.6**	**406.1**	**5.9%**
CO_2 from Fossil Fuel Combustion	339.6	370.6	338.6	359.3	379.1	367.0	371.4	385.1	5.6%

Stationary Combustion[c]	5.5	4.4	4.0	4.3	4.5	4.0	3.6	3.9	0.1%
Substitution of ODS[e]	0.3	9.9	9.6	9.8	10.1	10.3	10.6	11.0	0.2%
Settlement Soil Fertilization	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0	0.1%
U.S. Territories	**33.8**	**42.7**	**42.7**	**43.9**	**47.0**	**54.1**	**53.6**	**62.3**	**0.9%**
CO_2 from Fossil Fuel Combustion	33.8	42.7	42.7	43.9	47.0	54.1	53.6	62.3	0.9%
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**	**100.0%**
Sinks	**(1,042.0)**	**(930.0)**	**(881.0)**	**(826.1)**	**(822.4)**	**(826.9)**	**(826.5)**	**(828.0)**	**-12.0%**
Forests	(949.3)	(851.0)	(805.5)	(751.7)	(747.9)	(750.9)	(751.5)	(752.7)	-10.9%
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	-0.9%
Agricultural Soils	(8.1)	(7.4)	(4.3)	(4.3)	(5.7)	(7.1)	(6.2)	(6.6)	-0.1%
Landfilled Yard Trimmings	(26.0)	(12.9)	(12.5)	(11.4)	(10.2)	(10.3)	(10.2)	(10.1)	-0.1%
Net Emissions (Sources and Sinks)	**5,046.1**	**5,747.5**	**5,838.8**	**5,926.1**	**6,130.8**	**5,980.1**	**6,031.6**	**6,072.2**	

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%.
- Not applicable.
[a] Percent of total emissions for year 2003.
[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 2003. Emissions increased by 25 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**1,804.0**	**2,073.3**	**2,159.9**	**2,171.0**	**2,273.1**	**2,229.4**	**2,244.8**	**2,271.7**
CO_2 from Fossil Fuel Combustion	1,790.3	2,051.9	2,139.0	2,149.3	2,252.1	2,207.8	2,223.0	2,250.5
Coal	*1,513.0*	*1,758.4*	*1,786.4*	*1,792.4*	*1,880.0*	*1,817.4*	*1,839.7*	*1,876.3*
Natural Gas	*176.0*	*218.9*	*248.0*	*259.9*	*280.7*	*289.1*	*305.6*	*277.6*
Petroleum	*101.0*	*74.3*	*104.3*	*96.7*	*91.0*	*100.9*	*77.4*	*96.3*
Geothermal	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.3*
Waste Combustion	10.9	17.8	17.1	17.6	18.0	18.8	18.8	18.8
Limestone and Dolomite Use	2.8	3.6	3.7	4.0	3.0	2.9	2.9	2.4
CH_4	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Stationary Combustion*	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7
N_2O	**8.0**	**9.0**	**9.2**	**9.2**	**9.6**	**9.4**	**9.5**	**9.8**
Stationary Combustion*	7.6	8.6	8.9	8.9	9.3	9.0	9.1	9.3

Waste Combustion	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
SF_6	**29.2**	**21.7**	**17.1**	**16.4**	**15.6**	**15.4**	**14.7**	**14.1**
Electrical Transmission and Distribution	29.2	21.7	17.1	16.4	15.6	15.4	14.7	14.1
Total	**1,841.8**	**2,104.6**	**2,186.8**	**2,197.3**	**2,299.0**	**2,254.9**	**2,269.7**	**2,296.2**

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 2004a and Duffield 2004). 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 due to their relatively large share of electricity consumption. Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, CO_2 accounts for more than 75 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 2003.

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

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 2003

Sector/Gas	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**Percent[a]**
Industry	**2,075.7**	**2,247.3**	**2,223.2**	**2,190.1**	**2,207.7**	**2,074.0**	**2,062.9**	**2,040.1**	**29.6%**
Direct Emissions	**1,446.1**	**1,509.1**	**1,470.6**	**1,427.9**	**1,431.8**	**1,371.0**	**1,365.7**	**1,331.4**	19.3%
CO_2	1,103.0	1,183.2	1,143.2	1,118.6	1,123.7	1,086.7	1,081.7	1,059.0	15.3%
CH_4	240.9	228.4	225.3	216.5	218.7	216.4	211.2	207.9	3.0%
N_2O	40.5	39.8	34.9	33.6	33.7	28.7	31.1	29.8	0.4%
HFCs, PFCs, and SF_6	61.7	57.7	67.2	59.1	55.6	39.3	41.8	34.6	0.5%
Electricity-Related	**629.6**	**738.2**	**752.5**	**762.2**	**775.9**	**702.9**	**697.2**	**708.7**	10.3%
CO_2	616.7	727.2	743.3	753.1	767.2	695.0	689.5	701.2	10.2%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.7	3.2	3.2	3.2	3.3	2.9	2.9	3.0	+
SF_6	10.0	7.6	5.9	5.7	5.3	4.8	4.5	4.4	0.1%
Transportation	**1,509.9**	**1,696.1**	**1,731.8**	**1,793.2**	**1,843.0**	**1,823.2**	**1,854.8**	**1,867.6**	**27.1%**
Direct Emissions	**1,506.8**	**1,693.0**	**1,728.7**	**1,790.0**	**1,839.6**	**1,819.8**	**1,851.6**	**1,864.4**	27.0%
CO_2	1,458.7	1,614.9	1,645.6	1,703.0	1,749.8	1,730.8	1,763.2	1,777.4	25.8%
CH_4	4.4	3.5	3.4	3.1	2.9	2.6	2.4	2.2	+
N_2O	43.7	55.2	55.3	54.6	53.2	49.0	45.6	42.1	0.6%
HFCs[b]	+	19.4	24.4	29.3	33.8	37.4	40.4	42.7	0.6%

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[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.

Electricity-Related	**3.1**	**3.1**	**3.1**	**3.1**	**3.3**	**3.4**	**3.1**	**3.2**	+
CO_2	3.0	3.0	3.0	3.1	3.3	3.3	3.1	3.2	+
CH_4	+	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+	+	+
Commercial	**981.6**	**1,083.8**	**1,093.5**	**1,104.9**	**1,161.8**	**1,170.6**	**1,178.5**	**1,196.8**	**17.3%**
Direct Emissions	**435.4**	**445.2**	**424.2**	**426.8**	**440.7**	**431.4**	**440.2**	**453.5**	6.6%
CO_2	224.2	237.2	219.7	222.3	235.2	226.7	230.0	234.0	3.4%
CH_4	197.8	179.8	171.8	168.5	165.8	161.6	163.4	168.7	2.4%
N_2O	13.4	15.0	15.3	15.8	15.9	16.0	16.0	16.2	0.2%
HFCs	+	13.1	17.4	20.3	23.8	27.1	30.8	34.7	0.5%
Electricity-Related	**546.2**	**638.7**	**669.3**	**678.1**	**721.1**	**739.2**	**738.3**	**743.3**	10.8%
CO_2	535.0	629.2	661.0	670.0	713.0	730.9	730.2	735.3	10.7%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.4	2.7	2.8	2.8	3.0	3.1	3.1	3.2	+
SF_6	8.7	6.6	5.2	5.1	4.9	5.1	4.8	4.6	0.1%
Residential	**953.0**	**1,060.3**	**1,060.0**	**1,082.9**	**1,141.4**	**1,129.6**	**1,159.5**	**1,183.7**	**17.2%**
Direct Emissions	**350.9**	**391.0**	**358.4**	**379.5**	**399.7**	**387.1**	**391.6**	**406.1**	5.9%
CO_2	339.6	370.6	338.6	359.3	379.1	367.0	371.4	385.1	5.6%
CH_4	4.4	3.5	3.1	3.4	3.5	3.1	2.8	3.1	+
N_2O	6.6	7.1	7.0	7.1	6.9	6.7	6.8	6.9	0.1%
HFCs	0.3	9.9	9.6	9.8	10.1	10.3	10.6	11.0	0.2%
Electricity-Related	**602.1**	**669.3**	**701.6**	**703.4**	**741.7**	**742.5**	**767.9**	**777.6**	11.3%
CO_2	589.7	659.3	693.0	695.0	733.3	734.1	759.4	769.3	11.2%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.6	2.9	3.0	2.9	3.1	3.1	3.2	3.3	+
SF_6	9.6	6.9	5.5	5.2	5.0	5.1	5.0	4.8	0.1%
Agriculture	**534.1**	**547.4**	**568.6**	**537.3**	**552.3**	**555.5**	**548.8**	**549.8**	**8.0%**
Direct Emissions	**473.3**	**492.0**	**508.4**	**486.9**	**495.3**	**488.6**	**485.6**	**486.4**	7.0%
CO_2	46.3	58.4	57.6	60.0	50.4	50.3	52.3	52.2	0.8%
CH_4	157.0	163.1	164.4	164.8	162.1	162.0	161.6	162.0	2.3%
N_2O	270.0	270.5	286.3	262.1	282.8	276.3	271.7	272.2	3.9%
Electricity-Related	**60.8**	**55.4**	**60.2**	**50.4**	**57.0**	**66.9**	**63.2**	**63.4**	**0.9%**
CO_2	59.6	54.6	59.5	49.8	56.3	66.2	62.5	62.7	0.9%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.3	+
SF_6	1.0	0.6	0.5	0.4	0.4	0.5	0.4	0.4	+
U.S. Territories	**33.8**	**42.7**	**42.7**	**43.9**	**47.0**	**54.1**	**53.6**	**62.3**	**0.9%**
CO_2	33.8	42.7	42.7	43.9	47.0	54.1	53.6	62.3	0.9%
Total	**6,088.1**	**6,677.5**	**6,719.7**	**6,752.2**	**6,953.2**	**6,806.9**	**6,858.1**	**6,900.2**	**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 2003.

[b] Includes primarily HFC-134a.

Transportation

Transportation activities accounted for 27 percent of U.S. greenhouse gas emissions in 2003. 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 2003, transportation emissions rose by 24 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 35 percent from 1990 to 2003) 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 1990s.

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 22 percent from 1990 to 2003. This rise in CO_2 emissions, combined with an increase of 42.7 Tg CO_2 Eq. in HFC emissions over the same period, led to an increase in overall emissions from transportation activities of 24 percent.

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

Gas/Vehicle Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**1,461.7**	**1,618.0**	**1,648.7**	**1,706.2**	**1,753.1**	**1,734.2**	**1,766.4**	**1,780.7**
Passenger Cars	612.5	595.5	613.8	622.4	623.4	625.7	639.5	633.7
Light-Duty Trucks	312.2	421.6	432.1	449.2	452.1	456.2	468.1	478.8
Other Trucks	217.0	279.9	290.4	304.3	320.4	327.5	327.5	341.2
Buses	7.8	9.1	9.3	10.4	10.2	9.6	9.1	8.9
Aircraft[a]	177.2	179.0	181.3	186.7	193.2	183.4	174.9	171.3
Ships and Boats	49.2	38.7	32.4	42.3	63.1	42.7	57.2	57.5
Locomotives	36.3	40.0	40.5	41.7	41.8	42.8	41.0	42.8
Other[b]	49.4	54.2	48.7	49.3	48.9	46.1	49.0	46.6
International Bunker Fuels[c]	*93.6*	*106.1*	*103.3*	*102.7*	*102.2*	*98.5*	*89.5*	*84.2*
CH_4	**4.6**	**3.8**	**3.7**	**3.4**	**3.2**	**2.9**	**2.7**	**2.4**
Passenger Cars	2.6	1.9	1.8	1.7	1.5	1.4	1.2	1.1
Light-Duty Trucks	1.4	1.3	1.3	1.1	1.0	0.9	0.9	0.8
Other Trucks and Buses	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Aircraft	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1
Ships and Boats	0.1	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*	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**42.9**	**54.2**	**54.4**	**53.7**	**52.2**	**47.9**	**44.5**	**40.9**
Passenger Cars	25.5	26.7	26.7	25.9	24.7	23.1	21.6	19.9
Light-Duty Trucks	14.1	23.7	23.7	23.6	23.0	20.6	18.6	16.8
Other Trucks and Buses	0.9	1.4	1.6	1.7	1.7	1.7	1.8	1.8
Aircraft	1.7	1.7	1.8	1.8	1.9	1.8	1.7	1.7
Ships and Boats	0.4	0.3	0.3	0.3	0.5	0.3	0.5	0.5
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Motorcycles	+	+	+	+	+	+	+	+
International Bunker Fuels[c]	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*
HFCs	**+**	**19.4**	**24.4**	**29.3**	**33.8**	**37.4**	**40.4**	**42.7**
Mobile Air Conditioners[d]	+	13.8	17.4	20.8	24.0	26.7	28.8	30.3
Refrigerated Transport	+	5.5	7.0	8.5	9.8	10.8	11.5	12.3
Total	**1,509.3**	**1,695.4**	**1,731.1**	**1,792.5**	**1,842.2**	**1,822.4**	**1,853.9**	**1,866.7**

\+ 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 TEXT 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 2004) and fuel sales data (EIA 1991 through 2004). 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 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 TEXT BOX]

2.3. Ambient Air Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are referred to as "ambient air pollutants," and are regulated under the Clean Air Act in an effort to protect human health and the environment. These pollutants 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 pollutants 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). NMVOCs—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 t 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 ambient air pollutant formation into greenhouse gases is carbon monoxide's interaction with the hydroxyl radical—the major atmospheric sink for methane emissions—to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy methane.

Since 1970, the United States has published estimates of annual emissions of ambient air pollutants (EPA 2004).[6] Table 2-18 shows that fuel combustion accounts for the majority of emissions of these 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
NO_x	**22,860**	**22,284**	**21,964**	**20,530**	**20,288**	**19,414**	**18,850**	**18,573**
Stationary Fossil Fuel Combustion	9,884	9,578	9,419	8,344	8,002	7,667	7,523	7,222
Mobile Fossil Fuel Combustion	12,134	11,768	11,592	11,300	11,395	10,823	10,389	10,418
Oil and Gas Activities	139	130	130	109	111	113	135	124
Waste Combustion	82	140	145	143	114	114	134	121
Industrial Processes	591	629	637	595	626	656	630	648
Solvent Use	1	3	3	3	3	3	5	4
Field Burning of Agricultural Residues	28	34	35	34	35	35	33	33
Waste	0	3	3	3	2	2	2	2
CO	**130,580**	**101,138**	**98,984**	**94,361**	**92,895**	**89,329**	**87,451**	**85,077**
Stationary Fossil Fuel Combustion	4,999	3,927	3,927	5,024	4,340	4,377	4,020	4,454
Mobile Fossil Fuel Combustion	119,482	90,284	87,940	83,484	83,680	79,972	78,574	75,526
Oil and Gas Activities	302	333	332	145	146	147	116	125
Waste Combustion	978	2,668	2,826	2,725	1,670	1,672	1,672	1,674
Industrial Processes	4,124	3,153	3,163	2,156	2,217	2,339	2,308	2,431
Solvent Use	4	1	1	46	46	45	46	65
Field Burning of Agricultural Residues	689	767	789	767	790	770	707	794
Waste	1	5	5	13	8	8	8	8
NMVOCs	**20,937**	**16,994**	**16,403**	**15,869**	**15,228**	**15,048**	**14,222**	**13,939**
Stationary Fossil Fuel Combustion	912	1,016	1,016	1,045	1,077	1,080	926	1,007
Mobile Fossil Fuel Combustion	10,933	7,928	7,742	7,586	7,230	6,872	6,560	6,351
Oil and Gas Activities	555	442	440	414	389	400	340	345

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

Waste Combustion	222	313	326	302	257	258	281	263
Industrial Processes	2,426	2,038	2,047	1,813	1,773	1,769	1,725	1,711
Solvent Use	5,217	5,100	4,671	4,569	4,384	4,547	4,256	4,138
Field Burning of Agricultural Residues	NA	NA	NA	NA	NA	NA	NA	NA
Waste	673	157	161	140	119	122	133	125
SO_2	**20,936**	**17,091**	**17,189**	**15,917**	**14,829**	**14,452**	**13,928**	**14,463**
Stationary Fossil Fuel Combustion	18,407	15,104	15,191	13,915	12,848	12,461	11,946	12,477
Mobile Fossil Fuel Combustion	793	659	665	704	632	624	631	634
Oil and Gas Activities	390	312	310	283	286	289	315	293
Waste Combustion	39	29	30	30	29	30	24	28
Industrial Processes	1,306	985	991	984	1,031	1,047	1,009	1,029
Solvent Use	0	1	1	1	1	1	2	2
Field Burning of Agricultural Residues	NA	NA	NA	NA	NA	NA	NA	NA
Waste	0	1	1	1	1	1	1	1

Source: (EPA 2004) 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 69 percent in 2003. 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]

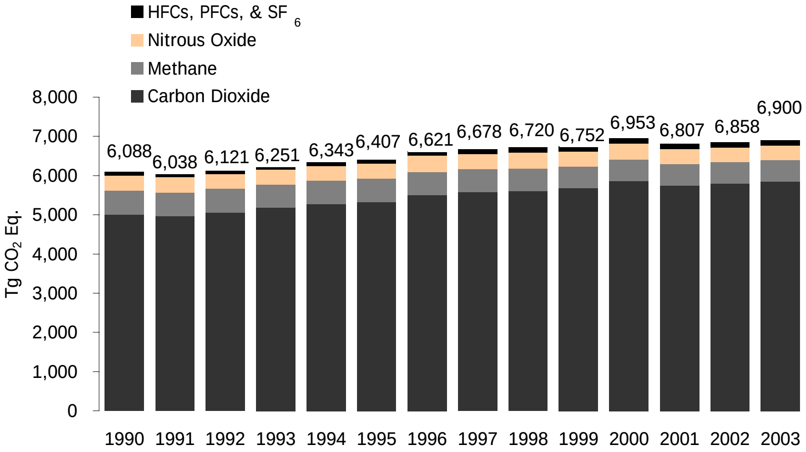


Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

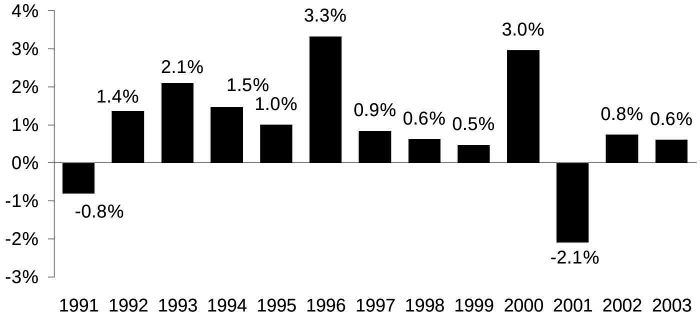


Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

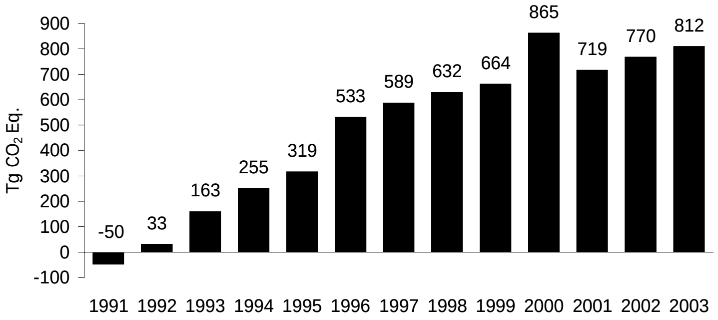


Figure 2-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

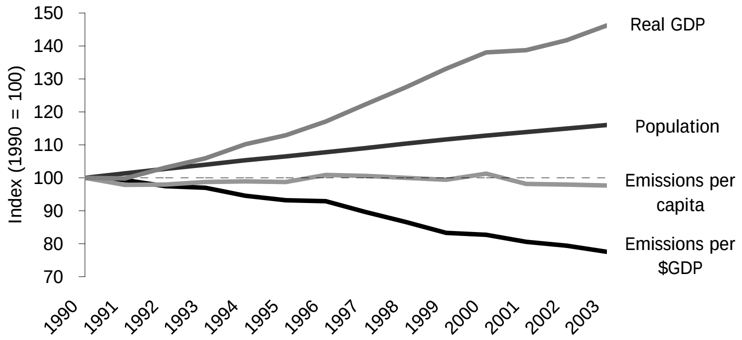


Figure 2-4: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

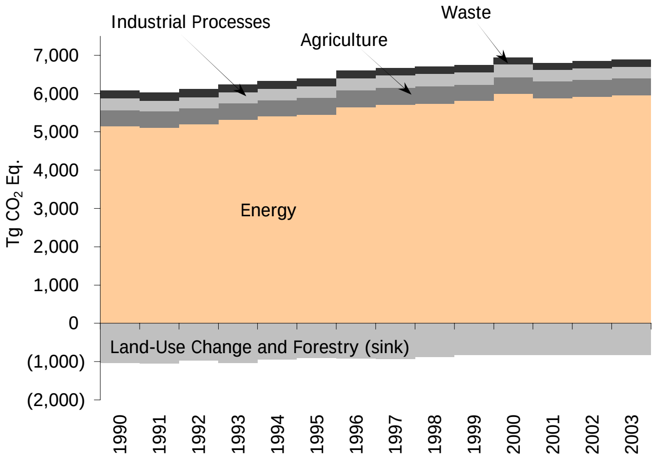


Figure 2-5: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

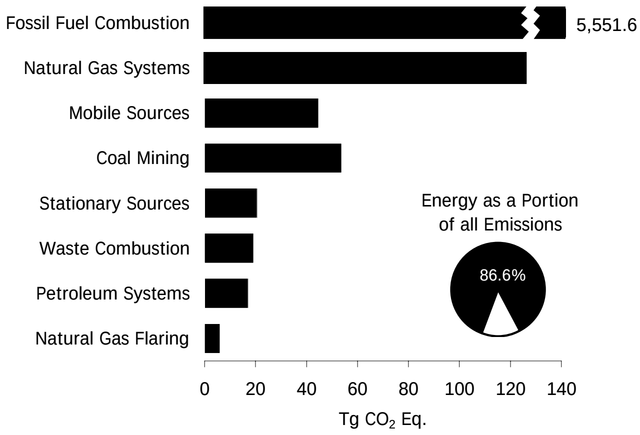
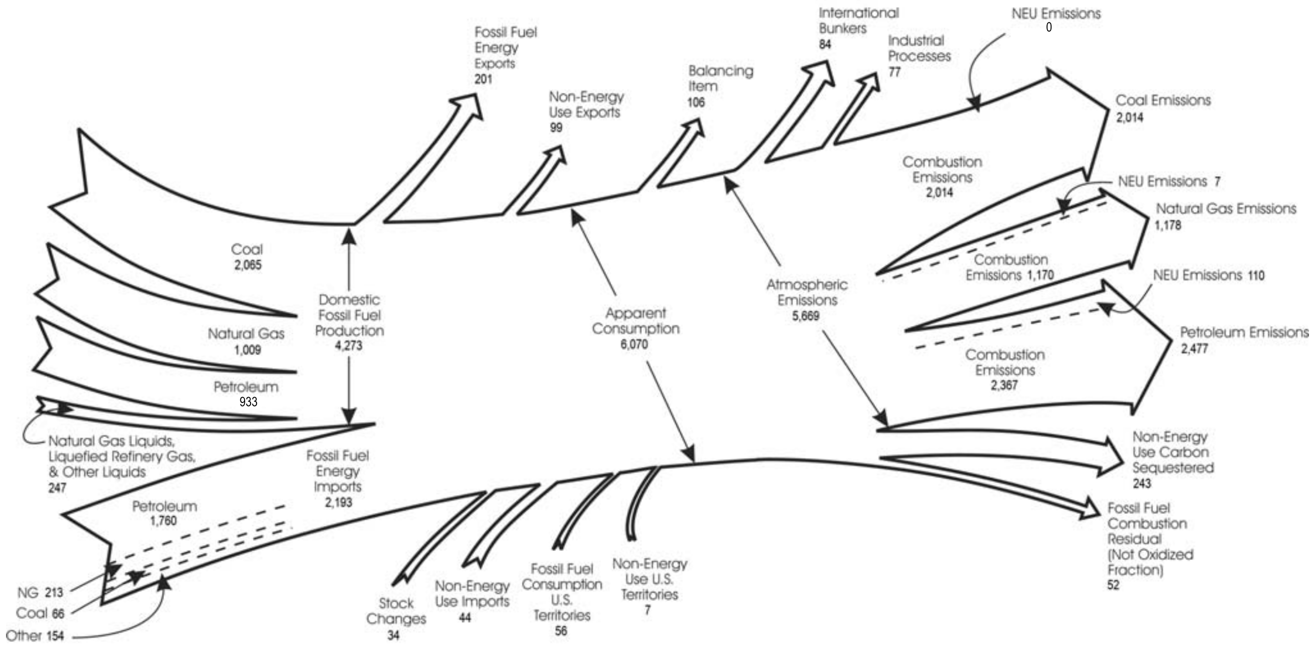


Figure 2-6: 2003 Energy Sector Greenhouse Gas Sources

Figure 2-7

2003 U.S. Fossil Carbon Flows (Tg CO$_2$ Eq.)



Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

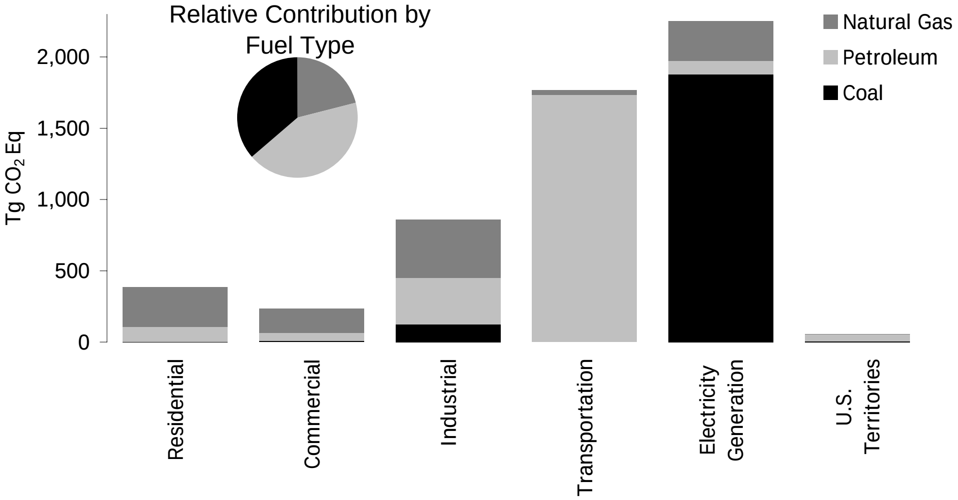


Figure 2-8: 2003 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricity generation.

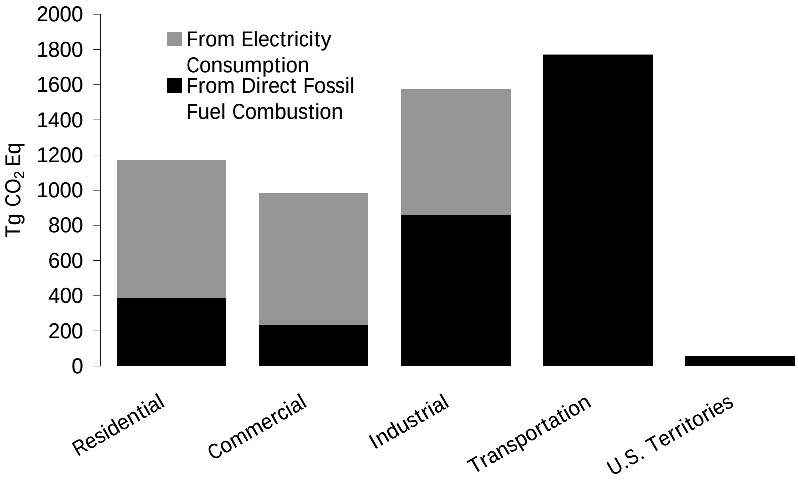


Figure 2-9: 2003 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

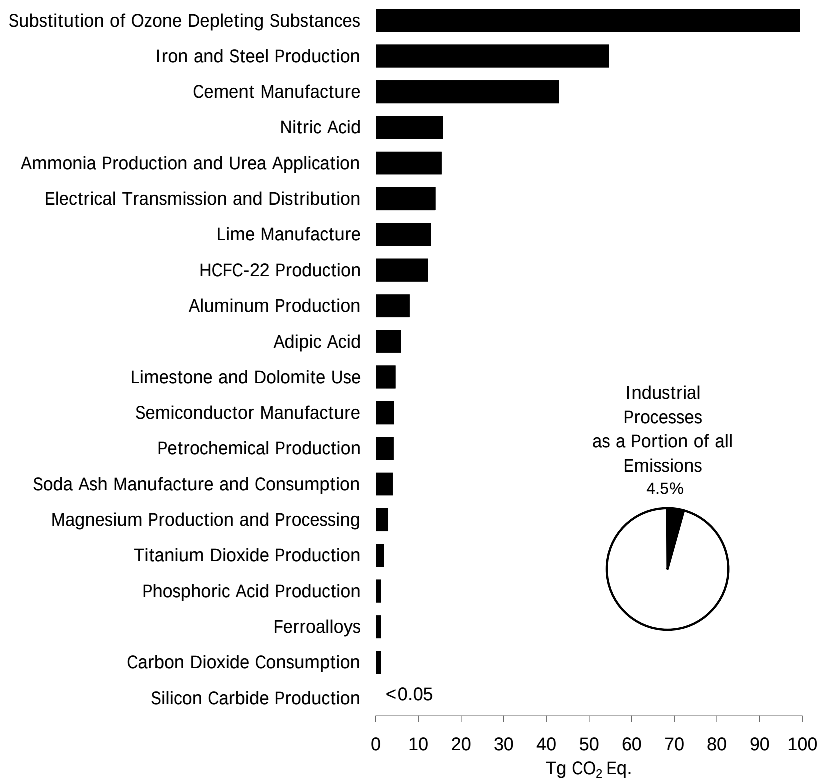


Figure 2-10: 2003 Industrial Processes Chapter Greenhouse Gas Sources

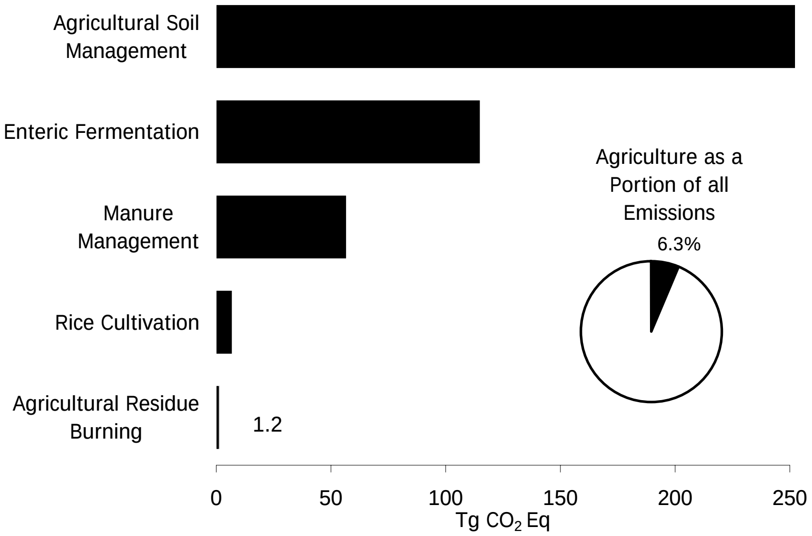


Figure 2-11: 2003 Agriculture Chapter GHG Sources

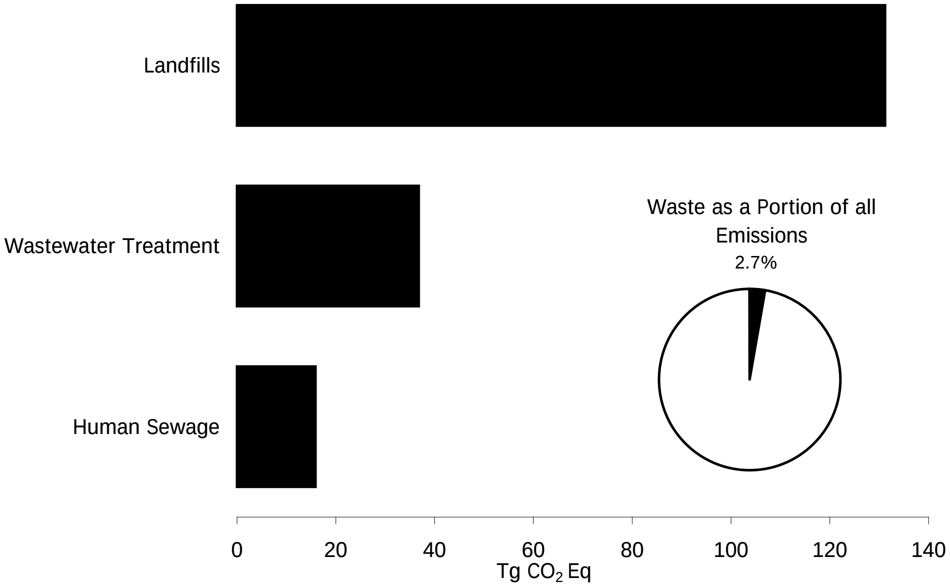


Figure 2-12: 2003 Waste Chapter Greenhouse Gas Sources

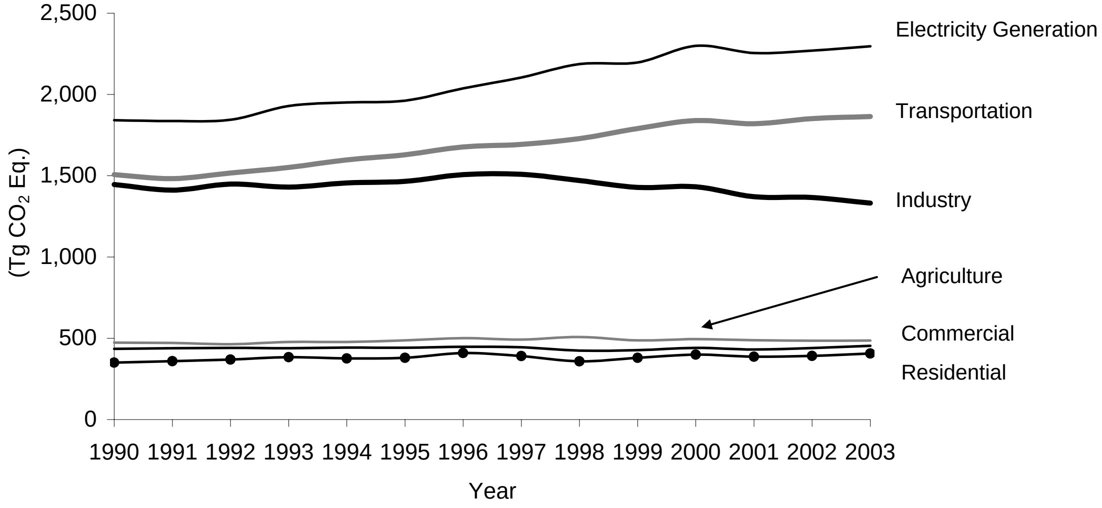


Figure 2-13: Emissions Allocated to Economic Sectors

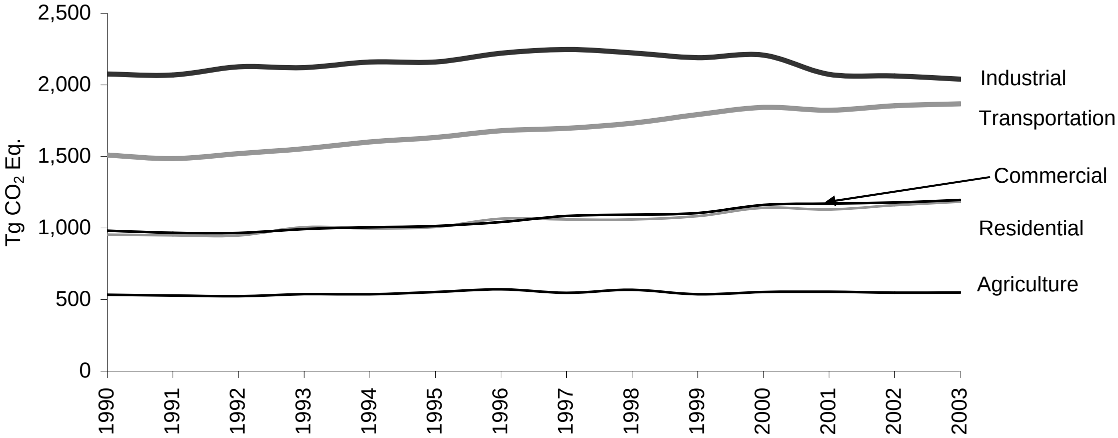


Figure 2-14: Emissions with Electricity Distributed to Economic Sectors

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 2003. 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 83 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 24,240 Tg CO_2 were added to the atmosphere through the combustion of fossil fuels in 2000, 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 ambient air pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane 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 ambient air pollutant emissions.

Figure 3-1: 2003 Energy Sector Greenhouse Gas Sources

Figure 3-2: 2003 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. Carbon dioxide emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the 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 Change and Forestry sector. 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 5,963.4 Tg CO_2 Eq. in 2003, an increase of 16 percent since 1990.

Table 3-1: Emissions from Energy (Tg CO_2 Eq.)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**4,836.4**	**5,409.1**	**5,437.7**	**5,512.1**	**5,693.5**	**5,592.9**	**5,645.3**	**5,694.3**
Fossil Fuel Combustion	4,711.7	5,263.2	5,278.7	5,345.9	5,545.1	5,448.0	5,501.4	5,551.6
Non-Energy Use of Fuels	108.0	120.3	135.4	141.6	124.7	120.1	118.8	118.0
Waste Combustion	10.9	17.8	17.1	17.6	18.0	18.8	18.8	18.8

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[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	7.9	6.6	6.9	5.8	6.1	6.2	6.0
*Biomass-Wood**	*212.5*	*226.3*	*209.5*	*214.3*	*217.6*	*190.8*	*195.8*	*201.0*
*International Bunker Fuels**	*113.5*	*109.9*	*114.6*	*105.3*	*101.4*	*97.9*	*89.5*	*84.2*
*Biomass-Ethanol**	*4.2*	*7.0*	*7.7*	*8.0*	*9.2*	*9.7*	*11.5*	*15.8*
CH_4	**248.9**	**234.6**	**230.9**	**222.1**	**224.3**	**221.6**	**215.8**	**212.7**
Natural Gas Systems	128.3	133.6	131.8	127.4	132.1	131.8	130.6	125.9
Coal Mining	81.9	62.6	62.8	58.9	56.2	55.6	52.4	53.8
Petroleum Systems	20.0	18.8	18.5	17.8	17.6	17.4	17.1	17.1
Stationary Sources	7.8	7.4	6.9	7.1	7.3	6.7	6.4	6.7
Mobile Sources	4.8	4.0	3.9	3.6	3.4	3.1	2.9	2.7
Abandoned Coal Mines	6.1	8.1	7.2	7.3	7.7	6.9	6.4	6.4
*International Bunker Fuels**	*0.2*	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.4**	**69.1**	**69.1**	**68.4**	**67.5**	**62.8**	**59.6**	**56.4**
Mobile Sources	43.7	55.2	55.3	54.6	53.2	49.0	45.6	42.1
Stationary Sources	12.3	13.5	13.4	13.5	14.0	13.5	13.5	13.8
Waste Combustion	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
*International Bunker Fuels**	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*
Total	**5,141.7**	**5,712.8**	**5,737.7**	**5,802.6**	**5,985.3**	**5,877.3**	**5,920.7**	**5,963.4**

* 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: Emissions from Energy (Gg)

Gas/Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	**4,836,430**	**5,409,100**	**5,437,734**	**5,512,062**	**5,693,544**	**5,592,947**	**5,645,251**	**5,694,332**
Fossil Fuel Combustion	4,711,741	5,263,164	5,278,721	5,345,904	5,545,083	5,447,969	5,501,427	5,551,580
Non-Energy Use of Fuels	107,964.9	120,300.6	135,352.1	141,582.9	124,713.8	120,104.1	118,810.6	118,001.4
Waste Combustion	10,919	17,761	17,094	17,632	17,979	18,781	18,781	18,781
Natural Gas Flaring	5,805	7,874	6,566	6,943	5,769	6,094	6,233	5,970
*Biomass-Wood**	*212,547*	*226,265*	*209,490*	*214,323*	*217,577*	*190,776*	*195,776*	*201,042*
*International Bunker Fuels**	*113,503*	*109,858*	*114,557*	*105,294*	*101,404*	*97,865*	*89,489*	*84,193*
*Biomass-Ethanol**	*4,155*	*6,978*	*7,711*	*8,017*	*9,188*	*9,701*	*11,473*	*15,771*
CH_4	**11,852**	**11,170**	**10,997**	**10,577**	**10,680**	**10,551**	**10,279**	**10,126**
Natural Gas Systems	6,112	6,363	6,276	6,066	6,289	6,277	6,221	5,998
Coal Mining	3,900	2,983	2,989	2,805	2,677	2,647	2,497	2,561
Petroleum Systems	951	895	879	848	836	831	815	815
Stationary Sources	373	351	328	338	349	318	305	319
Mobile Sources	228	193	185	172	161	147	138	128
Abandoned Coal Mines	288	385	341	349	369	331	303	306
*International Bunker Fuels**	*8*	*7*	*7*	*6*	*6*	*5*	*4*	*4*
N_2O	**182**	**223**	**223**	**221**	**218**	**203**	**192**	**182**
Mobile Combustion	141	178	179	176	171	158	147	136
Stationary Combustion	40	44	43	43	45	43	44	45
Waste Combustion	1	1	1	1	1	1	1	1
*International Bunker Fuels**	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*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.

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

Carbon dioxide emissions from fossil fuel combustion in 2003 increased 0.9 percent from the previous year. This increase is primarily a result of increased demand for fuels due to a growing economy, fuel-switching from natural gas to coal in the electric power sector, and increased use of heating fuels in the residential sector caused by a colder winter. In 2003, CO_2 emissions from fossil fuel combustion were 5,551.6 Tg CO_2 Eq., or 18 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	1997	1998	1999	2000	2001	2002	2003
Coal	**1,680.9**	**1,920.2**	**1,936.5**	**1,938.2**	**2,025.6**	**1,959.2**	**1,973.1**	**2,013.8**
Residential	2.4	1.5	1.2	1.3	1.1	1.1	1.0	1.1
Commercial	12.1	12.2	8.7	9.7	8.6	9.2	8.6	9.3
Industrial	152.6	147.2	139.2	133.8	135.0	130.6	122.7	123.4
Transportation	NE	NE	NE	NE	NE	NE	NE	NE
Electricity Generation	1,513.0	1,758.4	1,786.4	1,792.4	1,880.0	1,817.4	1,839.7	1,876.3
U.S. Territories	0.6	1.0	1.0	0.9	0.9	0.9	1.2	3.6
Natural Gas	**1,009.5**	**1,193.7**	**1,169.9**	**1,173.6**	**1,224.1**	**1,174.4**	**1,214.0**	**1,170.3**
Residential	238.8	270.2	246.5	256.5	270.3	259.7	265.9	277.3
Commercial	142.6	174.3	163.5	165.2	172.4	164.5	168.7	170.7
Industrial	416.3	489.1	476.7	456.4	464.6	426.0	435.5	407.9
Transportation	35.9	41.1	35.1	35.6	35.5	33.9	37.1	35.4
Electricity Generation	176.0	218.9	248.0	259.9	280.7	289.1	305.6	277.6
U.S. Territories	NO	NO	NO	NO	0.7	1.2	1.2	1.4
Petroleum	**2,020.9**	**2,148.9**	**2,172.0**	**2,233.7**	**2,295.0**	**2,314.0**	**2,314.0**	**2,367.1**
Residential	98.3	98.9	90.9	101.5	107.7	106.2	104.5	106.7
Commercial	69.5	50.7	47.5	47.3	54.2	53.1	52.7	53.9
Industrial	313.9	327.4	295.6	297.8	305.5	321.6	318.4	327.3
Transportation	1,410.9	1,562.2	1,598.3	1,655.2	1,702.2	1,685.8	1,715.2	1,731.8
Electricity Generation	101.0	74.3	104.3	96.7	91.0	100.9	77.4	96.3
U.S. Territories	27.4	35.5	35.4	35.2	34.3	46.5	45.7	51.2
Geothermal*	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
Total	**4,711.7**	**5,263.2**	**5,278.7**	**5,345.9**	**5,545.1**	**5,448.0**	**5,501.4**	**5,551.6**

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).

Carbon dioxide 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

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

energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent.[3] Producing a unit of heat or electricity using natural gas instead of coal can reduce the CO_2 emissions associated with energy consumption, and using nuclear or renewable energy sources (e.g., wind) can essentially eliminate emissions (see Box 3-2). Table 3-4 shows annual changes in emissions during the last six 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	1999 to 2000		2000 to 2001		2001 to 2002		2002 to 2003	
Electricity Generation	Coal	87.6	5%	-62.6	-3%	22.2	1%	36.6	2%
Electricity Generation	Natural Gas	20.8	8%	8.4	3%	16.5	6%	-28.0	-9%
Electricity Generation	Petroleum	-5.6	-6%	9.8	11%	-23.5	-23%	18.9	24%
Transportation[a]	Petroleum	47.0	3%	-16.4	-1%	29.4	2%	16.6	1%
Residential	Natural Gas	13.9	5%	-10.7	-4%	6.2	2%	11.5	4%
Commercial	Natural Gas	7.1	4%	-7.9	-5%	4.2	3%	2.0	1%
Industrial	Coal	1.1	1%	-4.4	-3%	-7.9	-6%	0.8	1%
Industrial	Natural Gas	8.2	2%	-38.5	-8%	9.5	2%	-27.6	-6%
All Sectors[b]	**All Fuels[b]**	**199.2**	**4%**	**-97.1**	**-2%**	**53.5**	**1%**	**50.2**	**1%**

[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 2003 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 2004a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 39 percent of total energy consumption from 1990 through 2003. 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 2004a).

Figure 3-3: 2003 U.S. Energy Consumption by Energy Source

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

Figure 3-5: 2003 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.

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[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 2003, weather conditions became cooler in both the winter and summer. Heating degree days in the United States were 2 percent below normal (see Figure 3-6), while cooling degree days in 2003 were 5 percent above normal (see Figure 3-7) (EIA 2004f).[5] Winter conditions were colder in 2003 than in 2002, which, coupled with a 1.2 percent increase in the U.S. housing stock (EIA 2004f), led to an increase in demand for heating fuels, despite escalating fuel prices for heating fuels. Though the summer of 2003 was cooler than the near record heat of 2002, demand for electricity increased most likely due to the growing economy and increase in housing stock.

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1949-2003)

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1949-2003)

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[6]) of existing plants remained high, at 88 percent in 2003. This utilization level actually represents a 2 percent decrease in electricity output by nuclear plants, down from a record high of 90 percent in 2002. Electricity output by hydroelectric power plants increased in 2003 by approximately 4 percent. Nevertheless, electricity generated by nuclear plants in 2003 provided almost 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2004a). 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 (1973-2003)

[END BOX]

For the purpose of international reporting, the 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.

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[5] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. Heating degree days have a considerably greater 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 2004a).

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 provided in Table 3-5.

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

Vehicle Mode	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Aviation	46.2	55.9	56.7	58.9	60.5	59.4	61.8	59.6
Marine	67.3	54.0	57.9	46.4	40.9	38.5	27.7	24.6
Total	**113.5**	**109.9**	**114.6**	**105.3**	**101.4**	**97.9**	**89.5**	**84.2**

* 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.[7] 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. In reality, sources of electricity vary widely in carbon intensity (e.g., coal versus wind power). By giving equal carbon-intensity weight to each sector's electricity consumption, emissions attributed to one end-use sector may be somewhat overestimated, while emissions attributed to another end-use sector may be slightly underestimated. 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Transportation	**1,449.8**	**1,606.4**	**1,636.5**	**1,693.9**	**1,741.0**	**1,723.1**	**1,755.4**	**1,770.4**
Combustion	1,446.8	1,603.3	1,633.4	1,690.8	1,737.7	1,719.7	1,752.3	1,767.2
Electricity	3.0	3.1	3.1	3.2	3.4	3.4	3.2	3.2
Industrial	**1,553.9**	**1,703.0**	**1,668.5**	**1,651.2**	**1,684.4**	**1,587.4**	**1,579.0**	**1,572.9**
Combustion	882.8	963.8	911.6	888.1	905.0	878.2	876.6	858.6
Electricity	671.1	739.2	757.0	763.1	779.4	709.3	702.4	714.3
Residential	**924.8**	**1,040.7**	**1,044.4**	**1,063.5**	**1,124.2**	**1,116.2**	**1,145.0**	**1,168.9**
Combustion	339.6	370.6	338.6	359.3	379.1	367.0	371.4	385.1
Electricity	585.3	670.2	705.8	704.2	745.0	749.2	773.6	783.8
Commercial	**755.1**	**876.7**	**892.9**	**901.2**	**959.5**	**972.7**	**973.9**	**983.1**
Combustion	224.2	237.2	219.7	222.3	235.2	226.7	230.0	234.0
Electricity	530.9	639.5	673.2	678.9	724.3	745.9	743.9	749.2
U.S. Territories	**28.0**	**36.4**	**36.3**	**36.2**	**35.9**	**48.6**	**48.1**	**56.2**
Total	**4,711.7**	**5,263.2**	**5,278.7**	**5,345.9**	**5,545.1**	**5,448.0**	**5,501.4**	**5,551.6**
Electricity Generation	**1,790.3**	**2,051.9**	**2,139.0**	**2,149.3**	**2,252.1**	**2,207.8**	**2,223.0**	**2,250.5**

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

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[7] See Glossary (Annex 6.8) for more detailed definitions of the industrial, residential, commercial, and transportation end-use sector, as well as electricity generation.

Figure 3-9: 2003 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 the largest share (approximately 32 percent) of CO_2 emissions from fossil fuel combustion.[8] Almost all of the energy consumed in the transportation sector was petroleum-based, with nearly two-thirds being 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.[9]

Carbon dioxide emissions from fossil fuel combustion for transportation increased by 22 percent from 1990 to 2003, to 1,770.4 Tg CO_2 Eq. The growth in transportation end-use sector emissions has been relatively steady, excluding a 4 percent single year increase in 1999 and slight decreases in 1991 and 2001. Like overall energy demand, transportation fuel demand is a function of many short and long-term factors. In the short term only minor adjustments can generally be made through consumer behavior (e.g., not driving as far for summer vacation). However, long-term adjustments such as vehicle purchase choices, transport mode choice and access (i.e., trains versus planes), and urban planning can have a significant impact on fuel demand.

In 2003, CO_2 emissions from the transportation sector increased by approximately 1 percent. A 12 percent increase in the price of motor gasoline in 2003 tempered the effects of the growing economy[10] on demand for vehicle fuel (see Figure 3-10).

Since 1990, travel activity in the United States has grown more rapidly than population, with a 16 percent increase in vehicle miles traveled per capita. In the meantime, improvements in the average fuel efficiency of the U.S. vehicle fleet stagnated after increasing steadily since 1976 (FHWA 1996 through 2004). The average miles per gallon achieved by the U.S. vehicle fleet has remained fairly constant since 1991. This trend is due, in part, to the increasing dominance of new motor vehicle sales by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 3-11).

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

Figure 3-11: Motor Vehicle Fuel Efficiency

Table 3-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-nine percent of the emissions from this end-use sector in 2003 were the result of the combustion of motor gasoline in passenger cars and light-duty trucks. Diesel highway vehicles and jet aircraft were also significant contributors, accounting for 18 and 12 percent of CO_2 emissions from the transportation end-use sector, respectively.[11] For information on transportation-related CO_2 emissions from agriculture and construction equipment, other off-road equipment, and recreational vehicles, please refer to Table 3-36 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**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Gasoline	**955.2**		**1,042.5**	**1,072.9**	**1,099.9**	**1,105.9**	**1,111.2**	**1,138.7**	**1,143.7**

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

[9] See Glossary (Annex 6.8) for a more detailed definition of the transportation end-use sector.

[10] Gross domestic product increased 3.1 percent between 2002 and 2003 (BEA 2004).

[11] These percentages include emissions from bunker fuels.

Automobiles	605.1		589.8	608.6	618.4	620.1	622.3	636.1	630.2
Light-Duty Trucks	301.0		406.1	416.3	432.6	435.3	438.7	450.9	460.9
Other Trucks	37.7		33.3	34.6	35.7	37.3	37.1	38.7	39.6
Buses	0.3		0.4	0.4	0.4	0.4	0.4	0.3	0.3
Motorcycles	1.7		1.7	1.8	1.8	1.8	1.6	1.6	1.6
Boats (Recreational)	9.4		11.2	11.2	11.1	11.2	11.2	11.1	11.0
Distillate Fuel Oil (Diesel)	**265.1**		**338.4**	**348.4**	**362.2**	**374.0**	**383.2**	**378.1**	**392.6**
Automobiles	7.4		5.6	5.2	4.0	3.4	3.5	3.4	3.4
Light-Duty Trucks	10.7		15.1	15.4	16.3	16.6	17.2	16.9	17.6
Other Trucks	178.4		246.2	255.2	268.1	282.7	289.9	288.3	301.1
Buses	7.5		8.6	8.7	9.7	9.4	8.8	8.2	8.0
Locomotives	33.3		37.0	37.4	38.5	38.4	39.4	37.9	39.6
Ships & Boats	16.3		16.9	15.0	17.4	17.3	19.1	18.4	17.0
Ships (Bunkers)	11.4		9.1	11.5	8.2	6.2	5.2	5.1	6.0
Jet Fuel	**220.4**		**232.1**	**235.6**	**242.9**	**251.2**	**240.4**	**234.4**	**228.6**
Commercial Aircraft	117.2		128.5	126.3	136.4	140.6	132.8	121.7	122.8
Military Aircraft	34.8		21.0	21.5	20.6	21.0	22.8	20.4	20.5
General Aviation Aircraft	6.3		6.1	7.7	9.2	9.2	9.0	9.3	9.4
Other Aircraft[b]	15.9		20.6	23.4	17.8	19.9	16.4	21.2	16.3
Aircraft (Bunkers)	46.2		55.9	56.7	58.9	60.5	59.4	61.8	59.6
Aviation Gasoline	**3.1**		**2.7**	**2.4**	**2.7**	**2.5**	**2.4**	**2.3**	**2.2**
General Aviation Aircraft	3.1		2.7	2.4	2.7	2.5	2.4	2.3	2.2
Residual Fuel Oil	**79.3**		**55.5**	**52.6**	**51.9**	**69.2**	**45.7**	**50.4**	**48.1**
Ships & Boats[c]	23.4		10.6	6.2	13.7	34.6	12.4	27.7	29.5
Ships (Bunkers)[c]	55.8		44.9	46.4	38.2	34.6	33.2	22.6	18.6
Natural Gas	**35.9**		**41.1**	**35.1**	**35.6**	**35.5**	**33.9**	**37.1**	**35.4**
Automobiles	+		+	+	+	+	+	+	+
Light Trucks	+		+	+	+	+	+	+	+
Buses	+		0.2	0.2	0.3	0.4	0.5	0.6	0.6
Pipeline	35.9		40.9	34.9	35.3	35.0	33.4	36.4	34.8
LPG	**1.4**		**0.8**	**1.0**	**0.8**	**0.7**	**0.8**	**0.9**	**0.8**
Light Trucks	0.5		0.4	0.4	0.3	0.3	0.3	0.3	0.3
Other Trucks	0.8		0.4	0.6	0.5	0.4	0.5	0.5	0.5
Buses	+		+	+	+	+	+	+	+
Electricity	**3.0**		**3.1**	**3.1**	**3.2**	**3.4**	**3.4**	**3.2**	**3.2**
Rail	3.0		3.1	3.1	3.2	3.4	3.4	3.2	3.2
Total (Including Bunkers)[d]	**1,563.3**		**1,716.2**	**1,751.1**	**1,799.2**	**1,842.5**	**1,821.0**	**1,844.9**	**1,854.6**
Total (Excluding Bunkers)[d]	**1,449.8**		**1,606.4**	**1,636.5**	**1,693.9**	**1,741.0**	**1,723.1**	**1,755.4**	**1,770.4**

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 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, 55 percent of these emissions resulted from the direct consumption of fossil fuels for steam and process heat production. The remaining 45 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.[12] The largest of these activities in terms of energy consumption is manufacturing, which was estimated in 1998 to have accounted for about 84 percent of industrial energy consumption (EIA 2001a). Just six industries—Petroleum, Chemicals, Primary Metals, Paper, Food, and Stone, Clay, and Glass products—represent 83 percent of total manufacturing energy use.

In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption is also affected by weather conditions.[13] 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 2002 to 2003, total industrial production and manufacturing output increased slightly, by 0.2 and 0.1 percent, respectively (FRB 2004). Also from 2002 to 2003, output increased for the Petroleum Refinery, Nonmetallic Mineral Product, and Chemical industries, but declined for the Primary Metal, Food, and Paper industries (see Figure 3-12).

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

Despite the growth in industrial output (44 percent) and the overall U.S. economy (46 percent) from 1990 to 2003, emissions from the industrial end-use sector increased only slightly (by 1 percent). The reasons for the disparity between rapid growth in industrial output and stagnant growth in industrial emissions are not entirely clear. It is likely, though, that several factors have influenced industrial emission trends, 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 2003, carbon dioxide emissions from fossil fuel combustion and electricity use within the industrial end-use sectors were 1,572.9 Tg CO_2 Eq., or 0.4 percent below 2002 emissions.

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 67 and 76 percent of emissions from the residential and commercial end-use sectors, respectively. The 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 2003, CO_2 emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,168.9 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).

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[12] See Glossary (Annex 6.8) for a more detailed definition of the industrial end-use sector.

[13] 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.

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 2003, these emissions increased by 4 and 1 percent, respectively, in each of these sectors. Colder winter conditions in the United States (see Figure 3-13) and an increasing U.S. housing stock led to higher demand for natural gas, despite drastic increases in natural gas prices (66 percent).

Figure 3-13: Heating Degree Days[14]

Electricity sales to the residential and commercial end-use sectors in 2003 increased by 1 and 0.4 percent, respectively. This trend can largely be attributed to the growing economy (3.1 percent) and increase in U.S. housing stock (1.2 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 expected with the cooler summer (see Figure 3-14), and increases in electricity prices (1 and 2 percent higher to the residential and commercial sectors, respectively). Electricity-related emissions in both sectors rose with increasing consumption and the higher carbon intensity of electricity generation. Total emissions from the residential sector increased by 2.1 percent in 2003, with emission from the commercial sector 0.9 percent higher than in 2002.

Figure 3-14: Cooling Degree Days[15]

Electricity Generation

The process of generating electricity is the single largest source of CO_2 emissions in the United States (39 percent). 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 41 percent in 2003.

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). While utilities primarily generate power for the U.S. electric grid for sale to retail customers, nonutilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers). However, the electric power industry in the United States has undergone significant changes as both federal and state government agencies have modified regulations to create a more competitive market for electricity generation. These changes have led to the growth of nonutility power producers, including the sale of generating capacity by electric utilities to nonutilities. As a result, the Department of Energy no longer categorizes electric power generation into these ownership groups, and instead uses three functional categories: the electric power sector, the commercial sector, and the industrial sector. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity, while the other sectors consist of those producers that indicate their primary business is other than the production of electricity.

In 2003, the amount of electricity generated decreased very slightly, by 0.3 percent. Although total U.S. electricity use actually increased by 1 percent, net generation declined due to increased net imports and reduced losses of

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[14] 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.

[15] 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.

electricity.[16] However, CO_2 emissions increased by 1.2 percent, as escalating natural gas prices caused power producers to switch from natural gas to coal, a more carbon-intensive fuel. Coal consumption for electricity generation increased by 2.0 percent in 2003, while natural gas consumption decreased by 9.2 percent. As a result of this shift, carbon intensity from energy consumption for electricity generation increased in 2003 (see Table 3-9). Coal is consumed primarily by the electric power sector in the United States, which accounted for 93 percent of total coal consumption for energy purposes in 2003. Electricity generation by nuclear and renewable resources remained relatively stable, increasing 1 percent in 2003.

[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.[17]

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.[18] 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.[19] 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.[20] 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 sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from

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[16] EIA statistics track net generation, imports, exports, and compare these with the end use of electricity. The difference between these values is classified as "T&D losses and Unaccounted for". T&D losses refer to electricity lost during the transmission and distribution of electricity from the source to the end user. There also exists a small amount of electricity not accounted for due to data collection time frame differences and nonsampling error.

[17] 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.

[18] 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.

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

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

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		1997	1998	1999	2000	2001	2002	2003
Residential[a]	57.0		56.5	56.5	56.6	56.6	56.7	56.6	56.5
Commercial[a]	59.3		57.4	57.1	57.1	57.2	57.3	57.2	57.3
Industrial[a]	66.1		65.8	65.2	65.1	65.1	64.7	64.5	65.0
Transportation[a]	70.3		70.1	70.1	70.2	70.3	70.3	70.3	70.3
Electricity Generation[b]	85.8		85.9	85.2	84.9	84.7	84.3	84.1	84.8
U.S. Territories[c]	73.3		73.3	73.2	73.0	72.5	72.9	73.0	73.5
All Sectors[c]	**72.6**		**72.5**	**72.6**	**72.5**	**72.5**	**72.3**	**72.2**	**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.[21] 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		1997	1998	1999	2000	2001	2002	2003
Transportation[a]	70.1		69.8	69.8	69.8	69.9	69.8	69.8	69.6
Other End-Use Sectors[a, b]	57.8		57.8	57.9	57.3	58.0	58.2	57.5	58.0
Electricity Generation[c]	58.4		58.9	59.1	58.2	59.2	59.3	58.3	59.0
All Sectors[d]	**61.1**		**61.0**	**61.1**	**60.8**	**61.3**	**61.5**	**60.9**	**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.

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[21] 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 thirteen-year period of 1990 through 2003, however, the carbon intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies has 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 has generally demonstrated a constant overall trend since 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 (2004a) 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 2004b). The United States does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Grillot (2004).[22]

   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.[23]

   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

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[22] 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 56 Tg CO_2 Eq. in 2003.

[23] 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.

adjusted to correspond to international standard, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[24]

2. *Subtract uses accounted for in the Industrial Processes chapter.* Portions of the fuel consumption data for five fuel categories—coking 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 (2004), EFMA (1995), U.S. Census Bureau (1991 through 1994), U.S. Census Bureau (1998 through 2003), U.S. Census Bureau (2003), U.S. Census Bureau (2004a), EIA (2000 through 2004), EIA (2001b), USGS (2003 through 2004), USGS (1998 through 2002), USGS (1995), USGS (1995 through 2004), USGS (1991 through 1994), USGS (1991 through 2003), U.S. International Trade Commission (2004a), U.S. International Trade Commission (2004b), and Onder and Bagdoyan (1993).[25]

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.[26] 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 (2004b) and data for synthetic natural gas were collected from EIA (2004e), and data for CO_2 exports were collected from the Dakota Gasification Company (2003), Fitzpatrick (2002), and Erickson (2003).

4. *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 (2004b).

5. *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).[27] 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 2004) supplied data on military jet fuel use. Commercial jet fuel use was obtained from BEA (1991 through

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[24] 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.

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

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

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

2004) and DOT (1991 through 2004); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2004). 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.

6. *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 2003* (EIA 2004c) and EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail EIA (EIA 2004b). They are presented in Annexes 2.1 and 2.2.

7. *Adjust for carbon that does not oxidize during combustion.* Because 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 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.[28] IPCC provided fraction oxidized values for petroleum and natural gas (IPCC/UNEP/OECD/IEA 1997). Bechtel (1993) provided the fraction oxidation value for coal.

8. *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.[29] 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 2004); 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 (2004), BEA (1991 through 2004), Benson (2002 through 2004), DOE (1993 through 2004), DESC (2004), DOC (1991 through 2004), DOT (1991 through 2004), EIA (2002a), EIA (2002b), EIA (2004a), EIA (2004b), EIA (2003 through 2004), EIA (1991 through 2004), EPA (2004c), and FAA (2004). Heat contents and densities were obtained from EIA (2004a) and USAF (1998).[30] The difference between total U.S. jet fuel consumption (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.

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

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

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

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 2003. 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.

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.[31] Triangular distributions were assigned for

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[31] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former 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.

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.[32]

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).[33] 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 2003 were estimated to be between 5,474.3 and 5,863.3 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 2003 emission estimate of 5,551.6 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	**2003 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]	**2,013.8**	**1,962.0**	**2,220.5**	**-3%**	**+10%**
Residential	1.1	1.1	1.3	-5%	+16%
Commercial	9.3	8.9	10.8	-4%	+16%
Industrial	123.4	120.0	144.1	-3%	+17%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,876.3	1815.7	2,072.5	-3%	+10%
U.S. Territories	3.6	3.2	4.3	-12%	+20%
Natural Gas[b]	**1,170.3**	**1,161.0**	**1,229.9**	**-1%**	**+5%**
Residential	277.3	270.5	297.7	-2%	+7%
Commercial	170.7	166.5	183.2	-2%	+7%
Industrial	407.9	396.6	439.0	-3%	+8%
Transportation	35.4	34.5	38.0	-2%	+7%
Electricity Generation	277.6	270.5	292.8	-3%	+5%
U.S. Territories	1.4	1.2	1.7	-12%	+17%
Petroleum[b]	**2,367.1**	**2,256.9**	**2,518.5**	**-5%**	**+6%**
Residential	106.7	101.7	112.5	-5%	+6%
Commercial	53.9	51.6	56.7	-4%	+5%
Industrial	327.3	283.4	386.0	-13%	+18%
Transportation	1,731.8	1,627.9	1,857.2	-6%	+7%
Electric Utilities	96.3	93.8	101.8	-3%	+6%
U.S. Territories	51.2	47.6	57.2	-7%	+12%
Total (excluding Geothermal)[b]	**5,551.2**	**5,474.0**	**5,863.0**	**-1%**	**+6%**

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[32] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[33] 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.

Geothermal	**0.3**	**NE**	**NE**	**NE**	**NE**
Total (including Geothermal)[b,c]	**5,551.6**	**5,474.3**	**5,863.3**	**-1%**	**+6%**

NA (Not Applicable)
NE (Not Estimated)
Notes:
[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

A major change this year was the decision to report emissions from fuels used for non-energy purposes separately from fuel combustion emission estimates. Previously, the carbon stored from non-energy uses was subtracted from total carbon in fuels. However, this method resulted in non-energy emissions being reported within the emission estimates for fuel combustion. This year, these emissions are reported separately in the section entitled “Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels.”

Bunker fuel consumption estimates are now subtracted out from total fuel consumption, instead of subtracting the total carbon in bunker fuels from total potential carbon. This change in methodology does not have any affect on emission estimates, though it allows for clearer and more transparent emission calculations.

Adjustments are now made to the consumption data for residual oil and other oils (>401 deg F) to subtract consumption for carbon black production, for which emissions are estimated in the Petrochemical Production section of the Industrial Processes chapter.

EIA statistics report consumption for non-energy use for a number of fuels to be roughly equivalent to total use of these fuels, though for certain years these data series did not match exactly. After discussions with EIA, it was assumed that 100 percent of the use of these fuels should be assumed to be for non-energy purposes. These fuels are asphalt & road oil, lubricants, naphtha, other oil (>401 deg. F), special naphtha, waxes, and miscellaneous products.

The Energy Information Administration (EIA 2004a) updated energy consumption data for all years. These revisions primarily impacted the emission estimates for 2002.

The combination of the methodological and historical data changes, as well as changes in the estimates of Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels and International Bunker Fuels (which affect emissions from this source) resulted in an average annual decrease of 115.8 Tg CO_2 Eq. (2.2 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2002. This decrease is largely a result of reporting emissions from non-energy uses separately this year.

Planned Improvements

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

- Currently, the IPCC guidelines recommend a default factor of 0.99 to represent the fraction of carbon in fossil fuels that is oxidized to CO_2 during the fuel combustion of petroleum, though national experts are encouraged to improve upon this assumption if better data is available. As a result, carbon mass balances for light-duty gasoline cars and trucks have been analyzed to assess what would be the most appropriate carbon oxidation fraction for these vehicles. The analysis, currently under peer review, suggests 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. Upon further peer review, the revised factor is expected to be used in future inventories. A further examination into diesel fueled vehicles is also planned.
- The 0.99 oxidation factor for coal will be further investigated in order to verify or revise this value.
- 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, and synthetic fibers.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 65 percent of the total carbon consumed for non-energy purposes is stored in products, and not released to the atmosphere; the remaining 35 percent is emitted.

There are several areas in which non-energy uses of fossil fuels relates closely 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 this sector in the 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 sector. To avoid double-counting, the "raw" non-energy fuel consumption data reported by EIA are modified to account for these overlaps, resulting in the adjusted consumption values shown in Table 3-12. 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; the effects of these adjustments are also shown in Table 3-11.

As shown in Table 3-11, fossil fuel emissions in 2003 from the non-energy uses of fossil fuels were 118.0 Tg CO_2 Eq., which constituted 2 percent of overall fossil fuel emissions, approximately the same proportion as in 1990. In 2003, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,264 TBtu, an increase of 24 percent since 1990 (see Table 3-12). About 66.1 Tg of the C (242.5 Tg CO_2 Eq.) in these fuels was stored, while the remaining 32.2 Tg C (118.0 Tg CO_2 Eq.) was emitted. The proportion of C emitted has remained about constant since 1990, at about 31 to 35 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	1997	1998	1999	2000	2001	2002	2003
Potential Emissions	299.3	348.3	373.3	395.0	365.8	357.8	360.9	360.5
Carbon Stored	191.4	228.0	238.0	253.4	241.1	237.7	242.1	242.5
Emissions	108.0	120.3	135.4	141.6	124.7	120.1	118.8	118.0

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 (2003) (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 sector.[34]

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 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 IPCC *Guidelines for National Greenhouse Gas Inventories*, 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.

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[34] These source categories include Iron and Steel Production, Ammonia Manufacture, Carbon Black Manufacture (included in Petrochemical Production), Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production.

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

Year	1990	1997	1998	1999	2000	2001	2002	2003
Industry	**3,993.2**	**4,794.6**	**5,127.6**	**5,398.1**	**4,985.1**	**4,933.3**	**5,016.4**	**5,023.4**
Industrial Coking Coal	20.5	27.6	15.4	6.3	14.8	23.7	7.0	3.0
Industrial Other Coal	8.2	11.2	10.4	11.1	12.4	11.3	12.0	11.9
Natural Gas to Chemical Plants, Other Uses	244.1	323.7	376.3	390.3	388.9	394.0	402.0	401.0
Asphalt & Road Oil	1,170.2	1,223.6	1,262.6	1,324.4	1,275.7	1,256.9	1,240.0	1,217.4
LPG	1,001.9	1,440.9	1,568.1	1,651.2	1,497.2	1,483.9	1,550.4	1,478.4
Lubricants	186.3	182.3	190.8	192.8	189.9	174.0	171.9	160.8
Pentanes Plus	69.9	260.9	185.2	239.0	214.7	193.2	164.6	162.4
Naphtha (<401 deg. F)	294.3	467.8	529.1	458.6	556.5	473.2	559.5	588.4
Other Oil (>401 deg. F)	615.4	608.8	593.8	619.5	515.5	506.1	460.9	530.0
Still Gas	21.3	2.1	0.0	16.1	12.6	35.8	57.8	133.0
Petroleum Coke	90.7	29.9	124.7	193.9	53.9	132.8	113.6	90.9
Special Naphtha	92.1	63.8	98.1	133.9	89.1	75.5	98.7	77.5
Distillate Fuel Oil	7.0	10.4	11.7	11.7	11.7	11.7	11.7	11.7
Waxes	33.3	43.7	42.4	37.4	33.1	36.3	32.2	31.0
Miscellaneous Products	137.9	97.8	119.0	111.9	119.3	124.9	134.2	126.0
Transportation	**176.0**	**172.1**	**180.2**	**182.1**	**179.4**	**164.3**	**162.4**	**151.8**
Lubricants	176.0	172.1	180.2	182.1	179.4	164.3	162.4	151.8
U.S. Territories	**86.7**	**92.5**	**94.8**	**114.5**	**165.5**	**80.3**	**80.6**	**88.7**
Lubricants	0.7	2.5	1.3	1.4	16.4	0.0	0.0	0.0
Other Petroleum (Misc. Prod.)	86.0	90.0	93.5	113.1	149.1	80.3	80.5	88.7
Total	**4,255.9**	**5,059.3**	**5,402.5**	**5,694.6**	**5,330.0**	**5,177.9**	**5,259.4**	**5,263.9**

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 sector.

- Not applicable.

Note: Totals may not sum due to independent rounding.

Table 3-13: 2003 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	**5,023.0**	**93.5**	-	**65.7**	**27.8**	**101.8**
Industrial Coking Coal	3.0	0.1	0.75	0.1	0.0	0.1
Industrial Other Coal	11.9	0.3	0.65	0.2	0.1	0.4
Natural Gas to Chemical Plants	401.0	5.8	0.65	3.8	2.0	7.4
Asphalt & Road Oil	1,217.4	25.1	1.00	25.1	0.0	0.0
LPG	1,478.4	24.9	0.65	16.2	8.7	31.9
Lubricants	160.8	3.3	0.09	0.3	3.0	10.8
Pentanes Plus	162.4	3.0	0.65	1.9	1.0	3.8
Naphtha (<401 deg. F)	588.4	10.7	0.65	6.9	3.7	13.7
Other Oil (>401 deg. F)	530.0	10.6	0.65	6.9	3.7	13.5
Still Gas	133.0	2.3	0.65	1.5	0.8	3.0
Petroleum Coke	90.9	2.5	0.50	1.3	1.3	4.6
Special Naphtha	77.5	1.5	0.65	1.0	0.5	2.0
Distillate Fuel Oil	11.7	0.2	0.50	0.1	0.1	0.4
Waxes	31.0	0.6	0.58	0.4	0.3	0.9
Miscellaneous Products	126.0	2.5	0.00	0.0	2.5	9.3
Transportation	**151.8**	**3.1**	-	**0.3**	**2.8**	**10.2**
Lubricants	151.8	3.1	0.09	0.3	2.8	10.2

U.S. Territories	**88.7**	**1.8**	-	**0.2**	**1.6**	**5.9**
Lubricants	0.0	0.0	0.09	0.0	0.0	0.0
Other Petroleum (Misc. Prod.)	88.7	1.8	0.10	0.2	1.60	5.9
Total	**5,263.9**	**98.3**		**66.1**	**32.2**	**118.0**

[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 sector.

- 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 fuel products such as asphalt, plastics, synthetic rubber, synthetic fibers, carbon black, personal cleansers, pesticides, and solvents, and industrial releases including VOC, solvent, and non-combustion CO emissions, TRI releases, refinery wastewater, 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 2004a), *Toxics Release Inventory, 1998* (2000a), *Biennial Reporting System* data (EPA 2004b), pesticide sales and use estimates (EPA 1998, 1999, 2002) and hazardous waste data (EPA 2004b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001b); 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); the American Plastics Council (APC 2000, 2001, 2003; 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); the Fiber Economics Bureau (FEB 2001); the; *Material Safety Data Sheets* (Miller 1999); and the Chemical Manufacturer's Association (CMA 1999); Specific data sources are listed in full detail in Annex 2.3.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the inventory estimate.

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 2003 was estimated to be between 97.5 and 130.9 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 17 percent below to 11 percent above the 2003 emission estimate of 118.0 Tg CO_2 Eq. The uncertainty in the emission estimates are 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**	**2003 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	75.3	61.0	90.5	-19%	+20%
Asphalt	CO_2	0.0	0.2	0.9	NA	NA
Lubricants	CO_2	21.1	17.4	24.4	-17%	+16%
Waxes	CO_2	0.9	0.7	1.5	-24%	+54%
Other	CO_2	20.9	8.9	23.2	-57%	+11%
Total	**CO_2**	**118.0**	**97.5**	**130.9**	**-17%**	**+11%**

[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**	**2003 Storage Factor (%)**	**Uncertainty Range Relative to Inventory Factor[a]**			
			(%)		**(%, Relative)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Feedstocks	CO_2	65%	63%	67%	-3%	+3%
Asphalt	CO_2	100%	99%	100%	-1%	+0%
Lubricants	CO_2	9%	4%	18%	-58%	+90%
Waxes	CO_2	58%	44%	69%	-24%	+19%
Other	CO_2	24%	18%	67%	-24%	+180%
Total	**CO_2**	**65%**	**63%**	**67%**	**-3%**	**+3%**

[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. 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 five fates that result in long-term storage (e.g., plastics production), and ten that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all 15 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. First and most fundamentally, this year the NEU analysis is presented as its own source category. In the past, the NEU component of this category was described in the context of a calculation sequence that first determined potential emissions (based on total fuel consumption for all purposes), and then deducted (1) C not oxidized (e.g., in ash) and (2) C put into long-term storage as a result of NEUs. In this context, the focus of the NEU section was previously on carbon storage rather than emissions. This year, the presentation within this source category emphasizes emissions, though the storage factors (i.e., fraction of C stored rather than emitted) are still presented to facilitate comparison with IPCC guidance.

Several substantive changes also appear in this year's inventory. First, a U.S.-specific storage factor (58 percent) was developed for waxes. Previously, the IPCC storage factor for wax (100 percent stored) had been used.

In addition, the methodology for calculating emissions and storage for feedstocks has been revised in several ways. First, three additional fuel types have been added as inputs to the system covered by the feedstocks mass balance calculations: other industrial coal, still gas, and special naphthas. The other significant improvement for feedstocks is that the estimates of U.S. plastics consumption have been revised: in previous years, the consumption data for some of the plastic resins in the dataset included consumption in Canada and Mexico. By adjusting the data to reflect U.S. (rather than North American) consumption for those resins, the accuracy of the estimate for feedstocks has improved. In addition, several minor adjustments were made (e.g., the calculations for storage now include synthetic rubber in durable and non-durable goods other than tires, and the calculations for emissions include losses due to abrasion/ oxidation of rubber from tires).

As noted in the beginning of the section, there are several areas where the boundaries of the NEU analysis adjoin the systems covered within the Industrial Processes sector. Carbon black production has been removed from the NEU analysis, as it is now addressed as a subcategory of IP-petrochemical emissions (if it was retained in NEU, there would be double-counting). As a result of this change, residual oil—which is an input to carbon black production, and had been among the fuels covered in the NEU section in previous years—no longer appears in the list of fuels in this section. A portion of other oils is also assumed to be used in the production of carbon black, and therefore other oils consumption is adjusted to account for the amount of fuel used in the C black calculation.

The storage factor for miscellaneous products also changed. In prior years, a value of 100 percent was used; in this year's inventory, based on a review of the specific applications of these products, there is now assumed to be no storage at all from these products.

There have been several updates to the data used to calculate storage factors, not only by adding information for 2003 (where available) but also for updating data sets for earlier years. For example, the results reflect new data for hazardous waste incineration (1999 through 2001) and fiber production (2001 through 2002).

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; an expanded import and export analysis (i.e., evaluating additional commodities); and improving the characterization of cleansers (to exclude any potential biogenic carbon sources).

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 ambient air pollutants NO_x, CO, and NMVOCs.[35] 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.

Nitrous oxide 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). Methane 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 15 percent overall to 6.7 Tg CO_2 Eq. (319 Gg) in 2003. This decrease in CH_4 emissions was primarily due to lower wood consumption in the residential sector. Conversely, N_2O emissions rose 13 percent since 1990 to 13.8 Tg CO_2 Eq. (45 Gg) in 2003. The largest source of N_2O emissions was coal combustion by electricity generators, which alone accounted for 63 percent of total N_2O emissions from stationary combustion in 2003. 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 NMVOCs. In 2003, 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 2003, emissions of NO_x and CO from stationary combustion decreased by 27 and 11 percent, respectively, and emissions of NMVOCs increased by 10 percent.

The decrease in NO_x emissions from 1990 to 2003 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 2003 are given in Table 3-20.[36]

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

Sector/Fuel Type	1990	1997	1998	1999	2000	2001	2002	2003
Electric Power	**0.6**	**0.6**	**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	0.1
Natural gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

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

[36] See Annex 3.1 for a complete time series of ambient air pollutant emission estimates for 1990 through 2003.

Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Industrial	**2.1**	**2.4**	**2.3**	**2.2**	**2.3**	**2.1**	**2.1**	**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	0.9	0.8	0.8	0.8
Wood	0.9	1.0	1.0	1.0	1.0	0.9	0.9	0.9
Commercial	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.8**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2
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	0.3	0.2	0.3	0.3
Residential	**4.4**	**3.5**	**3.1**	**3.4**	**3.5**	**3.1**	**2.8**	**3.1**
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	2.6	2.3	2.5	2.6	2.2	1.9	2.1
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	+	0.1	0.1	0.1	+	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**7.8**	**7.4**	**6.9**	**7.1**	**7.3**	**6.7**	**6.4**	**6.7**

+ 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Electric Power	**7.6**	**8.6**	**8.9**	**8.9**	**9.3**	**9.0**	**9.1**	**9.3**
Coal	7.1	8.2	8.3	8.3	8.7	8.5	8.6	8.7
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Wood	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2
Industrial	**3.2**	**3.5**	**3.3**	**3.3**	**3.3**	**3.1**	**3.2**	**3.2**
Coal	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6
Fuel Oil	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
Natural Gas	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Wood	1.7	2.0	1.9	1.9	1.9	1.7	1.8	1.8
Commercial	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	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	+	+	+
Residential	**1.1**	**0.9**	**0.8**	**0.9**	**1.0**	**0.9**	**0.8**	**0.9**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2
Wood	0.7	0.5	0.5	0.5	0.5	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**	**13.5**	**13.4**	**13.5**	**14.0**	**13.5**	**13.5**	**13.8**

+ 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	1997	1998	1999	2000	2001	2002	2003
Electric Power	**27**	**29**	**31**	**31**	**32**	**32**	**32**	**33**
Coal	16	19	19	19	20	19	20	20
Fuel Oil	4	3	4	4	3	4	3	4
Natural Gas	3	4	4	5	5	5	5	5
Wood	4	4	4	4	4	4	4	5
Industrial	**101**	**115**	**108**	**107**	**108**	**100**	**102**	**100**
Coal	17	16	15	14	15	14	13	13
Fuel Oil	6	6	5	5	6	6	6	6
Natural Gas	37	44	43	41	42	38	39	37
Wood	41	49	46	46	47	41	44	43
Commercial	**35**	**38**	**36**	**37**	**39**	**35**	**35**	**36**
Coal	1	1	1	1	1	1	1	1
Fuel Oil	10	7	7	7	8	7	7	8
Natural Gas	13	16	15	15	16	15	15	15
Wood	11	14	14	15	15	12	12	12
Residential	**209**	**167**	**150**	**160**	**167**	**148**	**132**	**146**
Coal	8	5	4	4	4	4	3	4
Fuel Oil	14	14	13	15	16	15	15	15
Natural Gas	21	24	22	23	24	23	24	25
Wood	166	123	110	118	123	105	89	102
U.S. Territories	**2**	**2**	**2**	**2**	**2**	**3**	**3**	**4**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	2	2	2	2	2	3	3	3
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**373**	**351**	**328**	**338**	**349**	**318**	**305**	**319**

+ 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	1997	1998	1999	2000	2001	2002	2003
Electricity Generation	**24**	**28**	**29**	**29**	**30**	**29**	**29**	**30**
Coal	23	26	27	27	28	27	28	28
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	1	1	1	+
Wood	+	1	1	1	1	+	1	1
Industrial	**10**	**11**	**11**	**11**	**11**	**10**	**10**	**10**
Coal	2	2	2	2	2	2	2	2
Fuel Oil	2	2	2	2	2	2	2	2
Natural Gas	1	1	1	1	1	1	1	1
Wood	5	7	6	6	6	5	6	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		2	1	2	2	1	1	1
U.S. Territories	**+**		**+**	**+**	**+**	**+**	**+**	**+**	**+**
Coal	+		+	+	+	+	+	+	+
Fuel Oil	+		+	+	+	+	+	+	+
Natural Gas	+		+	+	+	+	+	+	+
Wood	+		+	+	+	+	+	+	+
Total	**40**		**44**	**43**	**43**	**45**	**43**	**44**	**45**

+ 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 2003 (Gg)

Sector/Fuel Type	**NO_x**	**CO**	**NMVOC**
Electric Generation	**4,045**	**480**	**50**
Coal	3,447	240	24
Fuel Oil	135	30	4
Natural gas	301	101	11
Wood	34	NA	NA
Other Fuels[a]	NA	35	2
Internal Combustion	127	73	10
Industrial	**2,516**	**1,249**	**154**
Coal	522	138	10
Fuel Oil	154	50	8
Natural gas	920	402	52
Wood	NA	NA	NA
Other Fuels[a]	116	353	28
Internal Combustion	803	307	55
Commercial/Institutional	**244**	**149**	**29**
Coal	19	13	1
Fuel Oil	49	17	3
Natural gas	155	82	13
Wood	NA	NA	NA
Other Fuels[a]	21	37	11
Residential	**417**	**2,575**	**773**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	20	2,358	748
Other Fuels	397	217	25
Total	**7,222**	**4,454**	**1,007**

NA (Not Available)

[a] Includes LPG, waste oil, coke oven gas, and coke (EPA 2003), (EPA 2004a).

[b] Residential coal, fuel oil, and natural gas emissions are included in "Other Fuels" (EPA 2003), (EPA 2004a).

Note: Totals may not sum due to independent rounding. See Annex 3.1 for emissions in 1990 through 2003.

Methodology

Methane 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 2004). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by the Grillot (2004).[37] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[38] Construction and agricultural fuel use was obtained from EPA (2004b). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA.

Emission factors for the four end-use sectors were provided by the *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 2004a) 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 (2004a): 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

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

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended 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).

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[37] 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.

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

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.[39] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[40] However, the CH_4 emission factors differ from those used by EIA. Since these factors were obtained from IPCC/UNEP/OECD/IEA (1997), uncertainty ranges were assigned based on IPCC default uncertainty estimates (IPCC Good Practice Guidance 2000).

The uncertainty ranges for the activity-related input variables and N_2O emission factors were typically asymmetric around their inventory estimates. The uncertainty ranges for the non-biomass-related CH_4 emission factors were symmetric around their inventory estimates; for biomass, they were asymmetric around their emission factor estimates. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainty associated with the activity data and N_2O emission factor variables.[41] 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 3-21. Stationary combustion CH_4 emissions in 2003 (*including* biomass) were estimated to be between 4.8 and 13.4 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 28 percent below to 99 percent above the 2003 emission estimate of 6.7 Tg CO_2 Eq.[42] Stationary combustion N_2O emissions in 2003 (*including* biomass) were estimated to be between 10.9 and 39.5 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 22 percent below to 184 percent above the 2003 emissions estimate of 13.8 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**	**2003 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	6.7	4.8	13.4	-28%	+99%
Stationary Combustion	N_2O	13.8	10.9	39.5	-22%	+184%

[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 ambient air pollutants, uncertainties are

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[39] 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.

[40] 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.

[41] 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.

[42] 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.

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 ambient air pollutants from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

A few corrective actions were taken. It was determined that emissions from construction and farm use had been previously estimated in both this source category (in the industrial sector) and for mobile sources. To avoid double-counting, these emissions are now reported only under mobile sources. Therefore, it was necessary to subtract out energy consumption from construction and agriculture from the industrial sector. Also, a small error was corrected in the conversion of natural gas and wood energy consumption from gross calorific value to net calorific value.

Recalculations Discussion

Historical CH_4 and N_2O emissions from stationary sources (excluding CO_2) were revised due to several changes. First, industrial sector energy consumption was adjusted downward to avoid double-counting of emissions from construction and agriculture. Second, the conversion of natural gas and wood energy consumption from gross calorific value to net calorific value was corrected. These adjustments have been explained in the previous section. Third, slight changes to emission estimates for the other sectors are due to revised data from EIA (2004). This latter 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 0.4 Tg CO_2 Eq. (5.2 percent) in CH_4 emissions from stationary combustion and an average annual decrease of 0.4 Tg CO_2 Eq. (3.2 percent) in N_2O emissions from stationary combustion for the period 1990 through 2002.

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 ambient air pollutants NO_x, CO, and NMVOCs. While air conditioners and refrigerated units in vehicles also emit hydrofluorocarbons (HFCs), these gases are covered in Chapter 3, Industrial Processes, under the section entitled Substitution of Ozone Depleting Substances. 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. Nitrous oxide, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the 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 are given in Table 3-26 through Table 3-28.[43]

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 (11.2 percent) in the United States. From 1990 to 2003, CH_4 emissions declined by 44 percent, to 2.7 Tg CO_2 Eq. (128 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, resulted in higher N_2O emissions, causing a 27 percent increase in N_2O emissions from mobile sources between 1990 and 1998. Nitrous oxide emissions have subsequently declined 24 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 2003 were 4 percent lower than in 1990, at 42.1 Tg CO_2 Eq. (136 Gg) (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty gasoline 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	1997	1998	1999	2000	2001	2002	2003
Gasoline Highway	**4.3**	**3.5**	**3.3**	**3.0**	**2.7**	**2.4**	**2.2**	**2.0**
Passenger Cars	2.6	1.9	1.8	1.7	1.5	1.4	1.2	1.1
Light-Duty Trucks	1.4	1.3	1.3	1.1	1.0	0.9	0.8	0.8
Heavy-Duty Vehicles	0.3	0.2	0.2	0.2	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**	**0.5**
Ships and Boats	0.1	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	0.2	0.1	0.2	0.2	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
Otherb	+	+	+	+	+	+	0.1	0.1
Total	**4.8**	**4.0**	**3.9**	**3.6**	**3.4**	**3.1**	**2.9**	**2.7**

+ 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	1997	1998	1999	2000	2001	2002	2003
Gasoline Highway	**40.3**	**51.5**	**51.7**	**50.8**	**49.1**	**45.0**	**41.6**	**38.0**

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[43] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2003.

Passenger Cars	25.5	26.7	26.7	25.9	24.7	23.1	21.6	19.8
Light-Duty Trucks	14.1	23.7	23.7	23.6	23.0	20.6	18.6	16.7
Heavy-Duty Vehicles	0.7	1.1	1.3	1.3	1.3	1.4	1.4	1.4
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	0.2	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	**3.2**	**3.3**	**3.3**	**3.4**	**3.7**	**3.5**	**3.6**	**3.6**
Ships and Boats	0.4	0.3	0.3	0.3	0.5	0.3	0.5	0.5
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Farm Equipment	1.7	1.7	1.8	1.8	1.9	1.8	1.7	1.7
Construction Equipment	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Aircraft	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5
Other*	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**43.7**	**55.2**	**55.3**	**54.6**	**53.2**	**49.0**	**45.6**	**42.1**

+ 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Gasoline Highway	**205**	**166**	**158**	**143**	**130**	**116**	**105**	**95**
Passenger Cars	125	91	87	82	73	65	59	53
Light-Duty Trucks	65	64	60	52	49	44	40	38
Heavy-Duty Vehicles	13	10	10	9	7	6	5	5
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**	**3**	**4**	**4**	**5**	**5**	**6**
Non-Highway	**22**	**23**	**23**	**24**	**26**	**25**	**26**	**26**
Ships and Boats	4	3	3	3	5	3	4	4
Locomotives	3	3	3	3	3	3	3	3
Farm Equipment	7	7	7	7	7	7	7	7
Construction Equipment	4	5	5	5	5	6	6	6
Aircraft	2	3	3	3	3	3	3	3
Other*	2	2	2	2	2	2	2	2
Total	**228**	**193**	**185**	**172**	**161**	**147**	**138**	**128**

+ 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Gasoline Highway	**130**	**166**	**167**	**164**	**158**	**145**	**134**	**123**
Passenger Cars	82	86	86	84	80	74	70	64
Light-Duty Trucks	46	76	76	76	74	66	60	54
Heavy-Duty Vehicles	2	4	4	4	4	4	5	5
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
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Highway	**10**	**11**	**11**	**11**	**12**	**11**	**12**	**12**
Ships and Boats	1	1	1	1	2	1	2	1
Locomotives	1	1	1	1	1	1	1	1
Farm Equipment	6	6	6	6	6	6	6	5
Construction Equipment	1	1	1	1	1	1	1	1
Aircraft	1	1	1	1	1	1	1	1
Other*	1	1	1	1	1	1	1	1
Total	**141**	**178**	**179**	**176**	**171**	**158**	**147**	**136**

+ 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 CO, NO_x, and NMVOC emissions in the United States. In 2003, mobile combustion contributed 89 percent of CO emissions, 56 percent of NO_x emissions, and 46 percent of NMVOC emissions. Since 1990, emissions of NMVOCs from mobile combustion decreased by 42 percent, CO emissions decreased 37 percent, and emissions of NO_x decreased by 14 percent.

Table 3-26: NO_x Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1997	1998	1999	2000	2001	2002	2003
Gasoline Highway	**5,746**	**4,268**	**4,090**	**3,924**	**3,812**	**3,715**	**3,519**	**3,527**
Passenger Cars	3,847	2,447	2,316	2,158	2,084	2,027	1,920	1,924
Light-Duty Trucks	1,364	1,334	1,294	1,268	1,303	1,285	1,217	1,220
Heavy-Duty Vehicles	515	475	467	485	411	390	369	370
Motorcycles	20	13	13	13	13	14	13	13
Diesel Highway	**2,956**	**3,708**	**3,729**	**3,671**	**3,803**	**3,338**	**3,162**	**3,169**
Passenger Cars	39	13	11	10	7	6	6	6
Light-Duty Trucks	20	10	9	8	6	5	5	5
Heavy-Duty Vehicles	2,897	3,685	3,709	3,653	3,791	3,326	3,151	3,158
Alternative Fuel Highway[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Highway	**3,432**	**3,792**	**3,772**	**3,705**	**3,780**	**3,770**	**3,707**	**3,722**
Ships and Boats	953	963	919	818	966	971	954	958
Locomotives	857	962	973	910	908	907	891	895
Farm Equipment	63	75	83	84	80	73	72	72
Construction Equipment	437	487	487	497	484	480	472	474
Aircraft[b]	641	708	706	765	697	690	678	681
Other[c]	480	597	604	632	645	650	639	642
Total	**12,134**	**11,768**	**11,592**	**11,300**	**11,395**	**10,823**	**10,389**	**10,418**

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.

Table 3-27: CO Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1997	1998	1999	2000	2001	2002	2003
Gasoline Highway	**98,328**	**67,509**	**65,246**	**61,210**	**60,657**	**56,716**	**55,541**	**52,544**
Passenger Cars	60,757	36,825	35,686	32,921	32,867	31,600	30,945	29,275
Light-Duty Trucks	29,237	25,748	24,754	23,343	24,532	22,574	22,107	20,914
Heavy-Duty Vehicles	8,093	4,787	4,642	4,782	3,104	2,411	2,361	2,234

Motorcycles	240	150	163	164	154	131	129	122
Diesel Highway	**1,696**	**1,301**	**1,202**	**1,122**	**1,088**	**869**	**851**	**805**
Passenger Cars	35	13	10	10	7	6	6	5
Light-Duty Trucks	22	13	12	9	6	5	5	5
Heavy-Duty Vehicles	1,639	1,276	1,179	1,103	1,075	858	840	795
Alternative Fuel Highway[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Highway	**19,459**	**21,474**	**21,493**	**21,152**	**21,935**	**22,387**	**22,181**	**22,177**
Ships and Boats	1,679	1,948	1,943	2,121	1,946	1,952	1,934	1,934
Locomotives	85	89	83	98	90	90	89	89
Farm Equipment	217	250	274	285	245	233	231	231
Construction Equipment	582	636	633	630	626	621	615	615
Aircraft[b]	1,090	1,098	1,081	1,074	1,047	1,041	1,032	1,031
Other[c]	15,807	17,453	17,478	16,943	17,981	18,449	18,280	18,276
Total	**119,482**	**90,284**	**87,940**	**83,484**	**83,680**	**79,972**	**78,574**	**75,526**

IE = Included Elsewhere

Note: Totals may not sum due to independent rounding.

[a] CO 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.

Table 3-28: NMVOC Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Gasoline Highway	**8,110**	**5,167**	**5,067**	**4,924**	**4,615**	**4,285**	**3,931**	**3,832**
Passenger Cars	5,120	2,928	2,895	2,810	2,610	2,393	2,195	2,140
Light-Duty Trucks	2,374	1,882	1,812	1,734	1,750	1,664	1,527	1,488
Heavy-Duty Vehicles	575	336	335	351	232	206	189	184
Motorcycles	42	22	25	28	23	22	20	20
Diesel Highway	**406**	**263**	**249**	**230**	**216**	**207**	**190**	**185**
Passenger Cars	16	6	5	5	3	3	3	3
Light-Duty Trucks	14	8	7	6	4	4	3	3
Heavy-Duty Vehicles	377	249	237	219	209	201	184	179
Alternative Fuel Highway[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Highway	**2,416**	**2,498**	**2,427**	**2,432**	**2,398**	**2,379**	**2,438**	**2,333**
Ships and Boats	608	766	763	769	744	730	748	716
Locomotives	33	35	33	38	35	35	36	35
Farm Equipment	28	32	35	38	24	19	20	19
Construction Equipment	85	83	81	81	76	72	74	71
Aircraftb	149	142	137	141	130	125	128	123
Otherc	1,513	1,441	1,378	1,366	1,390	1,397	1,432	1,370
Total	**10,933**	**7,928**	**7,742**	**7,586**	**7,230**	**6,872**	**6,560**	**6,351**

IE (Included Elsewhere)

Note: Totals may not sum due to independent rounding.

[a] NMVOC 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 (2003) provided emissions estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[44] aircraft, and seven categories of non-highway vehicles.[45] These emission estimates were provided from 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. Emissions from alternative fuel vehicles (AFVs)[46] were based on VMT by vehicle and fuel type.

Emission factors for gasoline and diesel highway vehicles were developed by ICF (2004). These factors were based 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 primary 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 2003 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2004). VMT was then allocated from FHWA's vehicle categories to fuel-specific vehicle categories based on estimates of fuel consumption by fuel type for each vehicle category, developed using information on shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (2004) and information on total motor vehicle fuel

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[44] 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.

[45] 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).

[46] 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.

consumption by fuel type from FHWA (1996 to 2004). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2004b) 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 2004a, 2004d, 2000, 1998, and 1997). 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 (2004e) 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

Fuel consumption data were employed as a measure of activity for non-highway vehicles, and then fuel-specific emission factors were applied.[47] Activity data were obtained from AAR (2004), BEA (1991 through 2004), Benson (2002 through 2004), DOE (1993 through 2004), DESC (2004), DOC (1991 through 2004), DOT (1991 through 2004), EIA (2002a), EIA (2002b), EIA (2004a), EIA (2004b), EIA (2003 through 2004), EIA (1991 through 2004), EPA (2004c), and FAA (2004). Emission factors for non-highway modes were taken from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

This section discusses the uncertainty of the emissions 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 CO, NO_x, 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 emissions 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 2003 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.

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

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 2004), 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, unreported fuel sales to avoid fuel taxes, differences in achieved versus estimated fuel economy, and measurement and estimation errors. These VMT were apportioned by fuel type, 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 (2004b) 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 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.[48] The results of this analysis are reported in the section below, titled *Quantitative Estimates of Uncertainty*.

Non-Highway

Emissions from non-highway vehicles are a small portion of total emissions from mobiles sources, representing 20 percent of CH_4 emissions from mobile sources and 9 percent of N_2O emissions from mobile sources in 2003. 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

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[48] 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.

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 and Uncertainty Management in National Greenhouse Gas Inventories* 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 2004c). 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.

Distillate consumption for ships and boats was obtained from sales estimates from *EIA's Fuel Oil and Kerosene Sales* (EIA 1991 through 2004). The estimates for distillate consumption have associated uncertainty, as EIA's estimates are based on sales to economic sectors, and it can be difficult to determine how much of the fuel sold in each sector is used by mobile or stationary sources and to further attribute this consumption to specific final users. For example, some fuel purchased by the marine sector may be used for operating heavy equipment or even generators, instead of being used entirely by ships and boats. This distinction between mobile and stationary fuel users is not made by EIA.

EIA does provide coefficients of variation to estimate sampling error, which occurs due to the fact that these estimates are based on a sample set. However, as EIA points out, these coefficients do not take into account all the sources of potential bias, which includes incomplete information, misinterpretation of survey questions, and other factors that may cause estimates of fuel sales to be different from actual sales. In addition, diesel for ships and boats is adjusted for bunker fuel consumption, which introduces an additional (and much higher) level of uncertainty.

Domestic consumption for residual fuel consumption by ships and boats is obtained from EIA (2004a). These estimates fluctuate widely from year to year. Such fluctuations cannot be fully explained without further analysis of the underlying activity data sets and, as such, the estimates are believed to be highly uncertain. The estimate of domestic consumption is then adjusted downward to account for international bunker fuels, which represents the primary use of residual fuel by ships and boats. As the international bunker fuel data are considered to have a moderate level of uncertainty,[49] the overall uncertainty of the domestic ships and boats estimate for residual fuel consumption is considered high.

Domestic jet fuel and aviation gasoline consumption data are obtained from EIA (2004a). Like diesel and residual marine fuel consumption, jet fuel consumption for aviation is adjusted downward to account for international bunker fuels. The international bunker fuel estimates introduce 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.

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

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[49] This is discussed in the section on International Bunker Fuels.

(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.

Finally, U.S. aircraft emission estimates for CO, NO_x, and NMVOCs from EPA (2004e and 2003) are based on LTO cycles and only estimate near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates presented here may overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including LTO cycles by aircraft on international flights but underestimate total emissions because they exclude emissions from aircraft on domestic flight segments at cruising altitudes.

Quantitative Estimates of Uncertainty

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-29. Mobile combustion CH_4 emissions in 2003 were estimated to be between 2.5 and 2.8 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 9 percent below to 4 percent above the 2003 emission estimate of 2.7 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions in 2003 were estimated to be between 35.2 and 52.8 Tg CO_2 Eq., indicating a range of 16 percent below to 26 percent above the 2003 emission estimate of 42.1 Tg CO_2 Eq.

Table 3-29: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	2.7	2.5	2.8	-9%	+4%
Mobile Sources	N_2O	42.1	35.2	52.8	-16%	+26%

[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. Because significant changes were made to highway vehicle emission factors and non-highway fuel consumption estimates (see Recalculations Discussion below), QA/QC efforts were focused in particular on emissions impacted by these changes. 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, adjustments were made to emission factors and activity data to incorporate new research and additional data sources.

The most significant changes in this year's Inventory are the revisions to the highway emission factors for CH_4 and N_2O. The previous emission factors had been derived using methodology similar to that outlined in IPCC/UNEP/OECD/IEA (1997). However, preliminary tests suggested that these emission factors may not have been representative of actual emissions. EPA sponsored laboratory testing that resulted in the new emission factors used in this report. The emission factors changed notably, ranging from a decrease of 97 percent to an increase of 114 percent for individual vehicle/fuel type/technology types; the combined effect of these changes in emission factors significantly lowered CH_4 and N_2O emissions from highway vehicles. Given the large contribution of highway vehicles to the mobile totals, these new emission factors were major drivers behind the changes in CH_4 and N_2O estimates. However, because these emission factors do not impact CO_2 emissions, their impact is less significant when considering total mobile source emissions of all GHGs.

Additionally, the methodology for estimating VMT by vehicle/fuel type category (e.g., LDGV, LDDV, LDGT, LDDT, etc.) was revised. The purpose of this revision was to ensure that the VMT estimates for individual vehicle categories match up with VMT estimates by vehicle type from FHWA (1996 through 2004), which is the recognized source of national VMT estimates. The new methodology apportions FHWA's estimate of VMT for each vehicle category (e.g., light-duty vehicles, light-duty trucks, buses, heavy-duty trucks) to fuel-based vehicle categories based on estimates of gasoline and diesel fuel consumption for each vehicle category, drawn from DOE (2004). This change had a small impact on emissions.

The vehicle age distribution values for highway vehicles were also revised. Previously, the Inventory relied on one vehicle age distribution across 25 model years from EPA (2000), which was applied for each year. For the current Inventory, that same distribution was applied for years 1990 through 1998, and annually variable vehicle age distributions were applied for years 1999 through 2003 based on data obtained from EPA's MOVES model (EPA 2004b). The annually variable age distributions more accurately reflect changes in the vehicle stock, and include 31 model years.

Emissions from gasoline- and diesel-electric hybrid vehicles are now included under gasoline and diesel vehicles instead of alternative fuel/advanced technology category, since these vehicles only run on traditional motor gasoline. This change did not have an impact on total emissions.

EPA's NONROAD model is now used as the primary data source for fuel consumption by off-highway equipment (e.g., construction, agricultural, lawn and garden equipment), rather than data from FHWA's *Highway Statistics* (FHWA 1996 through 2004), EIA's *Fuel Oil and Kerosene Sales* (EIA 1991 through 2004), and several other sources. The NONROAD model is also used to estimate fuel consumption by recreational boats, rather than data from FHWA's *Highway Statistics.* Some of the individual sources used in the previous Inventory had not been updated for several years, while others had updated their methodologies, resulting in large variations in estimates from year to year. Use of the NONROAD Model for all of these estimates is believed to provide more accurate, up-to-date, and consistent estimates.

Other changes include minor revisions to historical aircraft fuel consumption estimates in FAA (2004) and rail consumption provided from Benson (2004). These revisions were not significant, and the overall impact on emissions estimates is small.

Overall, these changes resulted in an average annual decrease of 0.6 Tg CO_2 Eq. (14 percent) in CH_4 emissions from mobile combustion and an average annual decrease of 6.2 Tg CO_2 Eq. (11 percent) in N_2O emissions from mobile combustion for the period 1990 through 2002.

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 resource availability:

1) *Reconcile 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 EIA fuel consumption estimates, however, differ from the estimates derived using "bottom up" sources. For certain vehicle categories this leads to CO_2 emissions trends that conflict with those of the "bottom up" sources. Potential improvements include reconciling fuel consumption estimates from EIA and other data sources, and revising the current process of allocating CO_2 emissions to reflect trends from the more detailed vehicle category estimates of fuel consumption.

2) *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 emissions 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 current 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. Emission estimates would be improved through an investigation of more appropriate emission factors for off-road trucks.

3) *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 and other publications, or using VMT breakdowns by vehicle/fuel type combinations from the MOBILE6 or MOVES models. These sources should be investigated in order to develop a more robust apportionment method.

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 101 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 2003, ten 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. 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 2003 were estimated to be 53.8 Tg CO_2 Eq. (2,561 Gg), a decline of 34 percent since 1990 (see Table 3-30 and Table 3-31). Of this amount, underground mines accounted for 70 percent, surface mines accounted for 16 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. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 2003.

Table 3-30: CH_4 Emissions from Coal Mining (Tg CO_2 Eq.)

Activity	**1990**		**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Underground Mining	62.1		45.3	44.3	44.4	41.6	39.4	38.1	35.8	37.6
Liberated	67.6		59.8	55.7	58.6	54.4	54.0	54.2	53.3	53.6
Recovered & Used	(5.6)		(14.5)	(11.4)	(14.2)	(12.7)	(14.6)	(16.1)	(17.5)	(16.1)
Surface Mining	10.4		9.2	9.3	9.4	9.0	8.8	9.2	8.8	8.4
Post-Mining (Underground)	7.7		7.2	7.4	7.4	6.8	6.7	6.8	6.4	6.4
Post-Mining (Surface)	1.7		1.5	1.5	1.5	1.5	1.4	1.5	1.4	1.4
Total	**81.9**		**63.2**	**62.6**	**62.8**	**58.9**	**56.2**	**55.6**	**52.4**	**53.8**

Note: Totals may not sum due to independent rounding.

Table 3-31: CH_4 Emissions from Coal Mining (Gg)

Activity	**1990**		**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Underground Mining	2,956		2,158	2,111	2,117	1,982	1,876	1,816	1,705	1,788
Liberated	3,220		2,850	2,654	2,791	2,589	2,573	2,580	2,538	2,554
Recovered & Used	(265)		(692)	(543)	(674)	(607)	(697)	(765)	(833)	(766)
Surface Mining	497		438	445	448	428	417	438	420	402
Post-Mining (Underground)	367		341	354	352	325	317	323	304	305
Post-Mining (Surface)	81		71	72	73	69	68	71	68	65
Total	**3,900**		**3,008**	**2,983**	**2,989**	**2,805**	**2,677**	**2,647**	**2,497**	**2,561**

Note: Totals may not sum due to independent rounding.

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

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of CH_4 collected by each of the twenty-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 2003, ten active coal mines sold recovered CH_4 into the local gas pipeline

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[50] 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.

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 3-32) (EIA 2003), 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 3-32: 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

Uncertainty

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 possibly 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. Many of the recovery estimates use data on wells within 100 feet of a mined area. A level of uncertainty currently 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 3-33. Coal mining CH_4 emissions in 2003 were estimated to be between 51.9 and 55.7 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 4 percent below to 4 percent above the 2003 emission estimate of 53.8 Tg CO_2 Eq.

Table 3-33: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	53.8	51.9	55.7	-4%	+4%

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

Recalculations Discussion

In-situ gas content is the principal variable used to determine post-mining methane emissions of mined coal. Previously, in-situ values used were based on average CH_4 content values summarized in Exhibit 3-4 of the U.S. EPA publication, EPA/400/9-90/008; *Methane Emissions From Coal Mining, Issues and Opportunities, September 1990*. The original source of information is derived from three primary sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*, 1983 U.S. DOE Report (DOE/METC/83-76), *Methane Recovery from Coalbeds: A Potential Energy Source*, and a series of 1986-88 Gas Research Institute Topical Reports called *A Geologic Assessment of Natural Gas from Coal Seams.* No data was available for eight of the coal mining states and therefore default values from other coal basins were assigned to those states.

Since Circular 9067 contained only a portion of the gas content data compiled by USBM, the complete dataset, published in 1996 *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*, EPA/600/R-96-065, is now the basis of new in-situ gas content value. In addition, gas content data from the U.S. DOE Methane Recovery from Coalbed Projects (MRCP), which was the original source of data for the GRI Topical Reports noted above, was utilized. (Condensed versions of the original MRCP reports for 13 U.S. coal basins are compiled in *Coalbed Methane Resources of the United States, AAPG Studies in Geology Series #17*, published in 1984).

The compiled gas content data for each of the coal basins was sorted by depth to determine in-situ values for surface and underground mines, separately. Overburden depths of surface mines were analyzed using *Keystone Coal Industry Manuals* from 1991 through 2003 and found that the maximum depth was 250 feet. Therefore, gas content data from samples taken less than 250 feet deep were assigned to surface mines and the samples collected from deeper depths to underground mines. The combination of these changes resulted in an average annual decrease of 0.2 Tg CO_2 Eq. (0.3 percent) in CH_4 emissions from coal mining for the period 1990 through 2002.

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;
- Methane flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Gross abandoned mine methane emissions ranged from 6.1 to 9.6 Tg CO_2 Eq. from 1990 through 2003, varying as much as 1.3 Tg CO_2 Eq. 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 (8.6 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 (with slight increases in 1999 and 2000). There were fewer than thirteen gassy mine closures during each of the years from 1998 through 2003. By 2003, abandoned mine emissions were reduced to 6.4 Tg CO_2 Eq. (see Table 3-34 and Table 3-35).

Table 3-34: CH_4 Emissions from Abandoned Coal Mines (Tg CO_2 Eq.)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Abandoned Underground Mines	6.1	9.6	8.8	9.0	9.3	8.5	8.0	7.9
Recovered & Used	0	1.5	1.7	1.6	1.5	1.5	1.6	1.5
Total	**6.1**	**8.1**	**7.1**	**7.3**	**7.7**	**6.9**	**6.4**	**6.4**

Note: Totals may not sum due to independent rounding.

Table 3-35: CH_4 Emissions from Abandoned Coal Mines (Gg)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Abandoned Underground Mines	288	458	421	426	441	403	380	377
Recovered & Used	-	74	80	78	73	73	77	72
Total	**288**	**385**	**341**	**349**	**369**	**331**	**303**	**306**

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 is the gas rate at time t in mcf/d
- q_i is the initial gas rate at time zero (t_o) in million cubic feet per day (mcfd)
- b is the hyperbolic exponent, dimensionless
- D_i is the initial decline rate, 1/yr
- t is 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 is the gas flow rate at time t in mcf/d
- q_i is the initial gas flow rate at time zero (t_o) in mcfd
- D is the decline rate, 1/yr
- t is 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 434 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 256 of the 434 mines (or 59 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 methane flow to the atmosphere). The remaining 41 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 methane 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 259 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database. Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect ventilation emissions only for pre-1990 closures. Methane degasification amounts were added to ventilation data for the total CH_4 liberation rate for fourteen mines that closed between 1992 and 2003. 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. Once the 1991 through 2003 totals were calculated, they 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 methane recovery projects during that time.

Uncertainty

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, an approach 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 the 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 possibly 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 3-36. Abandoned coal mines CH_4 emissions in 2003 were estimated to be between 5.4 and 7.8 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 16 percent below to 22 percent above the 2003 emission estimate of 6.4 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 41 percent of the mines), with a ±50 percent uncertainty.

Table 3-36: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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 Coal Mines	CH_4	6.4	5.4	7.8	-16%	+22%

[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 13 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 43 percent of total mines.

Recalculations Discussion

In 2003, all methane emissions from abandoned coal mines were recalculated using: 1) an updated mine list based on 1985 and 1988 USBM records (adding 41 mines to the inventory), 2) updated coal seam permeabilities based on a 2004 EPA study, and 3) revised closure dates for 43 of the mines based on MSHA's data retrieval system. The combination of these changes resulted in an average annual increase of 2.8 Tg CO_2 Eq. (64.5 percent) in CH_4 emissions from abandoned coal mines for the period 1990 through 2002.

3.7. Petroleum Systems (IPCC Source Category 1B2a)

Methane 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 2003 were 17.1 Tg CO_2 Eq. (815 Gg). Since 1990, emissions declined due to a decline in domestic oil production and industry efforts to make emissions reductions (see Table 3-37 and Table 3-38). The various sources of emissions are detailed below.

Production Field Operations. Production field operations account for over 95 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 83 percent of the emissions from the production sector, fugitive emissions account for six percent, combustion emissions ten percent, and process upset emissions barely one percent. The most dominant sources of vented emissions are field storage tanks, natural-gas-powered pneumatic devices (low bleed, high bleed, and chemical injection pumps). These four sources alone emit 79 percent of the production field operations emissions. 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. Emissions from chemical injection pumps occur as high-pressure gas that is used to drive the pumps is vented to the atmosphere. Two additional large sources, oil well heads and gas engines, together account for 12 percent of emissions from the production sector. The remaining nine percent of the emissions are distributed among 33 additional activities within these four categories.

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 65 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 18 percent. The remaining 17 percent is distributed among 4 additional sources within these two categories.

Crude Oil Refining. Crude oil refining processes and systems account for only three 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 methane 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 3-37: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Production Field Operations	**19.3**	**18.1**	**17.8**	**17.1**	**16.9**	**16.8**	**16.4**	**16.4**
Pneumatic device venting	11.5	10.8	10.6	10.3	10.0	10.0	9.8	9.8
Tank Venting	3.8	3.4	3.4	3.2	3.2	3.2	3.2	3.2
Combustion & process upsets	2.2	2.0	2.0	1.9	1.9	1.9	1.8	1.8
Misc. venting & fugitives	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2
Wellhead fugitives	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
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 estimated emissions	**20.0**	**18.8**	**18.5**	**17.8**	**17.6**	**17.4**	**17.1**	**17.1**

Table 3-38: CH_4 Emissions from Petroleum Systems (Gg)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Production Field Operations	**920**	**862**	**846**	**815**	**803**	**799**	**783**	**782**
Pneumatic device venting	545	515	504	488	478	475	465	465
Tank Venting	179	164	162	153	154	154	151	151
Combustion & process upsets	103	96	94	90	89	89	87	86
Misc. venting & fugitives	66	62	61	60	59	59	58	57
Wellhead fugitives	26	25	25	24	22	22	21	21
Crude Oil Transportation	**7**	**6**	**6**	**6**	**5**	**5**	**5**	**5**
Refining	**25**	**27**	**27**	**27**	**28**	**27**	**27**	**27**
Total estimated emissions	**951**	**895**	**879**	**848**	**836**	**831**	**815**	**815**

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is a bottom-up approach, based on a comprehensive study of CH_4 emissions from U.S. petroleum systems (EPA 1999, Radian 1996e). These studies combined emission estimates from 70 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 39 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 70 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 70 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, an emission factor was calculated by dividing an emission estimate from the Minerals Management Service (MMS) by the number of platforms (MMS 2004b). Emission factors were held constant for the period 1990 through 2003.

Activity factors for years 1990 through 2003 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 2003 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 (1999). The remaining emission factors were taken from the following sources: EPA default values, MMS reports (MMS 1995), 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 1990-2003, 1995-2003a-b), the API *Basic Petroleum Data Book* (API 2003), *Methane Emissions from the Natural Gas Industry* by the Gas Research Institute and EPA (Radian 1996a-d), consensus of industry peer review panels, MMS reports (MMS 1995, 2000, 2004a-b), and the *Oil & Gas Journal* (OGJ 2003a-b). Forecasts of activity factors for petroleum systems were developed using production and refining capacity data from the EIA *Annual Energy Outlook* (EIA 2004) as well as offshore activity projections from MMS (2001 and 2004a). Annex 3.5 provides a complete list of references.

Uncertainty

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 70 activities analyzed for petroleum systems; therefore, some are estimated. Because of the dominance of six major sources, which account for 90 percent of the total emissions, the uncertainty surrounding these six 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 3-39. Petroleum systems CH_4 emissions in 2003 were estimated to be between 11.9 and 51.4 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 30 percent below to 200 percent above the 2003 emission estimate of 17.1 Tg CO_2 Eq.

Table 3-39: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]	
		(Tg CO_2 Eq.)	(Tg CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	17.1	11.9	51.4	-30%	+200%

[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 two changes with respect to previous inventories. First, the emission factor for CH_4 emissions from oil tanks in the production sector was modified to remove venting from condensate tanks and only account for venting from crude oil tanks. The previous methodology included an emissions factor that was averaged from the API E&P Tank Calc runs on both oil and condensate tanks. The new calculation is averaged from API E&P Tank Calc runs (DB Robinson Research Ltd. 1997) for API gravity of 44 degrees and below. The adjustment has been made so that vented emissions from condensate tanks can be moved into the emissions from natural gas systems, where they are more relevant. The second change was the development of a new activity factor for offshore Gulf of Mexico platform venting in the production sector. Previously, the activity factor was obtained through MMS, the total number of Gulf of Mexico platforms, and an assumption of what percentage were oil producing platforms. The number of Gulf of Mexico platforms, platform data, and field data is now available on an annual basis from MMS (2000, 2004b, 2004c). From the field and platform data, a new estimate was developed for the percentage of oil producing platforms. This change results in the model reflecting the trend towards more natural gas production than oil production in the Gulf of Mexico. A change in the Gulf of Mexico platform activity resulted in an indirect change in the emissions factor that is calculated from the known base-year emissions value.

The combination of these changes resulted in an average annual decrease of 7.1 Tg CO_2 Eq. (27.4 percent) in CH_4 emissions from petroleum systems for the period 1990 through 2002. Oil tank venting accounted for virtually all of the decrease while Gulf of Mexico platform venting and fugitives remained relatively unchanged.

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.

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 125.9 Tg CO_2 Eq. (5,998 Gg) of CH_4 in 2003, a slight decrease over 1990 emissions (see Table 3-40 and Table 3-41). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions (EPA 2002).

Methane 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 34 percent of CH_4 emissions from natural gas systems in 2003.

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. Methane emissions from 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 978,000 miles of distribution mains in 2003, an increase from just over 789,500 miles in 1990 (OPS 2002a). Distribution system emissions, which account for approximately 22 percent of emissions from natural gas systems, result mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[51] 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 2003 were 10 percent lower than 1990 levels.

Table 3-40: CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)*

Stage	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Field Production	36.3	40.4	41.2	37.5	41.0	44.5	44.5	43.4
Processing	14.8	14.9	14.7	14.6	14.9	15.1	14.6	14.5
Transmission and Storage	46.8	46.1	44.7	43.4	43.4	40.2	42.0	40.6
Distribution	30.5	32.4	31.2	31.9	32.8	32.1	29.5	27.4
Total	**128.3**	**133.6**	**131.8**	**127.4**	**132.1**	**131.8**	**130.6**	**125.9**

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

Table 3-41: CH_4 Emissions from Natural Gas Systems (Gg)*

Stage	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Field Production	1,731	1,921	1,962	1,785	1,953	2,117	2,121	2,068
Processing	704	708	702	696	708	717	693	691
Transmission and Storage	2,226	2,193	2,127	2,068	2,067	1,914	2,002	1,933
Distribution	1,450	1,541	1,484	1,517	1,560	1,530	1,405	1,305

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[51] The percentages of total emissions from each stage may not add to 100 because of independent rounding.

Total	**6,112**		**6,363**	**6,276**	**6,066**	**6,289**	**6,277**	**6,221**	**5,998**

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

Methodology

The 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 2002, 2003); Annual Energy Review (EIA 2002f); Historical Natural Gas Annual (EIA 2003e); Minerals and Management Service (MMS 1998, 1999, 2000, 2001, 2002a-b, 2003, 2004a-d); Monthly Energy Review (EIA 2004d); Natural Gas Annual (EIA 1993, 1996a, 1997a, 1998a-b, 2001a, 2002a, 2003a); Natural Gas Liquids Reserves Report (EIA 1996b, 1997b, 1998c, 1999, 2000, 2001c, 2002d); Natural Gas Monthly (EIA 2001b, 2002b-c, 2003b-d, 2004a-c,); the Natural Gas STAR Program annual emissions savings (EPA 2004); Oil and Gas Journal (OGJ 1999 - 2004); Office of Pipeline Safety (OPS 2004a-b) other Energy Information Administration publications (EIA 2002e, 2004e-f). The Gas Systems Analysis model was used to aid in collecting data for non-associated and associated wells (GSAM 1997). Data from a program for estimating emissions from hydrocarbon production tanks is incorporated (DB Robinson Research Ltd. 1997). Coalbed Methane well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2004) and the Alabama State Oil and Gas Board (Alabama 2004). Other state well data was taken from : American Association of Petroleum Geologists (AAPG 2204); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2004); Rocky Mountain Production Report (Lippman (2003); Montana Board of Oil and Gas Conservation (Montana 2004); Oklahoma Geological Survey (Oklahoma 2004); Utah Division of Oil, Gas and Mining (Utah 2004). Emissions factors were taken from EPA/GRI (1996).

Uncertainty

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 3-42. Natural gas systems CH_4 emissions in 2003 were estimated to be between 87.1 and 166.7 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 31 percent below to 32 percent above the 2003 emission estimate of 125.9 Tg CO_2 Eq.

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

Source	**Gas**	**2003 Emission Estimate**	**Uncertainty Range Relative to Emission Estimate**[a]			
		(Tg CO_2 Eq.)	**(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Natural Gas	CH_4	125.9	87.1	166.7	-31%	+32%

Systems

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

Recalculations Discussion

Emissions with Natural Gas STAR Program reductions were updated using new Gas STAR emissions reduction data from the iSTAR database. Gas STAR reductions reported retroactively for the years 1990 to 1992 are assumed to be characterized in the GRI/EPA 1996 study for the base year 1992. Therefore, to avoid double counting, those emissions reductions are not counted in the inventory. Gas STAR reductions are also subject to sunsetting rules that prevent perpetual crediting of all reductions. The inventory assumes that once an emissions reducing technology is put in place, it will continue to provide emissions savings and thus the sunsetting rule is not be implemented in the inventory.

Three new sources of emissions in the production sector of the natural gas systems were added this year:

- Gas condensate stored in tanks vents methane and other hydrocarbons to the atmosphere. Emissions from condensate tanks can be divided into two categories: tanks with control devices such as vapor recovery units or flares, and tanks that have no control devices. Condensate tanks contributed an estimated 52.3 Gg of methane emissions that represents 0.87 percent of total methane emissions from natural gas systems in 2003. In 1990, Condensate tanks were estimated to contribute 39.9 Gg of emissions or about 0.65 percent of total emissions from natural gas systems.

- Another source added to the production sector for the 2003 reporting year was unconventional gas well fugitives. Wells in this source were previously treated as conventional wells in the rest of U.S. (western) geographic region. Unconventional well fugitives include fugitive emissions from coal bed CH_4 and shale wells. From 1990 through 2003, unconventional well fugitives accounted for a small amount of emissions from natural gas systems.

- The production sector also had flaring from offshore Gulf of Mexico operations added, using a 2 percent uncombusted hydrocarbon factor. This source contributed to less than 0.1 percent to the emissions from the entire time series. A second Gulf of Mexico source added to the production sector was Gulf of Mexico offshore well venting. This contributed about 2.4 percent of the 2003 emissions and about 2.6 percent in 1990.

The combination of these methodological and historical data changes resulted in an average annual increase of 6.7 Tg CO_2 Eq. (5.3 percent) in CH_4 emissions from natural gas systems for the period 1990 through 2002.

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. Two improvements that are of particular note are in the production and processing sector. Recent data has suggested that the emission factor for well clean-ups in the production sector is low, and additional data sources are being investigated to produce a more robust emission factor. In the processing sector, improvements are being considered across the entire sector based on studies completed and near completion at five or more processing plants. These studies suggest the need for changing several emission factors as well as adding some additional sources within the processing sector.

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 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 Change and Forestry chapter (see Box 3-3). 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.

[Begin Text Box]

Box 3-3: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as CO_2. The quantity of carbon that these degradation processes cycle through the Earth’s atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. However, the focus of the UNFCCC is on emissions resulting from human activities and subject to human control, because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere’s natural greenhouse effect.

Carbon dioxide 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 10.1 Tg CO_2 Eq. in 2003, as described in the Land-Use Change and Forestry chapter.

[End Box]

Approximately 24 million metric tons of municipal solid wastes were combusted in the United States in 2003. Carbon dioxide emissions from combustion of municipal solid wastes rose 72 percent since 1990, to an estimated 18.8 Tg CO_2 Eq. (18,781 Gg) in 2003, as the volume of plastics and other fossil carbon-containing materials in MSW increased (see Table 3-43 and Table 3-44). Waste combustion is also a source of N_2O emissions (De Soete

1993). Nitrous oxide emissions from municipal solid waste combustion were estimated to be 0.5 Tg CO_2 Eq. (1 Gg) in 2003, and have not changed significantly since 1990.

Table 3-43: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Tg CO_2 Eq.)

Gas/Waste Product	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**10.9**	**17.8**	**17.1**	**17.6**	**18.0**	**18.8**	**18.8**	**18.8**
Plastics	8.0	11.9	11.4	12.0	12.1	12.7	12.7	12.7
Synthetic Rubber in Tires	0.2	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Carbon Black in Tires	0.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Synthetic Rubber in MSW	1.3	1.7	1.6	1.6	1.7	1.8	1.8	1.8
Synthetic Fibers	1.2	2.1	2.0	2.0	2.1	2.2	2.2	2.2
N_2O	**0.4**	**0.4**	**0.3**	**0.3**	**0.4**	**0.5**	**0.5**	**0.5**
Total	**11.3**	**18.1**	**17.4**	**18.0**	**18.3**	**19.2**	**19.2**	**19.2**

Table 3-44: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**10,919**	**17,761**	**17,094**	**17,632**	**17,979**	**18,781**	**18,781**	**18,781**
Plastics	7,953	11,914	11,427	11,950	12,145	12,718	12,718	12,718
Synthetic Rubber in Tires	191	891	887	890	893	895	895	895
Carbon Black in Tires	249	1,165	1,160	1,164	1,167	1,170	1,170	1,170
Synthetic Rubber in MSW	1,330	1,725	1,627	1,612	1,689	1,810	1,810	1,810
Synthetic Fibers	1,196	2,065	1,992	2,016	2,086	2,187	2,187	2,187
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Ambient air pollutants are also emitted during waste incineration and open burning, as shown in Table 3-45. These emissions are a relatively small portion of the overall ambient air pollutant emissions, comprising less than 5 percent for each gas over the entire time series.

Table 3-45: NO_x, CO, and NMVOC Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
NO_x	**82**	**140**	**145**	**143**	**114**	**114**	**134**	**121**
Waste Incineration	44	48	49	48	38	38	45	41
Open Burning	38	92	96	95	76	76	89	80
CO	**978**	**2,668**	**2,826**	**2,725**	**1,670**	**1,672**	**1,672**	**1,674**
Waste Incineration	337	68	69	66	40	41	41	41
Open Burning	641	2,600	2,757	2,659	1,630	1,631	1,631	1,633
NMVOCs	**222**	**313**	**326**	**302**	**257**	**258**	**281**	**263**
Waste Incineration	44	23	23	19	15	16	18	16
Open Burning	178	290	303	284	242	242	264	246

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). For synthetic rubber and carbon black in scrap tires, this information was provided by the *U.S. Scrap Tire Markets 2001* (RMA 2002) and *Scrap Tires, Facts and Figures* (STMC 2000, 2001, 2002, 2003). Data were not available for 2002 or 2003, so the values for these years were assumed to equal the value for 2001.

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 2002, 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 2003, so the value for this year was assumed to equal the most recent value available (2002). Table 3-46 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 3-46: 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]

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

EPA (2003) 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 2003 uncertainty analysis of CO_2 emissions are the same as the 2002 results, given that the data for the two years is identical (no data updated for 2003 were available). The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-47. Municipal solid waste combustion CO_2 emissions in 2003 were estimated to be between 15.2 and 21.6 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 19 percent below to 15 percent above the 2003 emission estimate of 18.8 Tg CO_2 Eq. Also at a 95 percent confidence level, municipal solid waste combustion N_2O emissions in 2003 were estimated to be between 0.13 and 1.34 Tg CO_2 Eq. This indicates a range of 71 percent below to 192 percent above the 2003 emission estimate of 0.5 Tg CO_2 Eq.

Table 3-47: Tier 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from Municipal Solid Waste Combustion (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	18.8	15.2	21.6	-19%	+15%
Municipal Solid Waste Combustion	N_2O	0.5	0.13	1.34	-71%	+192%

[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 3-48).

Table 3-48: 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	30,512,946	25,974,978
2001	30,569,746	29,694,205[a]
2002	NA	33,643,954
2003	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, 2003), 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

The N_2O emissions estimates for 2001 and 2002 are slightly different from those reported in last year's inventory because newly-available data (Kaufman et al. 2004) were used for the tonnage of waste burned in municipal solid waste combustion for those years. The change resulted in 2001 and 2002 N_2O emissions from municipal solid waste combustion that increased by less than 0.1 Tg CO_2 Eq. (14.7 percent and 26.4 percent, respectively).

The NO_x, CO, and NMVOC emissions estimates for 1999 through 2002 also vary slightly from last year's inventory due to revised criteria pollutant data from EPA. The change constituted less than a 1687 Gg decrease in NO_x, CO, and NMVOC emissions in 2002.

3.10. Natural Gas Flaring and Ambient Air Pollutant 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. Methane emissions from venting are accounted for in the Petroleum Systems source category. For 2003, total CO_2 emissions from flaring activities were estimated to be 5.9 Tg CO_2 Eq. (5,970 Gg), an increase of 3 percent from 1990 levels. On-shore flaring activities accounted for 5.7 Tg CO_2 Eq. (5,743 Gg), or 96 percent, of the total flaring emissions, while off-shore flaring constituted 0.2 Tg CO_2 Eq. (227 Gg), or 4 percent, of the total (see Table 3-49).

Table 3-49: CO_2 Emissions from On-Shore and Off-Shore Natural Gas Flaring (Tg CO_2 Eq.)

	1990		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
On-Shore Flaring	5.5		7.6	6.3	6.7	5.5	5.9	6.0	5.7
Off-Shore Flaring	0.3		0.3	0.3	0.3	0.2	0.2	0.2	0.2
Total Flaring	**5.8**		**7.9**	**6.6**	**7.0**	**5.8**	**6.1**	**6.2**	**5.9**

Note: Totals may not sum due to independent rounding.

Table 3-50: CO_2 Emissions from On-Shore and Off-Shore Natural Gas Flaring (Gg)

	1990		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
On-Shore Flaring	5,514		7,565	6,250	6,679	5,525	5,858	6,006	5,743
Off-Shore Flaring	296		309	316	264	244	236	227	227
Total Flaring	**5,810**		**7,874**	**6,566**	**6,943**	**5,769**	**6,094**	**6,233**	**5,970**

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. Ambient air pollutant emissions from this source from 1990 to 2003 are presented below (see Table 3-51).

Table 3-51: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	**NO_x**	**CO**	**NMVOCs**
1990	139	302	555
1996	126	321	433
1997	130	333	442
1998	130	332	440
1999	109	145	414
2000	111	146	389
2001	113	147	400

2002	135	116	340
2003	124	125	345

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. Ambient air pollutant 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 3-52. 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 3-52.

The total off-shore natural gas vented and flared was obtained from the Minerals Management Service's OGOR-B reports (MMS 2003). 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 3-53

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 3-52: 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	99,173	99,173	1,107
2003	94,929	94,929	1,106

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

Table 3-53: Volume Flared Offshore (MMcf) and Fraction Vented and Flared (Percent)

	1990		1997	1998	1999	2000	2001	2002	2003
Total Gulf of Mexico (GOM)									
Vented & Flared (MMcf)	13,610		15,440	16,280	14,057	12,971	12,990	12,487	12,487

Estimated Flaring Fraction of GOM Vented & Flared	36%		33%	32%	31%	31%	30%	30%	30%
Total	**4,900**		**5,095**	**5,210**	**4,358**	**4,021**	**3,897**	**3,746**	**3,746**

Uncertainty

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 ambient air pollutant 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 increase in CO_2 emissions from flaring of 0.1 Tg CO_2 Eq. (2.3 percent) for the period 1990 through 2002.

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.[52] 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).[53]

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.[54] Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[55] 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.,

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[52] 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).

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

[54] 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.

[55] 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).

departing) from the United States are reported here. The standard fuel used for civil aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[56]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Methane, 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). Methane, 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.[57] 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.[58] The vast majority of aircraft NO_x emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[59]

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. Carbon dioxide 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 2003 from the combustion of international bunker fuels from both aviation and marine activities were 85.1 Tg CO_2 Eq., or 26 percent below emissions in 1990 (see Table 3-54). Although emissions from international flights departing from the United States have increased significantly (29 percent), emissions from international shipping voyages departing the United States have decreased by 63 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 3-55).

Table 3-54: Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**113.5**	**109.9**	**114.6**	**105.3**	**101.4**	**97.9**	**89.5**	**84.2**
Aviation	46.2	55.9	56.7	58.9	60.5	59.4	61.8	59.6
Marine	67.3	54.0	57.9	46.4	40.9	38.5	27.7	24.6
CH_4	**0.2**	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	+	+	+	+	+	+	+	+
Marine	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.0**	**1.0**	**1.0**	**0.9**	**0.9**	**0.9**	**0.8**	**0.8**
Aviation	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Marine	0.5	0.4	0.4	0.4	0.3	0.3	0.2	0.2
Total	**114.6**	**111.0**	**115.7**	**106.4**	**102.4**	**98.9**	**90.4**	**85.1**

\+ Does not exceed 0.05 Tg CO_2 Eq.

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

[57] Currently there are only around a dozen civilian supersonic aircraft in service around the world that fly at these altitudes, however.

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

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

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

Table 3-55: Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**113,503**	**109,858**	**114,557**	**105,294**	**101,404**	**97,865**	**89,489**	**84,193**
Aviation	46,230	55,899	56,657	58,865	60,545	59,388	61,787	59,558
Marine	67,272	53,960	57,900	46,429	40,859	38,477	27,701	24,635
CH_4	**8**	**7**	**7**	**6**	**6**	**5**	**4**	**4**
Aviation	1	2	2	2	2	2	2	2
Marine	7	5	6	5	4	4	3	2
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**2**
Aviation	1	2	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1	1
CO	**115**	**124**	**127**	**124**	**124**	**120**	**118**	**113**
Aviation	76	92	93	97	100	98	102	98
Marine	39	32	34	27	24	23	16	15
NO_x	**1,985**	**1,668**	**1,778**	**1,478**	**1,334**	**1,266**	**988**	**900**
Aviation	182	221	224	233	240	235	245	236
Marine	1,803	1,446	1,554	1,245	1,095	1,031	743	664
NMVOC	**59**	**52**	**55**	**48**	**44**	**42**	**35**	**32**
Aviation	11	14	14	15	15	15	15	15
Marine	48	38	41	33	29	27	20	18

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. Heat content and density conversions were taken from EIA (2004) 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 2004). 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 2004). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT (1991 through 2004) 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 3-56. 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 2004). 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 3-57.

Table 3-56: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S. Carriers	1,954	2,457	2,462	2,625	2,737	2,619	2,495	2,418
Foreign Carriers	2,051	2,939	3,009	3,093	3,166	3,118	3,537	3,388
U.S. Military	862	496	502	488	480	524	482	473
Total	**4,867**	**5,892**	**5,973**	**6,206**	**6,384**	**6,261**	**6,515**	**6,280**

Note: Totals may not sum due to independent rounding.

Table 3-57: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Residual Fuel Oil	4,781	3,843	3,974	3,272	2,967	2,846	1,937	1,597
Distillate Diesel Fuel & Other	617	421	627	308	290	204	158	137
U.S. Military Naval Fuels	522	484	518	511	329	318	348	459
Total	**5,920**	**4,748**	**5,119**	**4,091**	**3,586**	**3,368**	**2,443**	**2,193**

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.[60] 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.

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

Particularly for aviation, the DOT (1991 through 2004) 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 2004) 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 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.[61]

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 Component 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.[62]

There is also concern as to the reliability of the existing DOC (1991 through 2004) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

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[61] 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.

[62] 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.

QA/QC and Verification

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

Recalculations Discussion

Historical activity data for aviation was 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 (1991 through 2004). These historical data changes resulted in minimal changes to the emission estimates for 1990 through 2002, which averaged to an annual increase in emissions from international bunker fuels of less than 0.1 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions, annual increase of less than 0.1 Tg CO_2 Eq. (less than 0.1 percent) in CH_4 emissions, and annual increase of less than 0.1 Tg CO_2 Eq. (0.1 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 Change and Forestry chapter.

In 2003, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 201.0 Tg CO_2 Eq. (201,042 Gg) (see Table 3-58 and Table 3-59). 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 3-58: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Industrial	135.3	162.4	150.5	152.0	153.6	135.4	143.7	143.1
Residential	59.9	44.6	39.9	42.7	44.7	38.2	32.3	37.0
Commercial	4.0	5.0	5.0	5.4	5.5	4.2	4.3	4.4
Electricity Generation	13.3	14.1	14.1	14.2	13.9	13.0	15.5	16.6
Total	**212.5**	**226.3**	**209.5**	**214.3**	**217.6**	**190.8**	**195.8**	**201.0**

Note: Totals may not sum due to independent rounding.

Table 3-59: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	**1990**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Industrial	135,347	162,447	150,510	152,019	153,559	135,413	143,694	143,084
Residential	59,911	44,650	39,920	42,677	44,685	38,153	32,276	37,019
Commercial	4,037	5,042	4,963	5,394	5,481	4,175	4,319	4,369
Electricity Generation	13,252	14,126	14,097	14,233	13,851	13,034	15,487	16,570
Total	**212,547**	**226,265**	**209,490**	**214,323**	**217,577**	**190,776**	**195,775**	**201,042**

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 2003, the United States consumed an estimated 239 trillion Btus of ethanol, and as a result, produced approximately 15.8 Tg CO_2 Eq. (15,771 Gg) (see Table 3-60) 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 3-60: CO_2 Emissions from Ethanol Consumption

Year	Tg CO_2 Eq.	Gg
1990	4.2	4,155
1997	7.0	6,978
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

Methodology

Woody biomass emissions were estimated by taking U.S. consumption data (EIA 2004) (see Table 3-61), 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 carbon dioxide 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 2004) (see Table 3-62).

Table 3-61: Woody Biomass Consumption by Sector (Trillion Btu)

Year	Industrial	Residential	Commercial	Electricity Generation
1990	1,442	581	39	129
1997	1,731	433	49	137
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	1,531	313	42	150
2003	1,524	359	42	161

Table 3-62: Ethanol Consumption

Year	Trillion Btu
1990	63
1997	106
1998	117

1999	122
2000	139
2001	147
2002	174
2003	239

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 0.3 Tg CO_2 Eq. (0.1 percent) from 1990 through 2002.

[BEGIN BOX]

Box 3-4: Formation of CO_2 through Atmospheric CH_4 Oxidation

Methane 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.[63] 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). Methane 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

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[63] 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).

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 respective sections of this report, and are presented in Table 3-63. The CO_2 estimates are summarized in Table 3-64.

Table 3-63: CH_4 Emissions from Non-Combustion Fossil Sources (Gg)

Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Coal Mining	3,900	2,983	2,989	2,805	2,677	2,647	2,497	2,561
Abandoned Coal Mines	288	385	341	349	369	331	303	306
Natural Gas Systems	6,112	6,363	6,276	6,066	6,289	6,277	6,221	5,998
Petroleum Systems	951	895	879	848	836	831	815	815
Petrochemical Production	56	78	80	81	80	68	72	72
Silicon Carbide Production	1	1	1	1	1	+	+	+
Iron and Steel Production	63	60	57	56	57	51	48	49
Total	**11,371**	**10,765**	**10,622**	**10,205**	**10,308**	**10,206**	**9,956**	**9,801**

Note: These emissions are accounted for under their respective source categories. Totals may not sum due to independent rounding.

Table 3-64: Formation of CO_2 through Atmospheric CH_4 Oxidation (Tg CO_2 Eq.)

Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Coal Mining	10.7	8.2	8.2	7.7	7.4	7.3	6.9	7.0
Abandoned Coal Mines	0.8	1.1	0.9	1.0	1.0	0.9	0.8	0.8
Natural Gas Systems	16.8	17.5	17.3	16.7	17.3	17.3	17.1	16.5
Petroleum Systems	2.6	2.5	2.4	2.3	2.3	2.3	2.2	2.2
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	0.2	0.1	0.1	0.1
Total	**31.3**	**29.6**	**29.2**	**28.1**	**28.3**	**28.1**	**27.4**	**27.0**

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.

Carbon dioxide 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.[64]

[END BOX]

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[64] See Annex 2.3 for a more detailed discussion on accounting for indirect emissions from CO and NMVOCs.

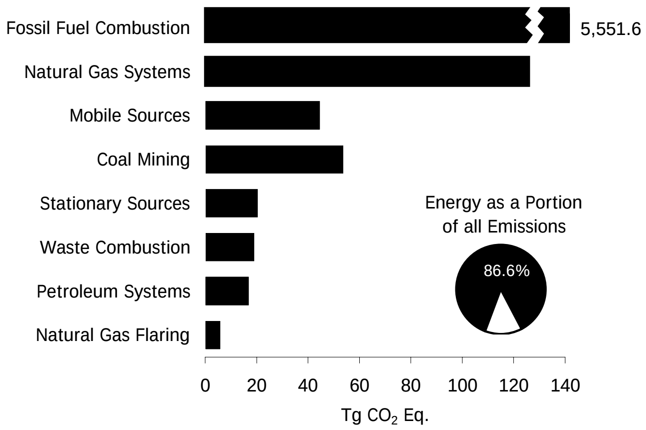
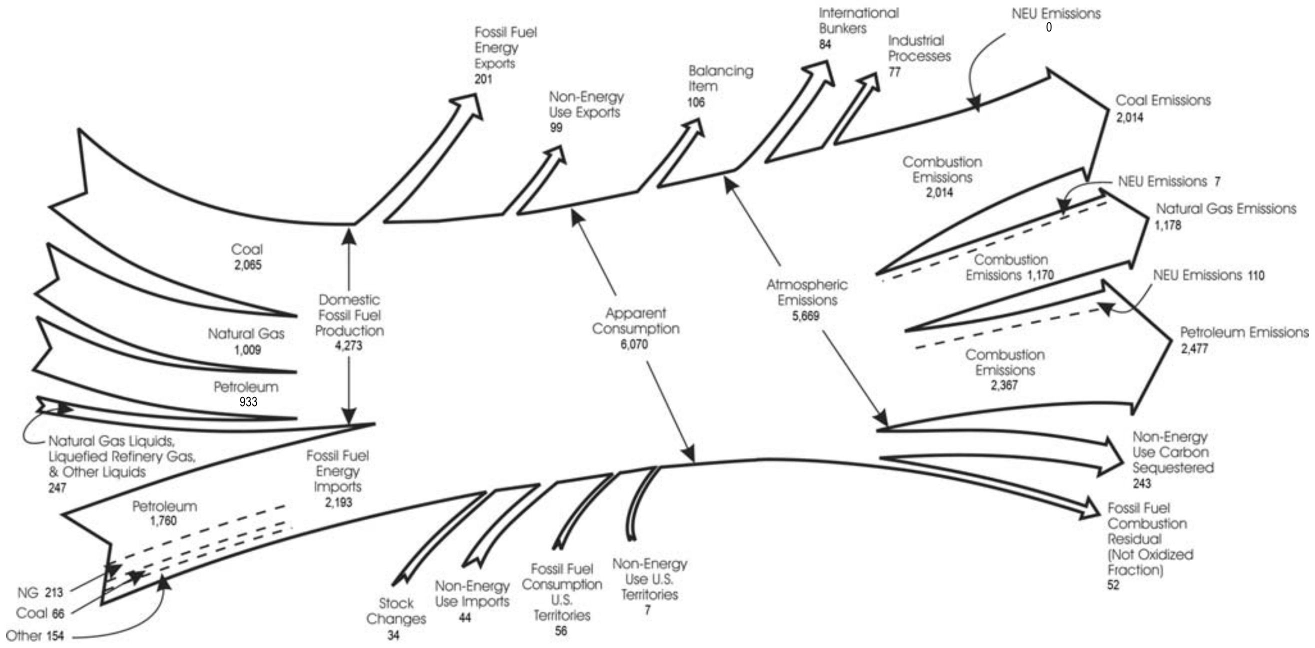


Figure 3-1: 2003 Energy Sector Greenhouse Gas Sources

Figure 3-2

2003 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

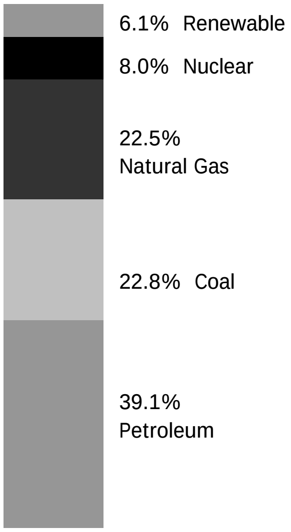


Figure 3-3: 2003 U.S. Energy Consumption by Energy Source

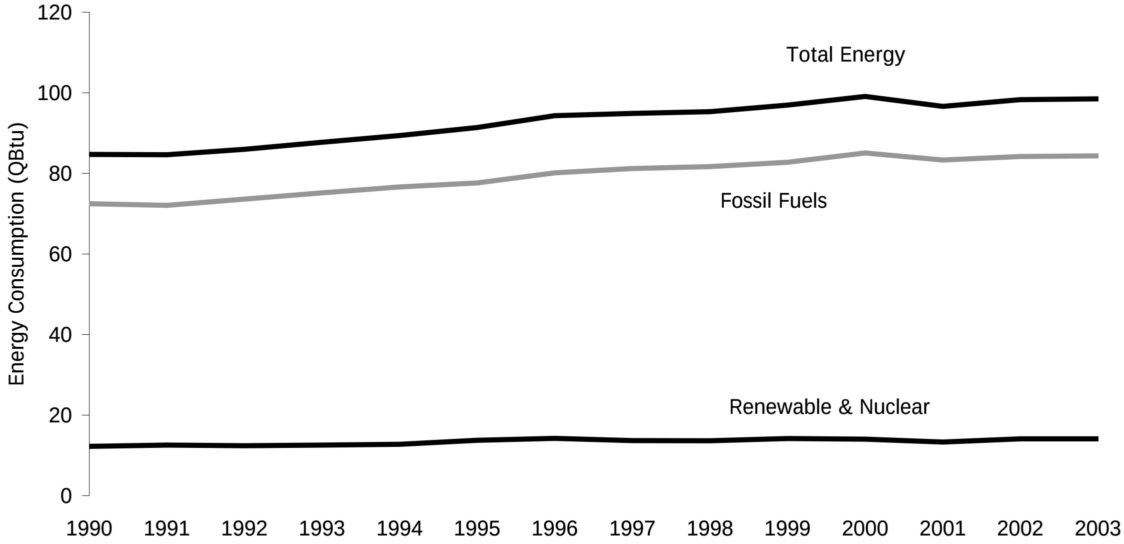


Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)
Note: Expressed as gross calorific values.

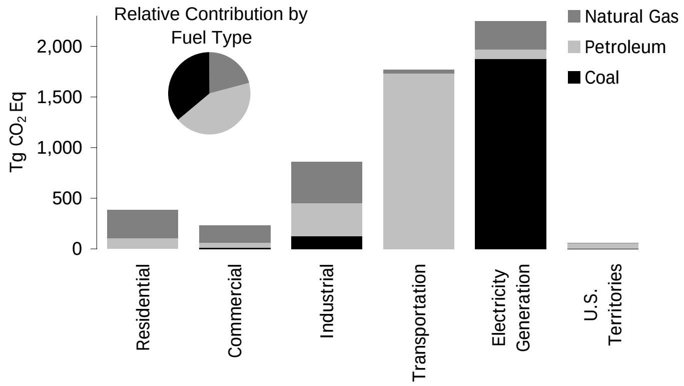


Figure 3-5: 2003 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: The electricity generation sector also includes emissions of less than 0.01 Tg CO_2 Eq. from geothermal-based electricity generation

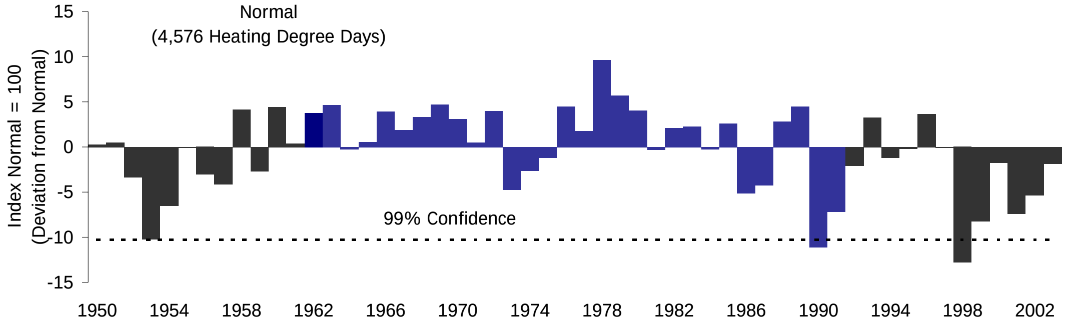


Figure 3-6. Annual Deviations from Normal Heating Degree Days for the United States (1949-2003)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

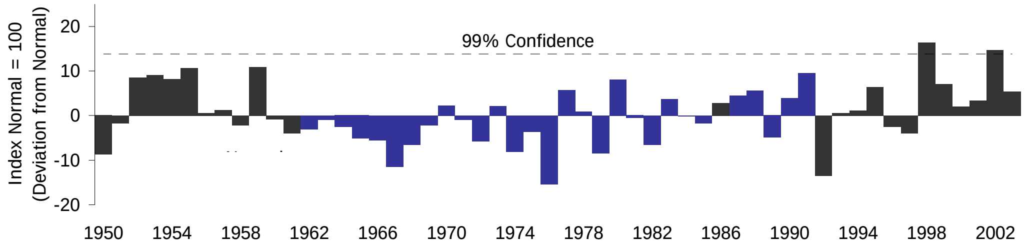


Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1949-2003)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

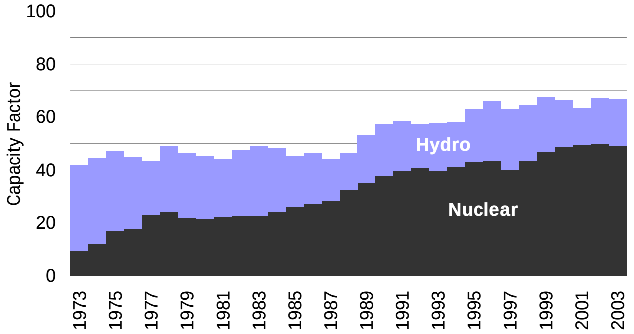


Figure 3-8: Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1973-2003)

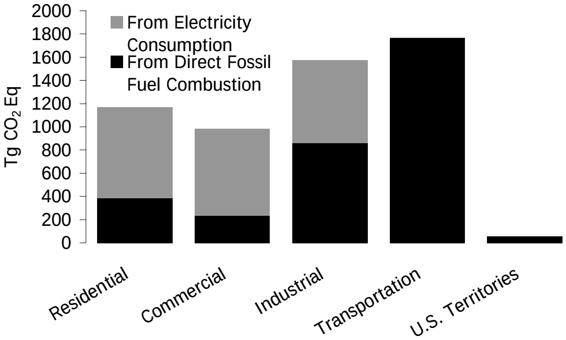


Figure 3-9: 2003 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

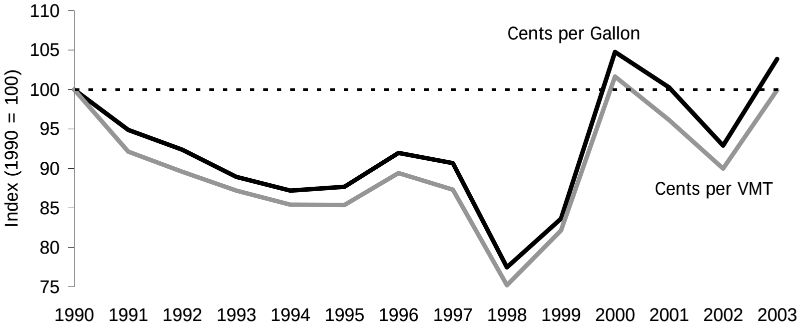


Figure 3-10: Motor Gasoline Retail Prices (Real)

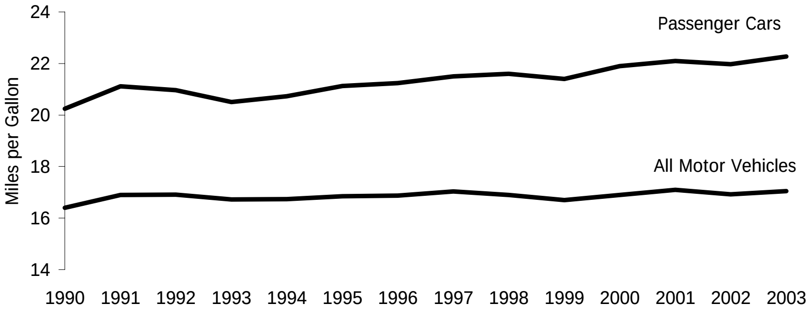


Figure 3-11: Motor Vehicle Fuel Efficiency

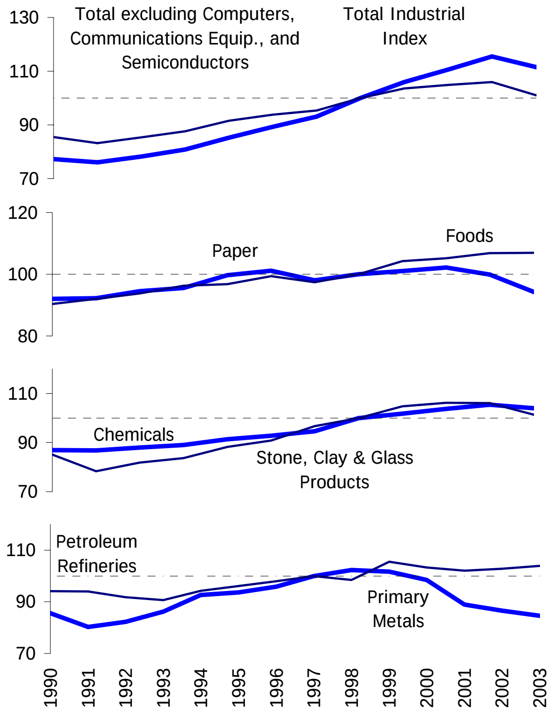


Figure 3-12: Industrial Production Indexes (Index 1997=100)

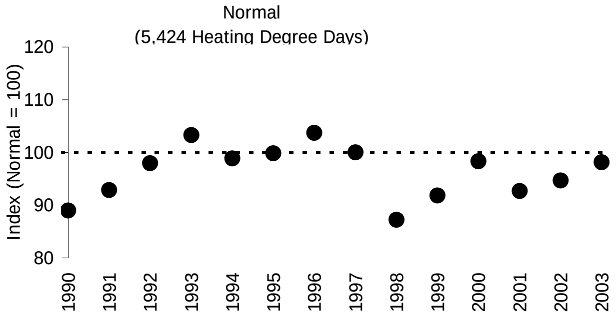


Figure 3-13: Heating Degree Days
Note: Excludes Alaska and Hawaii

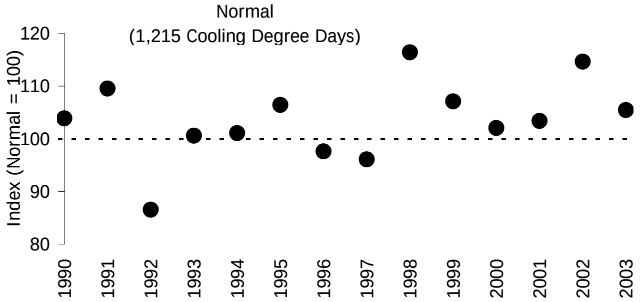


Figure 3-14: Cooling Degree Days
Note: Excludes Alaska and Hawaii

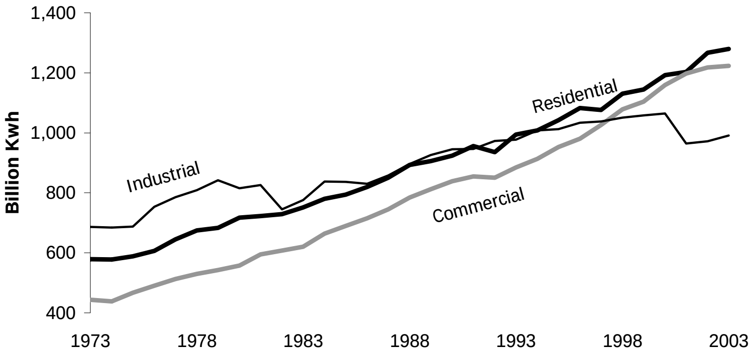


Figure 3-15: Electric Generation Retail Sales by End-Use Sector
Note: The transportation end-use sector consumes minor quanties of electricity.

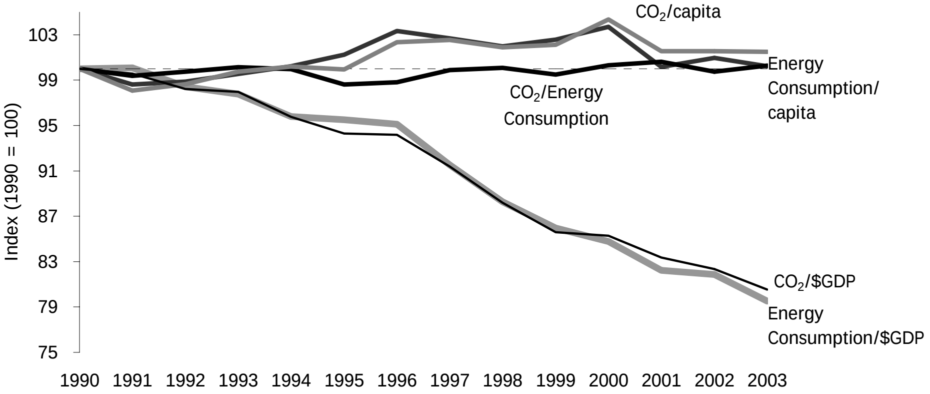


Figure 3-16: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

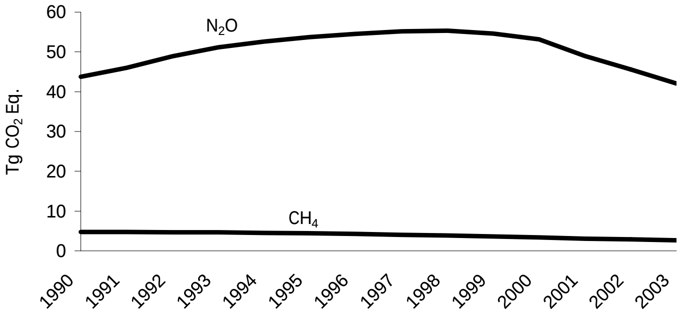


Figure 3-17: Mobile Source CH_4 and N_2O Emissions

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, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1: 2003 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 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 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 2003, industrial processes generated emissions of 308.6 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 4.5 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 147.2 Tg CO_2 Eq. (147,172 Gg) in 2003. This amount accounted for only 2.5 percent of national CO_2 emissions. Methane emissions from petrochemical, silicon carbide, and iron and steel production resulted in emissions of approximately 2.5 Tg CO_2 Eq. (121 Gg) in 2003, which was 0.5 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 21.8 Tg CO_2 Eq. (71 Gg) in 2003, or 5.8 percent of total U.S. N_2O emissions. In 2003, combined emissions of HFCs, PFCs and SF_6 totaled 137.0 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 2.9 percent from 1990 to 2003 despite decreases in emissions from several industrial processes, such as iron and steel, electrical transmission and distribution, HCFC-22 production, and aluminum production. 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 4-2.

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

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CO_2	**173.1**	**170.9**	**169.4**	**165.9**	**164.7**	**151.8**	**151.5**	**147.2**
Iron and Steel Production	85.4	71.9	67.4	64.4	65.7	58.9	55.1	53.8
Cement Manufacture	33.3	38.3	39.2	40.0	41.2	41.4	42.9	43.0
Ammonia Manufacture & Urea Application	19.3	20.7	21.9	20.6	19.6	16.7	18.6	15.6
Lime Manufacture	11.2	13.7	13.9	13.5	13.3	12.8	12.3	13.0
Limestone and Dolomite Use	5.5	7.2	7.4	8.1	6.0	5.7	5.9	4.7
Aluminum Production	6.3	5.6	5.8	5.9	5.7	4.1	4.2	4.2

Soda Ash Manufacture and Consumption	4.1	4.4	4.3	4.2	4.2	4.1	4.1	4.1
Petrochemical Production	2.2	2.9	3.0	3.1	3.0	2.8	2.9	2.8
Titanium Dioxide Production	1.3	1.8	1.8	1.9	1.9	1.9	2.0	2.0
Phosphoric Acid Production	1.5	1.5	1.6	1.5	1.4	1.3	1.3	1.4
Ferroalloy Production	2.0	2.0	2.0	2.0	1.7	1.3	1.2	1.4
Carbon Dioxide Consumption	0.9	0.8	0.9	0.8	1.0	0.8	1.0	1.3
CH_4	**2.5**	**2.9**	**2.9**	**2.9**	**2.9**	**2.5**	**2.5**	**2.5**
Petrochemical Production	1.2	1.6	1.7	1.7	1.7	1.4	1.5	1.5
Iron and Steel Production	1.3	1.3	1.2	1.2	1.2	1.1	1.0	1.0
Silicon Carbide Production	+	+	+	+	+	+	+	+
N_2O	**33.0**	**31.5**	**26.9**	**25.6**	**25.6**	**20.8**	**23.1**	**21.8**
Nitric Acid Production	17.8	21.2	20.9	20.1	19.6	15.9	17.2	15.8
Adipic Acid Production	15.2	10.3	6.0	5.5	6.0	4.9	5.9	6.0
HFCs, PFCs, and SF_6	**91.2**	**121.7**	**135.7**	**134.8**	**138.9**	**129.5**	**138.3**	**137.0**
Substitution of Ozone Depleting Substances	0.4	46.5	56.6	65.8	75.0	83.3	91.5	99.5
HCFC-22 Production	35.0	30.0	40.1	30.4	29.8	19.8	19.8	12.3
Electrical Transmission and Distribution	29.2	21.7	17.1	16.4	15.6	15.4	14.7	14.1
Aluminum Production	18.3	11.0	9.1	9.0	9.0	4.0	5.2	3.8
Semiconductor Manufacture	2.9	6.3	7.1	7.2	6.3	4.5	4.4	4.3
Magnesium Production and Processing	5.4	6.3	5.8	6.0	3.2	2.6	2.6	3.0
Total	**299.9**	**327.1**	**334.9**	**329.2**	**332.1**	**304.7**	**315.4**	**308.6**

+ 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	1997	1998	1999	2000	2001	2002	2003
CO_2	**173,122**	**170,884**	**169,425**	**165,908**	**164,657**	**151,835**	**151,506**	**147,172**
Iron and Steel Production	85,413	71,863	67,428	64,376	65,693	58,887	55,082	53,763
Cement Manufacture	33,278	38,323	39,218	39,991	41,190	41,357	42,898	43,030
Ammonia Manufacture & Urea Application	19,306	20,650	21,934	20,615	19,616	16,719	18,571	15,560
Lime Manufacture	11,238	13,685	13,914	13,466	13,315	12,823	12,304	12,983
Limestone and Dolomite Use	5,533	7,242	7,449	8,057	5,959	5,733	5,885	4,720
Aluminum Production	6,315	5,621	5,792	5,895	5,723	4,114	4,220	4,219
Soda Ash Manufacture and Consumption	4,141	4,354	4,325	4,217	4,181	4,147	4,139	4,082
Petrochemical Production	2,221	2,919	3,015	3,054	3,004	2,787	2,857	2,777
Titanium Dioxide Production	1,308	1,836	1,819	1,853	1,918	1,857	1,997	2,013
Phosphoric Acid Production	1,529	1,544	1,593	1,539	1,382	1,264	1,338	1,382
Ferroalloy Production	1,980	2,038	2,027	1,996	1,719	1,329	1,237	1,374
Carbon Dioxide Consumption	860	808	912	849	957	818	978	1,267
CH_4	**120**	**139**	**138**	**138**	**138**	**119**	**120**	**121**
Petrochemical Production	56	78	80	81	80	68	72	72
Iron and Steel Production	63	60	57	56	57	51	48	49
Silicon Carbide Production	1	1	1	1	1	+	+	+
N_2O	**107**	**102**	**87**	**83**	**83**	**67**	**75**	**70**
Nitric Acid Production	58	68	67	65	63	51	56	51
Adipic Acid Production	49	33	19	18	19	16	19	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	3	2	2	1
Electrical Transmission and Distribution[b]	1	1	1	1	1	1	1	1
Aluminum Production	M	M	M	M	M	M	M	M

Semiconductor Manufacture	M	M	M	M	M	M	M	M
Magnesium Production and Processing[b]	+	+	+	+	+	+	+	+
NO_x	**591**	**629**	**637**	**595**	**626**	**656**	**630**	**648**
CO	**4,124**	**3,153**	**3,163**	**2,156**	**2,217**	**2,339**	**2,308**	**2,431**
NMVOCs	**2,426**	**2,038**	**2,047**	**1,813**	**1,773**	**1,769**	**1,725**	**1,711**

+ 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 procedures and checks have been performed on all industrial process sources. If performed, Tier 2 procedures focused on the emission factor and activity data sources and methodology used for estimating emissions procedures, 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 CO2 and CH4 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 Intergovernmental Panel on Climate Change (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 2003 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 elicitation. 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 coke. Coke oven gas and coal tar are carbon 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. Carbon dioxide is produced as the metallurgical coke used in the blast furnace process is oxidized. 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 2003 were 53.8 Tg CO_2 Eq. (53,763 Gg) and 1.0 Tg CO_2 Eq. (48.7 Gg), respectively (see Table 4-3 and Table 4-4). Emissions have fluctuated significantly from 1990 to 2003 due to changes in domestic economic conditions and changes in product imports and exports. In 2003, domestic production of pig iron and coal coke increased by 2.2 and 2.4 percent, respectively. Despite these increases, domestic pig iron and coke production have declined since the 1990s. Pig iron production in 2003 was 15 percent lower than in 2000 and 19 percent below 1995 levels. Coke production in 2003 was 17 percent lower than in 2000 and 38 percent below 1990 levels. A slowdown in the domestic and worldwide economy and the availability of low-priced imports limit growth in domestic production (USGS 2002).

Table 4-3: CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	85.4		71.9	67.4	64.4	65.7	58.9	55.1	53.8
CH_4	1.3		1.3	1.2	1.2	1.2	1.1	1.0	1.0
Total	**86.7**		**73.1**	**68.6**	**65.5**	**66.9**	**60.1**	**56.1**	**54.8**

Table 4-4: CO_2 and CH_4 Emissions from Iron and Steel Production (Gg)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	85,413		71,863	67,428	64,376	65,693	58,887	55,082	53,763
CH_4	63		60	57	56	58	51	48	49

Methodology

Since coke is consumed as a reducing agent during the manufacture of pig iron, the corresponding quantity of coal consumed during coking operations was identified. This quantity of coal is considered a non-energy use. Data were also collected on the amount of imported coke consumed in the blast furnace process. These data were converted to their energy equivalents. The carbon content of the combusted coal and imported coke was estimated by multiplying their 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 and imported pig iron in the steel production process were calculated by assuming that all the associated carbon-content of these materials are released during combustion. Steel has an associated carbon-content of approximately 0.4 percent, while pig iron is assumed to contain 4 percent carbon by weight.

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 coking process and its carbon-related emissions have already been accounted for earlier in the iron and steel emissions calculation as part of the coking process, the emission factor was reduced by 20 percent to avoid double counting. Additionally, emissions from the coal tar pitch component of carbon anodes consumed during the production of aluminum, which are accounted for in the aluminum production section of this chapter, have been subtracted from the total coal tar emissions that were calculated above.

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 by-weight carbon content of 4 percent.

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 *1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (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, for the production of coke for domestic consumption in blast furnaces, as well as the quantity of coke imported for iron production were taken from the Energy Information Administration (EIA), *Quarterly Coal Report* January through December 2003 (EIA 2004); *U.S. Coal Domestic and International Issues* (EIA 2001); *Mineral Yearbook: Iron and Steel* (USGS 1993, 1995a, 1997, 1999, 2000a, 2001a, 2002a) and the American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2001, 2002, 2003, 2004). Scrap steel and imported pig iron consumption data for 1990 through 2003 were obtained from *Annual Statistical Reports* (AISI 1995, 2001, 2002, 2003, 2004) (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). 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 and Uncertainty Management* (IPCC 2000). Aluminum production data for 1990 through 2003 were obtained from *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995b, 1998, 2000b, 2001b, 2002b, 2003, 2004a). Annual consumption of iron ore used in sinter production for 1990 through 2003 were obtained from the USGS Iron Ore yearbook (USGS 1994, 1995c, 1996, 1997b, 1998b, 1999b, 2000c, 2001c, 2002c, 2004b). 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 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		1997	1998	1999	2000	2001	2002	2003
CO_2									
Coal Consumption at Coke Plants	35,289		27,400	25,573	25,499	26,253	23,655	21,460	21,997

Coke Consumption for Pig Iron	24,946	22,100	19,800	18,700	19,215	17,129	15,850	15,379
Domestic Pig Iron Production for Steel	49,061	48,676	47,470	45,677	47,399	41,740	39,600	40,487
Basic Oxygen Furnace Steel Production	56,227	55,386	54,146	52,364	53,964	47,359	45,463	45,873
Electric Arc Furnace Steel Production	33,517	43,098	44,513	45,063	47,859	42,743	46,124	47,803
CH_4								
Coke Production	25,054	20,063	18,181	18,240	18,877	17,190	15,220	15,579
Iron Ore Consumption for Sinter	12,239	11,426	10,791	11,072	10,784	9,234	9,018	8,984
Domestic Pig Iron Production for Steel	49,061	48,676	47,470	45,677	47,399	41,740	39,600	40,487

Uncertainty

The time series data for production of coal coke, sinter, pig iron, steel, and aluminum and import and export data upon which the calculations are based are considered to be consistent for the entire time series. The estimates of CO_2 emissions from the production and utilization of coke are based on energy consumption data, average carbon contents, and the fraction of carbon oxidized. 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 uncertainty in the most accurate CO_2 emission factor for carbon anode consumption in aluminum production. Emissions vary depending on the specific technology used by each plant (Prebake or Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provide CO_2 emission factors for each technology type. Consistent with the assumptions used in the Aluminum Production source, it was assumed that production was split 80 percent prebake and 20 percent Soderberg for the whole time series. 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 32.0 and 76.4 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 41 percent below and 42 percent above the emission estimate of 53.8 Tg CO_2 Eq. Iron and Steel CH_4 emissions were estimated to be between 0.9 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 11 percent below and 11 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**	**2003 Emission Estimate**	**Uncertainty Range Relative to Emission Estimate**[a]			
		(Tg CO_2 Eq.)	**(Tg CO_2 Eq.)**		**(%)**	

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Iron and Steel	CO_2	53.8	32.0	76.4	-41%	+42%
Iron and Steel	CH_4	1.0	0.9	1.1	-11%	+11%

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

Recalculations Discussion

Estimates of CO_2 from iron and steel production increased due to revised production data found in American Iron and Steel Institute's *2003 Annual Statistical Report* (AISI 2004) and EIA's *2003 Quarterly Coal Report* (EIA 2004). These changes resulted in an average increase of 0.2 Tg CO_2 Eq. (0.5 percent) in CO_2 emissions from iron and steel production for 2001 and 2002.

Estimates of CH_4 2002 were revised due to revised sinter production data provided by the U.S. Geological Survey's *Iron and Steel Report 2003* (USGE 2004b). This change resulted in an increase of less than 0.1 Tg CO_2 Eq. (0.8 percent) in CH_4 emissions from iron and steel production for 2002.

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, and the United States is the world's third largest cement producer (IPCC 1997, USGS 2003). Cement is manufactured in nearly 40 states. Carbon dioxide 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 2003, U.S. clinker production—including Puerto Rico—totaled 83,214 thousand metric tons (Van Oss 2004). The resulting emissions of CO_2 from 2003 cement production were estimated to be 43.0 Tg CO_2 Eq. (43,030 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
1997	38.3	38,323
1998	39.2	39,218
1999	40.0	39,991

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[1] The CO_2 emissions related to the consumption of energy for cement manufacture are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

2000	41.2	41,190
2001	41.4	41,357
2002	42.9	42,898
2003	43.0	43,030

* 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 2003, emissions increased by 29 percent. Cement is a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, have had considerable influence on cement production.

Methodology

Carbon dioxide emissions from cement 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:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Carbon dioxide emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 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:

$$EF_{\text{Clinker}} = 0.646\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\,\text{CO}_2}{56.08\ \text{g/mole}\,\text{CaO}}\right] = 0.507\ \text{tons}\ \text{CO}_2/\text{ton clinker}$$

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 2003 activity data for clinker and masonry cement production (see Table 4-9) was obtained through a personal communication with Hendrick Van Oss (Van Oss 2004) of the USGS and through the USGS *Mineral Yearbook: Cement* (USGS 1992 through 2003). Data for 2003 masonry cement production were unavailable and were assumed to equal 2002 data. 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	69,786	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	83,214	4,449

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. There is also an uncertainty in 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 46.3 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 43.0 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**	**2003 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**
Cement Manufacture	CO_2	43.0	39.7	46.3	-8%	+8%

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

QA/QC and Verification

Based on the results of the Tier 2 uncertainty analysis conducted on the cement emissions estimate for the 2004 U.S. GHG Inventory, the United States decided to conduct Tier 2 QA procedures on two elements of the cement emissions estimate for the current inventory submission: the CaO content of clinker and emissions from production of CKD. The United States currently uses the IPCC default values for these input values and the current investigation seeks to determine whether these default values are reflective of U.S. circumstances. We are currently in the process of conducting a form of expert elicitation on these values. Preliminary results suggest that the default values seem appropriate for the U.S. cement industry however there may be small differences. We are currently investigating any differences and will include any results in future inventories, if appropriate.

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 ammonia 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. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released.

The conversion process for conventional steam reforming of CH_4, including primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88\ CH_4 + 1.26\ \text{Air} + 1.24\ H_2O \xrightarrow{\text{(catalyst)}} 0.88\ CO_2 + N_2 + 3\ H_2$$

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced in the production of ammonia is emitted directly to the atmosphere. Both ammonia and carbon dioxide 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 2003 were 9.1 Tg CO_2 Eq. (9,097 Gg), and are summarized in Table 4-11 and Table 4-12. Emissions of CO_2 from urea application in 2003 totaled 6.5 Tg CO_2 Eq. (6,463Gg), and are summarized in Table 4-11 and Table 4-12.

Table 4-11: CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq.)

Source	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**

Ammonia Manufacture	12.6		14.0	14.2	12.9	12.1	9.3	10.6	9.1
Urea Application	6.8		6.6	7.7	7.7	7.5	7.4	8.0	6.5
Total	**19.3**		**20.7**	**21.9**	**20.6**	**19.6**	**16.7**	**18.6**	**15.6**

Table 4-12: CO_2 Emissions from Ammonia Manufacture and Urea Application (Gg)

Source	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Ammonia Manufacture	12,553		14,028	14,215	12,948	12,128	9,321	10,561	9,097
Urea Application	6,753		6,622	7,719	7,667	7,488	7,398	8,010	6,463

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 and Table 4-14, respectively) were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 2004) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Import and export data for 2003 were unavailable and were assumed to equal 2002 data (see Table 4-15). These data 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 2002, 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.

Table 4-13: Ammonia Production (Gg)

Year	Gg
1990	15,425
1991	15,576
1992	16,261
1993	15,599
1994	16,211
1995	15,788
1996	16,260
1997	16,231
1998	16,761
1999	15,728
2000	14,342
2001	11,092
2002	12,577
2003	10,468

Table 4-14: Urea Production (Gg)

Year	Gg
1990	8,124
1991	7,373
1992	8,142
1993	7,557
1994	7,584
1995	7,363
1996	7,755
1997	7,430
1998	8,042
1999	8,080
2000	6,969
2001	6,080
2002	7,038
2003	5,783

Table 4-15: Urea Net Imports (Gg)

Year	Gg
1990	1,086
1991	648
1992	656
1993	2,305
1994	2,249
1995	2,055
1996	1,051
1997	1,600
1998	2,483
1999	2,374
2000	3,241
2001	4,008
2002	3,884
2003	3,030

Uncertainty

The uncertainties contained in these estimates 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; EIA 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 from that sector 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 would be assumed to remain sequestered [see the section of

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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.

this chapter on Carbon Dioxide 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-16. Ammonia CO_2 emissions were estimated to be between 7.7 and 10.4 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 15 percent below and 15 percent above the emission estimate of 9.1 Tg CO_2 Eq. Urea CO_2 emissions were estimated to be between 6.0 and 7.0 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 6.5 Tg CO_2 Eq.

Table 4-16: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	CO_2	9.1	7.7	10.4	-15%	+15%
Urea	CO_2	6.5	6.0	7.0	-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 for the years 2000, 2001, and 2002 were updated to reflect revisions made to the methodology to include ammonia manufactured from petroleum coke. The plant, located in Kansas, began ammonia production in 2000. This change resulted in an average annual increase in CO_2 emissions from ammonia manufacture of 0.5 Tg CO_2 Eq. (2.7 percent) for the years 2000 through 2002.

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. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce CaO and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere. Some of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC)[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 19,164 thousand metric tons in 2003 (USGS 2004). This resulted in estimated CO_2 emissions of 13.0 Tg CO_2 Eq. (or 12,983 Gg) (see Table 4-17 and Table 4-18).

Table 4-17: Net CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	11.2
1997	13.7
1998	13.9
1999	13.5
2000	13.3
2001	12.8
2002	12.3
2003	13.0

Table 4-18: CO_2 Emissions from Lime Manufacture (Gg)

Year	Potential	Recovered*	Net Emissions
1990	11,730	(493)	11,238
1997	14,649	(964)	13,685
1998	14,975	(1,061)	13,914
1999	14,655	(1,188)	13,466
2000	14,548	(1,233)	13,315
2001	13,941	(1,118)	12,823
2002	13,355	(1,051)	12,304
2003	14,132	(1,149)	12,983

* For sugar refining and precipitated calcium carbonate production.
Note: Totals may not sum due to independent rounding.

At the turn of the 20th Century, over 80 percent of lime consumed in the United States went for construction uses. The contemporary quicklime market is distributed across four end-use categories as follows: metallurgical uses, 35 percent; environmental uses, 28 percent; chemical and industrial uses, 23 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. The use of hydrated lime for traditional building increased by nearly seven percent in 2003 (USGS 2004).

Lime production in 2003 increased by nearly seven percent from 2002, the first increase in production in five years. Overall, from 1990 to 2003, lime production has increased by 17 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).

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[3] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

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 19,164 thousand metric tons in 2003 (USGS 2004), resulting in potential CO_2 emissions of 14.1 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 1,926 thousand metric tons in 2003. 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 13.0 Tg CO_2 Eq.

The activity data for lime manufacture and lime consumption by sugar refining and PCC production for 1990 through 2003 (see Table 4-19) were obtained from USGS (1992 through 2004). Hydrated lime production is reported separately in Table 4-20. 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 4-19: 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

[a] Includes hydrated lime.
[b] Includes dead-burned dolomite.

Table 4-20: 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

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). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2; whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. 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 most sulfate mills recover the waste calcium carbonate 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.

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

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[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.

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 4-21. Lime CO_2 emissions were estimated to be between 12.0 and 14.1 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 13.0 Tg CO_2 Eq.

Table 4-21: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	13.0	12.0	14.1	-8%	+8%

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

4.5. Limestone and Dolomite Use (IPCC Source Category 2A3)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[6] 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 2003, approximately 8,074 thousand metric tons of limestone and 2,446 thousand metric tons of dolomite were consumed for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 4.7 Tg CO_2 Eq. (4,720 Gg) (see Table 4-22 and Table 4-23). Emissions in 2003 decreased 20 percent from the previous year and have decreased 15 percent overall from 1990 through 2003.

Table 4-22: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Flux Stone	3.0	5.0	5.1	6.0	2.8	2.5	2.4	2.1
Glass Making	0.2	0.3	0.2	0	0.4	0.1	0.1	0.3
FGD	1.4	1.4	1.2	1.2	1.8	2.6	2.8	1.9
Magnesium Production	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Other Miscellaneous Uses	0.8	0.4	0.9	0.7	0.9	0.5	0.7	0.4
Total	**5.5**	**7.2**	**7.4**	**8.1**	**6.0**	**5.7**	**5.9**	**4.7**

Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 4-23: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Flux Stone	2,999	5,023	5,132	6,030	2,829	2,514	2,405	2,072

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[6] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Limestone	2,554		3,963	4,297	4,265	1,810	1,640	1,330	904
Dolomite	446		1,060	835	1,765	1,020	874	1,075	1,168
Glass Making	217		319	157	0	368	113	61	337
Limestone	189		319	65	0	368	113	61	337
Dolomite	28		0	91	0	0	0	0	0
FGD	1,433		1,426	1,230	1,240	1,773	2,551	2,766	1,932
Magnesium Production	64		73	73	73	73	53	0	0
Other Miscellaneous Uses	819		401	858	713	915	501	652	380
Total	**5,533**		**7,242**	**7,449**	**8,057**	**5,959**	**5,733**	**5,885**	**4,720**

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

Carbon dioxide 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 2003 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 4-24) were obtained from personal communication with Valentine Tepordei of the USGS regarding data in the *Minerals Yearbook: Crushed Stone Annual Report* (Tepordei 2002, 2003, 2004 and USGS 1993, 1995a, 1995b, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a, 2002a, 2003a). The production capacity data for 1990 through 2003 of dolomitic magnesium metal (see Table 4-25) also came from the USGS (1995c, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b, 2002b, 2003b, 2004). 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.[7]

Table 4-24: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Flux Stone	6,738	11,226	11,514	13,390	6,248	5,558	5,275	4,501
Limestone	5,804	9,007	9,767	9,694	4,113	3,727	3,023	2,055
Dolomite	933	2,219	1,748	3,696	2,135	1,831	2,252	2,466
Glass Making	489	725	340	0	836	258	139	765
Limestone	430	725	149	0	836	258	139	765
Dolomite	59	0	191	0	0	0	0	0
FGD	3,258	3,242	2,795	2,819	4,030	5,798	6,286	4,390
Other Miscellaneous Uses	1,835	898	1,933	1,620	2,080	1,138	1,483	863
Total	**12,319**	**16,091**	**16,582**	**17,830**	**13,194**	**12,751**	**13,183**	**10,520**

Note: "Other miscellaneous uses" includes chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 4-25: 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

Note: Production capacity for 2002 and 2003 amount to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002).

Uncertainty

Uncertainties in this estimate are due, in part, 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.

Uncertainties also exist in the 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 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

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[7] This approach was recommended by USGS.

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 4-26. Limestone and Dolomite Use CO_2 emissions 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 and 8 percent above the emission estimate of 4.7 Tg CO_2 Eq.

Table 4-26: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	4.7	4.4	5.1	-7%	+8%

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

Recalculations Discussion

A spreadsheet error was corrected for the limestone and dolomite use emission estimate for 2002. The change resulted in an increase of less than 0.1 Tg CO_2 Eq. (0.8 percent) in CO_2 emissions from limestone and dolomite use for that year.

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 the largest soda ash-producing country in the world. 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.[8] During the production process used in Wyoming, trona ore is treated to produce soda ash. Carbon dioxide 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 2003, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.5 Tg CO_2 Eq. (1,509 Gg). Soda ash consumption in the United States generated 2.6 Tg CO_2 Eq. (2,573 Gg) in 2003. Total emissions from soda ash manufacture in 2003 were 4.1 Tg CO_2 Eq. (4,082 Gg) (see Table 4-27 and Table 4-28). Emissions

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[8] 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.

have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2003 decreased by approximately 1 percent from the previous year, and have decreased overall by approximately 1 percent since 1990.

Table 4-27: CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq.)

Year	Manufacture	Consumption	Total
1990	1.4	2.7	4.1
1997	1.7	2.7	4.4
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

Note: Totals may not sum due to independent rounding.

Table 4-28: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,431	2,710	4,141
1997	1,665	2,689	4,354
1998	1,607	2,718	4,325
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	2,573	4,082

Note: Totals may not sum due to independent rounding.

The United States has the world's largest deposits of trona and represents about one-third of total world soda ash output. The distribution of soda ash by end-use in 2003 was glass making, 49 percent; chemical production, 26 percent; soap and detergent manufacturing, 11 percent; distributors, five percent; flue gas desulfurization, pulp and paper production, two percent each; water treatment, one percent; and miscellaneous, four percent (USGS 2004).

Although the United States continues to be the major supplier of world soda ash, China's soda ash manufacturing capacity is rapidly increasing and is expected to surpass that of the United States. This will likely cause greater competition in Asian markets in the future. The world market for soda ash is expected to grow 1.5 to 2 percent annually (USGS 2004).

Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as by-products of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$2(Na_3H(CO_3)_2 \cdot 2H_2O) \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$$

[trona] [soda ash]

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 15.5 million metric tons of trona mined in 2003 for soda ash production (USGS 2004) resulted in CO_2 emissions of approximately 1.5 Tg CO_2 Eq. (1,509 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 4-29) 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 4-29: 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	6,200

* Soda ash manufactured from trona ore only.

Uncertainty

Emission estimates from soda ash manufacture are considered to have low associated uncertainty. Both the emission factor and activity data are reliable. However, 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 4-30. Soda Ash Manufacture and Consumption CO_2 emissions were estimated to be between 3.9 and 4.2 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 4 percent below and 4 percent above the emission estimate of 4.1 Tg CO_2 Eq.

Table 4-30: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2003 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	4.1	3.9	4.2	-4%	+4%

[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. Carbon dioxide 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 2003 were 2.0 Tg CO_2 Eq. (2,013 Gg), an increase of less than one percent from the previous year and 54 percent from 1990, due to increasing production within the industry (see Table 4-31).

Table 4-31: CO_2 Emissions from Titanium Dioxide (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.3	1,308
1997	1.8	1,836
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

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 titanium dioxide produced each year, and it was assumed that 97 percent of the total production in 2003 was produced using the chloride process. It was assumed that titanium dioxide 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 titanium dioxide produced using the chloride process was produced using petroleum coke, although some titanium dioxide may have been produced with graphite or other carbon inputs. The amount of petroleum coke consumed annually in titanium dioxide 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 titanium dioxide 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 2003 (see Table 4-32) were obtained from personal communication with Joseph Gambogi, USGS Commodity Specialist, of the USGS (Gambogi 2004) and through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2003). Data for the percentage of the total titanium dioxide production capacity that is chloride process for 1994 through 2002 were also taken from the USGS *Minerals Yearbook* and from Joseph Gambogi for 2003. 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 4-32: 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

Uncertainty

Although some titanium dioxide may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs may generate differing amounts of CO_2 per unit of titanium dioxide produced compared to the use of petroleum coke. The most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than the amount of titanium dioxide produced. These data were not available, however.

Also, annual titanium production is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity is reported. It was assumed that titanium dioxide 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. 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 titanium dioxide production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the titanium dioxide chloride process; however, this composition information was not available.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-33. Titanium Dioxide Consumption CO_2 emissions were estimated to be between 1.7 and 2.3 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 16 percent below and 16 percent above the emission estimate of 2.0 Tg CO_2 Eq.

Table 4-33: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2003 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	2.0	1.7	2.3	-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 carbon dioxide. 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 2003 was 38.7 million metric tons. Approximately 86 percent of domestic phosphate rock production was mined in Florida and North Carolina, while approximately 14 percent of production was mined in Idaho and Utah. Florida alone represented more than 75 percent of domestic production. In addition, 2.4 million metric tons of crude phosphate rock was imported for consumption in 2003. Marketable phosphate rock production, including domestic production and imports for consumption, increased by approximately 3.7 percent between 2002 and 2003. However, over the 1990 to 2003 period, production decreased by 12 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. (1,382 Gg) in 2003 (see Table 4-34).

Table 4-34: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
1997	1.5	1,544
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

Methodology

Carbon dioxide 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 4-35). Data for domestic production of phosphate rock, exports of phosphate rock, and imports of phosphate rock for consumption for 1990 through 2003 were obtained from USGS Mineral Yearbook, Phosphate Rock (USGS 1994 through 2004).

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 4-36).

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 (86 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 (14 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 4-35: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location/Year	1990		1997	1998	1999	2000	2001	2002	2003
U.S. Production									
FL & NC	42,494		36,604	38,000	35,900	31,900	28,100	29,800	31,300
ID & UT	7,306		5,496	5,640	5,540	5,470	4,730	4,920	5,100
Exports - FL & NC	6,240		335	378	272	299	9	62	64
Imports - Morocco	451		1,830	1,760	2,170	1,930	2,500	2,700	2,400
Total U.S. Consumption	**44,011**		**43,595**	**45,022**	**43,338**	**39,001**	**35,321**	**37,358**	**38,746**

Source: USGS 2004, 2003, 2002, 2001, 2000, 1999, 1998, 1997, 1996, 1995.

Table 4-36: Chemical Composition of Phosphate Rock (percent by weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.0	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	—	0.1
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.0	5.0

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 2003. The phosphate rock production data are not considered to be a significant source of uncertainty, because all eleven of the domestic phosphate rock producers are reporting 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 4-36, 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 2003). Total production of phosphate rock in Utah and Idaho combined amounts to approximately 14 percent of total domestic production in 2003. 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 5 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2003a). 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 5 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 5 percent.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-37. Phosphoric acid production CO_2 emissions were estimated to be between 1.1 and 1.6 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 18 percent below and 18 percent above the emission estimate of 1.4 Tg CO_2 Eq.

Table 4-37: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	1.6	-18%	+18%

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

Recalculations Discussion

The historical activity data used to calculate the emissions from phosphoric acid production were updated for the year 2002. The change resulted in a decrease of less than 0.1 Tg CO_2 Eq. (less than 0.1 percent) in CO_2 emissions from phosphoric acid production for that year.

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)

Carbon dioxide 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:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

Emissions of CO_2 from ferroalloy production in 2003 were 1.4 Tg CO_2 Eq. (1,374 Gg) (see Table 4-38), an 11 percent increase from the previous year and a 31 percent reduction since 1990.

Table 4-38: CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	2.0	1,980
1997	2.0	2,038
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	1.4	1,374

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 2003 (see Table 4-39) were obtained from the USGS through personal communications with Lisa Corathers (2004), the Silicon Commodity Specialist, and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003). 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 4-39). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Table 4-39: 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
1997	175,000	147,000	187,000	106,000
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	98,600	113,000	NA
2003	113,000	75,800	189,000	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.[9] 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 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 4-40. Ferroalloy Production CO_2 emissions were estimated to be between 1.3 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 3 percent below and 3 percent above the emission estimate of 1.4 Tg CO_2 Eq.

Table 4-40: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	1.4	1.3	1.4	-3%	+3%

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

4.10. Carbon Dioxide Consumption (IPCC Source Category 2B5)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected into the underground reservoirs to increase the reservoir pressure to enable additional petroleum to be produced.

For the most part, CO_2 used in non-EOR applications will eventually be released to the atmosphere, and for the purposes of this analysis CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. Carbon dioxide used in EOR applications is 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. Carbon dioxide 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 process include fugitive emissions from the compressors, pipeline equipment, and wellheads. Also, the CO_2 used for EOR may show up at the wellhead after a few years of injection (Hangebrauk et al. 1992) or may be partially recovered

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[9] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

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.

Carbon dioxide 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. Carbon dioxide 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. Carbon dioxide 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 Carbon Dioxide 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.[10]

Carbon dioxide 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.[11] 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, R. et al. 2000). In 2003, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere were 1.3 Tg CO_2 Eq. (1,267 Gg) (see Table 4-41). This amount represents an increase of 29 percent from the previous year and an increase of 47 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 4-41: CO_2 Emissions from Carbon Dioxide Consumption (Tg CO_2 Eq. and Gg)

Year	**Tg CO_2 Eq.**	**Gg**

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[10] 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.

[11] 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.

1990	0.9	860
1997	0.8	808
1998	0.9	912
1999	0.8	849
2000	1.0	957
2001	0.8	818
2002	1.0	979
2003	1.3	1,267

Methodology

Carbon dioxide emission estimates for 2001, 2002, and 2003 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). Carbon dioxide 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.

Carbon dioxide production data for the Jackson Dome, Mississippi facility in 2001, 2002, and 2003 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, Denbury Resources 2003b, Denbury Resources 2004). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001, 2002, and 2003, and reported the percentage of the total average annual production that was used for EOR. Carbon dioxide production data for the Bravo Dome, New Mexico facility were obtained from the New Mexico Bureau of Geology and Mineral Resources for the years 1990 through 2001 (Broadhead 2003). 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 2003). Production data for 2002 and 2003 were not available for Bravo Dome, so it is assumed that the production values for those years are equal to the 2001 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 total domestic commercial consumption of CO_2 in commercial applications other than EOR as reported by the U.S. Census Bureau was about 11,414 thousand metric tons in 2001. The total non-EOR CO_2 produced from the Jackson Dome and Bravo Dome natural reservoirs in 2001 was about 820 thousand metric tons, corresponding to 7.2 percent of the total domestic non-EOR commercial CO_2 consumption. This 7.2 percent factor was applied to the annual non-EOR commercial CO_2 consumption data for the years 1990 through 2000 to estimate annual CO_2 emissions from non-EOR commercial consumption of CO_2 produced from naturally occurring CO_2 reservoirs. The remaining 92.8 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 4-42) 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 2003 were obtained from the U.S. Census Bureau's *Industry Report, 1996, 1998, 2000, 2002, and 2003* (U.S. Census 1997, 1999, 2001, 2003, 2005).

Table 4-42: Carbon Dioxide Consumption (Metric Tons)

Year	Metric Tons
1990	11,997,726

1997	11,268,219
1998	12,716,070
1999	11,843,386
2000	13,354,262
2001	11,413,889
2002	11,313,478
2003	11,103,777

Uncertainty

Uncertainty exists in the assumption that 92.6 percent of the total domestic CO_2 production for commercial consumption other than EOR from 1990 through 2000 came from energy and industrial production processes, while 7.4 percent came from naturally occurring CO_2 reservoirs. The allocation for these years is assumed to be the same allocation as for 2001, the last year for which data are available to calculate the allocation.

Uncertainty also exists with respect to 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.

Uncertainty also exists in 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 4-43. Carbon dioxide consumption CO_2 emissions were estimated to be between 1.2 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 5 percent below to 5 percent above the emission estimate of 1.3 Tg CO_2 Eq.

Table 4-43: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Carbon Dioxide Consumption (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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**
Carbon Dioxide Consumption	CO_2	1.3	1.2	1.3	-5%	+5%

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

Recalculations Discussion

Carbon dioxide consumption values were updated for 2001 for the Bravo Dome, and for both 2001 and 2002 for the Jackson Dome. For the Bravo Dome, updated values are based on new production data from the facility. For Jackson Dome, previous production data was based on fourth quarter reporting by Denbury Resources, which was annualized for the entire year. Updated production values are based on annual production numbers reported by Denbury Resources. For 2001, updated production values resulted in a 4 percent decrease in emissions, and for 2002 updated production values resulting in a 23 percent decrease in emissions. Based on updated 2001 consumption values for Jackson Dome, the percent of CO_2 emissions from CO_2 consumption in commercial applications other than EOR applied to years 1990 through 2000 decreased by 0.2 percent relative to the percent previously assumed. These changes resulted in an average annual decrease in CO_2 emissions from CO_2 consumption of less than 0.1 Tg CO_2 Eq. (5.1 percent) for the years 1990 through 2002.

4.11. 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. Methane 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. The United States produces close to one quarter of the world's supply of methanol.

Emissions of CO_2 and CH_4 from petrochemical production in 2003 were 2.8 Tg CO_2 Eq. (2,777 Gg) and 1.5 Tg CO_2 Eq. (72 Gg), respectively (see Table 4-44 and Table 4-45). While emissions of CO_2 from carbon black production in 2003 decreased by three percent from the previous year, there has been an overall increase in CO_2 emissions from carbon black production of 25 percent since 1990. Methane emissions from petrochemical production decreased by less than one percent from the previous year and increased 30 percent since 1990.

Table 4-44: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	2.2		2.9	3.0	3.1	3.0	2.8	2.9	2.8
CH_4	1.2		1.6	1.7	1.7	1.7	1.4	1.5	1.5
Total	**3.4**		**4.6**	**4.7**	**4.8**	**4.7**	**4.2**	**4.4**	**4.3**

Table 4-45: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CO_2	2,221		2,919	3,015	3,054	3,004	2,787	2,857	2,777
CH_4	56		78	80	81	80	68	72	72

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,[12] 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 4-46) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2003 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (2003).

Table 4-46: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Carbon Black	1,307		1,719	1,775	1,798	1,769	1,641	1,682	1,635
Ethylene	16,542		23,088	23,474	25,118	24,971	22,521	23,623	22,957
Ethylene Dichloride	6,282		10,324	11,080	10,308	9,866	9,294	9,288	9,952
Styrene	3,637		5,171	5,183	5,410	5,420	4,277	4,974	5,239
Methanol	3,785		5,743	5,860	5,303	4,876	3,402	3,289	3,166

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-methane 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 4-47) 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

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[12] 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 ($C_2H_2Cl_2$).

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 4-47: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	1990		1997	1998	1999	2000	2001	2002	2003
Primary Feedstock	1,864		2,450	2,530	2,563	2,521	2,339	2,398	2,331
Secondary Feedstock	302		378	397	410	415	408	379	388

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 4-48. Petrochemical production CH_4 emissions were estimated to be between 1.4 and 1.6 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 7 percent below to 7 percent above the emission estimate of 1.5 Tg CO_2 Eq. Petrochemical production CO_2 emissions were estimated to be between 2.8 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 10 percent below to 10 percent above the emission estimate of 2.8Tg CO_2 Eq.

Table 4-48: 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	2003 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(Tg CO_2 Eq.)	(Tg CO_2 Eq.)		(%)	

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CH_4	1.5	1.4	1.6	-7%	+7%
Petrochemical Production	CO_2	2.8	2.5	3.1	-10%	+10%

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

Recalculations Discussion

In previous inventories, CO_2 emissions from carbon black production were not calculated and reported separately in the Industrial Processes sector, but were included in the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels in the Energy sector. Although the CH_4 emissions from petrochemical production did not change for 1990 through 2002 compared to the previous Inventory, the addition of CO_2 emissions from carbon black production caused a large increase in petrochemical production emissions for every year of the time series. Overall, the change resulted in an average annual increase of 2.7 Tg CO_2 Eq. (183 percent) in combined CO_2 and CH_4 emissions from petrochemical production for the period 1990 through 2002.

4.12. Silicon Carbide Production (IPCC Source Category 2B4)

Methane is emitted from the production of silicon carbide, a material used as an industrial abrasive. To make silicon carbide (SiC), quartz (SiO_2) is reacted with carbon in the form of petroleum coke. During this reaction, methane 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 silicon carbide process are accounted for in the Non-energy Uses of Fossil Fuels section in the Energy Chapter. Emissions of CH_4 from silicon carbide production in 2003 were 0.4 Gg CH_4 (0.01 Tg CO_2 Eq.) (see Table 4-49).

Table 4-49: CH_4 Emissions from Silicon Carbide Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	+	1
1997	+	1
1998	+	1
1999	+	1
2000	+	1
2001	+	+
2002	+	+
2003	+	+

+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg

Methodology

Emissions of CH_4 were calculated by multiplying annual silicon carbide production by an emission factor (11.6 kg CH_4/metric ton silicon carbide). This emission factor was derived empirically from measurements taken at Norwegian silicon carbide plants (IPCC/UNEP/OECD/IEA 1997).

Production data for 1990 through 2003 (see Table 4-50) were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004).

Table 4-50: Production of Silicon Carbide (Metric Tons)

Year	Metric Tons
1990	105,000
1991	78,900

1992	84,300
1993	74,900
1994	84,700
1995	75,400
1996	73,600
1997	68,200
1998	69,800
1999	65,000
2000	45,000
2001	40,000
2002	30,000
2003	35,000

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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-51. Silicon carbide production CO_2 emissions were estimated to be between 0.008 and 0.01Tg 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 0.009 Tg CO_2 Eq.

Table 4-51: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Silicon Carbide Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Emission Estimate**	**Uncertainty Range Relative to Emission Estimate**[a]			
		(Tg CO_2 Eq.)	**(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Silicon Carbide Production	CO_2	+	+	+	-10%	+10%

[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.

4.13.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.

Nitrous oxide emissions from this source were estimated to be 15.8 Tg CO_2 Eq. (51.1 Gg) in 2003 (see Table 4-52). Emissions from nitric acid production have decreased by 11 percent since 1990, with the trend in the time series closely tracking the changes in production.

Table 4-52: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.8	58
1997	21.2	68
1998	20.9	67
1999	20.1	65
2000	19.6	63
2001	15.9	51
2002	17.2	56
2003	15.8	51

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emission factor was determined as a weighted average of 2 kg N_2O / metric ton HNO_3 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 4-53) was obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2001). Nitric acid production data for 1991 through 1992 (see Table 4-53) were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2002). Nitric acid production data for 1993 through 2003 were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2004). The emission factor range was taken from Choe et al. (1993).

Table 4-53: 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	6,388

Uncertainty

The uncertainties contained in these estimates are primarily due to the current organization within the nitric acid industry. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosives manufacturing. As a result, only a small quantity of nitric acid is sold on the market, making production quantities difficult to track. Emission factors are also difficult to determine because of the large number of plants using a diverse range of technologies.

The results of the Tier 1 quantitative uncertainly analysis are summarized in Table 4-54. Nitric acid production N_2O emissions were estimated to be between 13.2 and 18.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 17 percent above to below the 2003 emission estimate of 15.8 Tg CO_2 Eq.

Table 4-54: Tier 1 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**Year 2003 Emissions (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
Nitric Acid Production	N_2O	15.8	17%	13.2	18.5

Recalculations Discussion

The nitric acid production values for all years 1993 through 2002 were updated using newly published figures (C&EN 2004). Published figures remained consistent for all years of the historical time series except 2002. The updated production data for 2002 resulted in an increase of 0.5 Tg CO_2 Eq. (2.8 percent) in N_2O emissions from nitric acid production for that year.

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. Also, any large scale updates to abatement configurations would be useful in revising the national profile.

4.14. 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. 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. Nitrous oxide 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.[13] Only one small plant, representing approximately two percent of production, does not control for N_2O (Reimer 1999).

Nitrous oxide emissions from this adipic acid production were estimated to be 6.0 Tg CO_2 Eq. (19.4 Gg) in 2003 (see Table 4-55).

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[13] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

Table 4-55: N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	15.2	49
1997	10.3	33
1998	6.0	19
1999	5.5	18
2000	6.0	20
2001	4.9	16
2002	5.9	19
2003	6.0	19

National adipic acid production has increased by approximately 28 percent over the period of 1990 through 2003, 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. Measured estimates for 2003 were unavailable and, thus, were calculated by applying a 1.8 percent production growth rate representative of the industry (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 actual 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 MT of N_2O per MT of product (Thiemens and Trogler 1991). Emissions are estimated using the following equation:

N_2O emissions = [production of adipic acid (MT of adipic acid)] × [0.3 MT N_2O / mt adipic acid] × [1 – (N_2O destruction factor × 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.

In order to calculate emissions for the two plants where direct emissions measurements were not available, plant-specific production data needed to be estimated since it was unavailable due to reasons of confidentiality. 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.

National adipic acid production data (see Table 4-56) for 1990 through 2002 were obtained from the American Chemistry Council (ACC 2003). Production Data for 2003 were estimated based on an abstract from a Chemical Economics Handbook report entitled "*Adipic Acid*" indicating that production will increase by an annual average of 1.8 percent from year 2002 to 2006. 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 2003, the plant capacities for these three plants were kept the same as the year 2000 capacities. Plant capacity data for 1999 to 2003 for the one remaining plant was kept the same as 1998.

Table 4-56: 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	937

Uncertainty

The emission factor for adipic acid was based on experiments (Thiemens and Trogler 1991) that attempt to replicate the industrial process and, thereby, measure the reaction stoichiometry for N_2O production in the preparation of adipic acid. However, the extent to which the lab results are representative of actual industrial emission rates is not known.

The allocation of national production data for the two facilities where direct emission measurements were unavailable creates a degree of uncertainty in the adipic acid production data as all plants are assumed to operate at equivalent utilization levels as represented by their capacities. Also, plant capacity reference data is inconsistently available from year to year, which can affect the uncertainty of the allocated production through the time series.

A 5 percent uncertainty level was associated with the activity data available for the two plants that reported emissions. For the remaining two plants, a 20 percent uncertainty level was assumed for production. The emission factor uncertainty for each of these two plants was estimated separately to account for the differences in the use of abatement technologies. For the plant that uses no abatement technology, a 10 percent IPCC-default emission factor uncertainty was assumed appropriate. The abatement factor uncertainty used for the second plant was based on a 5 percent IPCC estimate for the N_2O destruction factor and an assumed 5 percent uncertainty in the abatement system utility factor (IPCC 2000). These two estimates result in an overall uncertainty associated with abatement potential of 7 percent. This abatement uncertainty, combined with the 10 percent IPCC default uncertainty value associated with the emissions factor for unabated emissions, results in an overall 12 percent emission factor uncertainty. Combining the reporting plants emissions uncertainty with the activity data uncertainty and the emission factor uncertainty for the remaining two plants yields an overall uncertainty for the inventory estimate equal to 9 percent of 2003 emissions (see Table 4-57).

The results of the Tier 1 quantitative uncertainly analysis are summarized in Table 4-57. Adipic acid production N_2O emissions were estimated to be between 5.5 and 6.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 9 percent above to below the 2003 emission estimate of 6.0 Tg CO_2 Eq.

Table 4-57: Tier 1 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	Year 2003	Uncertainty	Uncertainty Range Relative to

		Emissions (Tg CO_2 Eq.)	**(%)**	**2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
Adipic Acid Production	N_2O	6.0	9%	5.5	6.5

QA/QC and Verification

In addition to performing Tier 1 level QA/QC and verification, trends in the production of the synthetic nylon fibers industry were compared to trends in adipic acid production to confirm a reasonable agreement, since almost 90 percent of the adipic acid produced in the United States is used in the production of nylon 6,6.

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 QA 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.

4.15. 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.[14] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs, are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-58 and Table 4-59.

Table 4-58: Emissions of HFCs and PFCs from ODS Substitution (Tg CO_2 Eq.)

Gas	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
HFC-23	+	+	+	0.1	0.1	0.1	0.1	0.1
HFC-32	+	0.2	0.3	0.3	0.3	0.3	0.3	0.4
HFC-125	+	7.0	8.8	10.0	11.2	12.3	13.4	14.7
HFC-134a	+	31.4	36.7	42.2	48.0	52.7	56.9	60.5
HFC-143a	+	3.5	5.2	6.6	8.2	10.1	12.2	14.6
HFC-236fa	+	0.1	0.4	0.9	1.4	1.8	2.1	2.3
CF_4	+	+	+	+	+	+	+	+
Others*	0.4	4.2	5.2	5.7	5.9	6.1	6.5	6.9
Total	**0.4**	**46.5**	**56.6**	**65.8**	**75.0**	**83.3**	**91.5**	**99.5**

+ 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 4-59: Emissions of HFCs and PFCs from ODS Substitution (Mg)

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[14] [42 U.S.C § 7671, CAA § 601]

Gas	1990	1997	1998	1999	2000	2001	2002	2003
HFC-23	+	3	4	4	5	5	6	6
HFC-32	+	289	430	439	441	459	492	541
HFC-125	+	2,516	3,134	3,571	4,004	4,385	4,777	5,246
HFC-134a	+	24,136	28,202	32,491	36,888	40,512	43,798	46,559
HFC-143a	+	926	1,369	1,738	2,162	2,647	3,203	3,834
HFC-236fa	+	9	64	142	214	281	341	369
CF_4	+	+	1	1	1	1	2	2
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.[15] 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 99.5 Tg CO_2 Eq. in 2003. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

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 40 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

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[15] R-404A contains HFC-125, HFC-143a, and HFC-134a.

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 40 end-uses, but the uncertainty estimation was performed on only the top 14 end-uses, which account for 95 percent of emissions from this source category. 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, which necessitated these 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 results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-60. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 89.9 and 108.4 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 10 percent below to 10 percent above the emission estimate of 99.5 Tg CO_2 Eq.

Table 4-60: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitution (Tg CO_2 Eq. and Percent)

Source	**Gases**	**2003 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	99.5	89.9	108.4	-10%	+9%

[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 increase of less than 0.1 Tg CO_2 Eq. (4.1 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2002.

4.16. 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 rose 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.[16] Feedstock production, however, is permitted to continue indefinitely.

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[16] 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]

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, or may be captured for use in a limited number of applications.

Emissions of HFC-23 in 2003 were estimated to be 12.3 Tg CO_2 Eq. (1.1 Gg). This quantity represents a 38 percent decline from 2002 emissions and a 65 percent decline from 1990 emissions. Both declines are 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 2003, two of which used thermal oxidation to significantly lower their HFC-23 emissions.

Table 4-61: HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	35.0	3
1997	30.0	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

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; RTI 1997). Annual estimates of U.S. HCFC-22 production are presented in Table 4-62.

Table 4-62: HCFC-22 Production (Gg)

Year	Gg
1990	138.9
1991	142.7
1992	149.6
1993	132.4
1994	146.8
1995	154.7
1996	166.1
1997	164.5
1998	182.8

1999	165.5
2000	186.9
2001	152.4
2002	144.2
2003	138.0

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 4-63. HCFC-22 production HFC-23 emissions were estimated to be between 11.1 and 13.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 10 percent above and below the 2003 emission estimate of 12.3 Tg CO_2 Eq.

Table 4-63: Tier 1 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**Year 2003 Emissions (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
HCFC-22 Production	HFC-23	12.3	10%	11.1	13.6

Recalculations Discussion

The historical time series was adjusted to fully reflect reports from the Alliance for Responsible Atmospheric Policy. These changes resulted in an average annual decrease of less than 0.1 Tg CO_2 Eq. (0.01 percent) in HFC emissions from HCFC-22 through the period 1990 through 2002.

4.17. 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 2002). 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 14.1 Tg CO_2 Eq. (0.6 Gg) in 2003. This quantity represents a 52 percent decrease from the estimate for 1990 (see Table 4-64 and Table 4-65). This decrease, which is reflected in the atmospheric record (Maiss and Brenninkmeijer 2000), 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 4-64: SF_6 Emissions from Electric Power Systems and Original Equipment Manufactures (Tg CO_2 Eq.)

Year	**Electric Power Systems**	**Original Equipment Manufacturers**	**Total**
1990	28.9	0.3	**29.2**
1997	21.3	0.3	**21.7**
1998	16.7	0.4	**17.1**
1999	15.8	0.6	**16.4**

2000	15.0	0.7	**15.6**
2001	14.7	0.7	**15.4**
2002	14.0	0.7	**14.7**
2003	13.4	0.7	**14.1**

Table 4-65: SF_6 Emissions from Electric Power Systems and Original Equipment Manufacturers (Gg)

Year	Emissions
1990	1.2
1997	0.9
1998	0.7
1999	0.7
2000	0.7
2001	0.6
2002	0.6
2003	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 2003 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2003 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.) Between 1999 and 2003, participating utilities represented between 31 percent and 35 percent of total U.S. transmission miles. The emissions reported by participating utilities each year were added to the emissions estimated for non-reporting utilities in that year. Emissions from non-reporting utilities 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. As described further below, the transmission miles of the various types of non-reporting utilities were multiplied by the appropriate regression coefficients, yielding an estimate of emissions. Transmission miles are clearly physically related to emissions, since in the United States, SF_6 is contained primarily in transmission equipment rated at or above 34.5 kV.

The regression equations reflect two distinctions among non-reporting utilities: (1) between small and large utilities (i.e., with less or more than 10,000 transmission miles, respectively), and (2) between utilities that do not participate in the SF_6 Emission Reduction Partnership (non-partners) and those that participate but that have not reported in a given year (non-reporting partners). (Historically, these non-reporting partners have accounted for 5 percent or less of total estimated partner emissions.) The distinction between small and large utilities was made because the regression analysis showed that the relationship between emissions and transmission miles differed for small and large facilities. The distinction between non-partners and non-reporting partners was made because the emission trends of these two groups were believed to be different. Reporting partners have reduced their emission rates significantly since 1999. The emission trend of non-reporting partners was believed to be similar to that of the reporting partners, because all partners commit to reducing SF_6 emissions through technically and economically feasible means. However, non-partners were assumed not to have implemented any changes that would have reduced emissions over time.

To estimate emissions from non-partners in every year since 1999, the following regression equations were used. These 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):

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):

$$\text{Emissions} = 0.558 \times \text{Transmission Miles}$$

To estimate emissions from non-reporting partners in each year, the regression equations based on the emissions reported by partners in that year were used. To estimate non-reporting partner emissions in 2003, the regression equations were based on the 2003 SF_6 emissions reported by 51 partner utilities, and updated 2003 transmission mileage data obtained from the 2004 UDI Directory of Electric Power Producers and Distributors (UDI 2004). The resulting equations for 2003 are:

Non-reporting partner small utilities (less than 10,000 transmission miles, 2003, in kilograms):

$$\text{Emissions} = 0.398 \times \text{Transmission Miles}$$

Non-reporting partner large utilities (more than 10,000 transmission miles, 2003, in kilograms):

$$\text{Emissions} = 0.387 \times \text{Transmission Miles}$$

As indicated from the 2001 and 2004 UDI Directories of Electric Power Producers and Distributors (UDI 2001, 2004), the U.S. transmission system has grown by over 14,000 miles between 2000 and 2003. To reflect the fact that this increase probably occurred gradually, transmission mileage was assumed to increase exponentially at an annual rate of approximately 0.7 percent during the 2000 to 2003 time period.

For each year, total emissions were then determined by summing the partner-reported emissions, the non-reporting partner emissions (determined with that year's regression equation for the partners), and the non-partner emissions (determined using the 1999 regression equation).

1990 to 1998 Emissions from Manufacture of Electric Equipment

Because most participating utilities reported emissions only for 1999 through 2003, 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 report, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2001):

$$\text{Emissions (kilograms)} = SF_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity of retiring equipment (kilograms)}$$

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 hexaflouride 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 (2002) survey. To estimate the quantity of SF_6 released 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 2001). The 30-year lifetime for electrical equipment is also drawn from IPCC (2001). 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 15.8 Tg CO_2 Eq.).

1990 to 2003 Emissions from Manufacture of Electrical Equipment

The 1990 to 2003 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 2003 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

For electric power systems, individual partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. This uncertainty was assumed to incorporate potential errors associated with the weighing of SF_6 cylinders and the tracking of SF_6 purchases and use. Using error propagation, the cumulative uncertainty of all partner-reported data was estimated to be 5 percent.

There are two sources of uncertainty associated with the regression equations used to extrapolate U.S. emissions from participant reports: 1) uncertainty in the coefficients (as defined by the regression standard error estimate); and 2) the uncertainty in total transmission miles for non-partners and non-reporting partners, which is assumed to be 10 percent. In addition, there is also uncertainty in the basic assumption that all non-reporting partners will follow the trend defined by reporting partners in a specific year, as well as uncertainty that the emission factor used for utilities that were not participants, which accounted for approximately 65 percent of U.S. transmission miles, will remain at levels defined by partners who reported in 1999. However, neither of these uncertainties was modeled.

For OEMs, uncertainty estimates are based on the assumption that SF_6 statistics obtained from NEMA have an uncertainty of 10 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 emission estimate for SF_6 from electrical transmission and distribution. For each defined parameter (i.e., equation coefficient, transmission mileage, and partner-specific 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 4-67. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 12.3 and 16.1 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 13 percent below and 14 percent above the emission estimate of 14.1 Tg CO_2 Eq.

Table 4-66: Simulated Variables for Tier 2 Uncertainty Analysis

Parameter	Probability Distribution	Uncertainty[a] (%)
Total Partner-Reported SF_6 Data (kg SF_6)	Normal	5
Coefficient – Small Utilities, Non-Partners	Normal	11
Coefficient – Large Utilities, Non-Partners	Normal	21
Coefficient – Small Utilities, Non-Reporting Partners	Normal	21
Coefficient – Large Utilities, Non-Reporting Partners	Normal	NA[b]
Transmission Miles – Small Utilities, Non-Partners	Normal	10

Transmission Miles – Large Utilities, Non-Partners	Normal	10
Transmission Miles – Small Utilities, Non-Reporting Partners	Normal	10
Transmission Miles – Large Utilities, Non-Reporting Partner	Normal	NA[b]
OEM SF_6 Emission Rate (percent)	Normal	65
SF_6 Charged to Equipment (kg SF_6)	Normal	10

[a] Reflects a 95 percent confidence interval.

[b] Not applicable. In 2003, all large utility partners reported to the SF_6 Emission Reduction Partnership.

Table 4-67: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to 2003 Emission Estimate[a]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Electrical Transmission and Distribution	SF_6	14.1	12.3	16.1	-13%	+14%

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

Recalculations Discussion

Electric power system emission estimates for the years 2000, 2001 and 2002 were recalculated based on a combination of additional historical partner data and the incorporation of more up-to-date transmission mileage data. For historical partner submissions, the regression equations for each respective year were updated and new extrapolations to non-reporting partners were made. Additionally, recalculations were conducted using updated transmission mileage data, which reflect the growth of the U.S. transmission system. Previously-reported 2001 and 2002 emission estimates had utilized the 2001 UDI Directory of Electric Power Producers and Distributors (UDI 2001) for transmission mileage data (i.e., 2000 data). As mentioned above, transmission mileage data for 2001 and 2002 were adjusted to account for increases in transmission mileage during this period. These adjustments have been incorporated in non-reporting partner regression equation re-calculations, resulting in revised estimates of non-partner and non-reporting partner emissions. The combination of these changes resulted in an average annual decrease of less than 0.1 Tg CO_2 Eq. (0.2 percent) in SF_6 emissions from electrical transmission and distribution for the period 2000 through 2002.

4.18. Aluminum Production (IPCC Source Category 2C3)

Aluminum is a light-weight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. In 2003, the United States was the third largest producer of primary aluminum, with 10 percent of the world total (USGS 2004). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of CO_2 and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a 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 4.2 Tg CO_2 Eq. (4,219 Gg) in 2003 (see Table 4-68). 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 4-68: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	6.3	6,315
1997	5.6	5,621
1998	5.8	5,792
1999	5.9	5,895
2000	5.7	5,723
2001	4.1	4,114
2002	4.2	4,220
2003	4.2	4,219

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, 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, a corresponding rise in emission levels occurs.

Emissions of PFCs from primary aluminum production are estimated to have declined 79 percent since 1990. Since 1990, emissions of CF_4 and C_2F_6 have declined 80 percent and 77 percent, respectively, to 3.3 Tg CO_2 Eq. of CF_4 (0.5 Gg) and 0.5 Tg CO_2 Eq. of C_2F_6 (0.1 Gg) in 2003, as shown in Table 4-69 and Table 4-70. This decline was 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.

Table 4-69: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	16.1	2.3	18.3
1997	9.8	1.2	11.0
1998	8.1	1.0	9.1
1999	8.0	0.9	9.0
2000	8.1	0.9	9.0
2001	3.5	0.5	4.0
2002	4.5	0.7	5.2
2003	3.3	0.5	3.8

Note: Totals may not sum due to independent rounding.

Table 4-70: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.5	0.2
1997	1.5	0.1
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

U.S. primary aluminum production for 2003—totaling 2.7 million metric tons—remained similar to 2002 production levels. 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 current production levels that were nearly 26 percent lower than 2000 levels in 2003. The transportation industry remained the largest domestic consumer of primary aluminum, accounting for about 35 percent of U.S. consumption (USGS 2004).

Methodology

Carbon dioxide is generated during alumina reduction to aluminum metal following the reaction below:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

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 Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) 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). Based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, production was assumed to be split 80 percent prebake and 20 percent Soderberg for the whole time series.

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 2002, smelter-specific coefficients were available and were used for 12 out of the 23 U.S. smelters. To estimate 2003 emissions, smelter-specific coefficients were available and were used for 6 out of the 17 operating U.S. smelters. For the remaining 11 operating smelters, technology-specific slope coefficients from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2001) were applied. The slope coefficients were combined with smelter-specific anode effect data, collected by aluminum companies and reported to the VAIP, to estimate emission factors over time. In 2003, smelter-specific anode effect data was available for 15 of the 17 operating smelters. Where smelter-specific anode effect data were not available (i.e., 2 out of 17 smelters in 2003, 2 out of 23 smelters between 1990 and 2002), industry averages were used. For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. In 2003, smelter-specific production data was available for 16 of the 17 operating smelters; production at the one remaining smelter was estimated based on national aluminum production and capacity data (USGS). Between 1990 and 2003, 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 *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2001).

National primary aluminum production data for 1990 through 2001 (see Table 4-71) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002). For 2002 and 2003, national aluminum production data were obtained from the United States Aluminum Association's *Primary*

Aluminum Statistics (USAA 2004). The CO_2 emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 4-71: 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

Uncertainty

The overall uncertainty associated with the 2003 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, and 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 emissions estimate for the U.S. aluminum industry as a whole and the results are provided below.

In determining uncertainty associated with emissions of CF_4 and C_2F_6, for each smelter, uncertainty associated with the quantity of aluminum produced and the frequency and duration of anode effects was estimated. 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. Data on anode effect frequency and duration and production 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. The uncertainty of the anode effect frequency was assumed to be 2 percent if the data was reported; however, if the data was estimated, the uncertainty ranged from 33 to 78 percent, depending on the smelter technology type. Similarly, the uncertainty in anode effect duration was assumed to be 5 percent for data that was reported, but between 28 and 70 percent for data that was estimated. The uncertainty ranges for estimated technology-specific anode effect frequency and duration are based on the standard deviation of reported anode-effect frequency and duration in the International Aluminum Institute's anode effect survey (IAI 2000).

Additionally, for CF_4 and C_2F_6 emission estimates, uncertainties associated with slope coefficients were calculated. Data for the slope coefficients are assumed to be characterized by a normal distribution. 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 4-72. Aluminum production CO_2 emissions were estimated to be between 2.8 and 5.9 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 34 percent below to 40 percent above the emission estimate of 4.2 Tg CO_2 Eq. Also at the 95 percent confidence interval, aluminum production CF_4 emissions were estimated to be between 2.9 and 3.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below to 11 percent above the emission estimate of 3.3 Tg CO_2 Eq. Finally aluminum production C_2F_6 emissions were estimated to be between 0.46 and 0.59 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below to 13 percent above the emission estimate of 0.5 Tg CO_2 Eq.

Table 4-72: Tier 2 Quantitative Uncertainty Estimates for PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to 2003 Emission Estimate**[a]			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Aluminum Production	CO_2	4.2	2.8	5.9	-34%	+40%
Aluminum Production	CF_4	3.3	2.9	3.7	-11%	+11%
Aluminum Production	C_2F_6	0.5	0.5	0.6	-12%	+13%

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

Occasionally, SF_6 may be used by the aluminum industry as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. In its application as a cover gas, SF_6 is mixed with nitrogen or CO_2 and injected above the surface of molten aluminum. As a fluxing and degassing agent, SF_6 is mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum. These practices are not employed extensively by primary aluminum producers and are generally isolated to secondary casting firms. The aluminum industry in the United States and Canada has been estimated to use 230 metric tons of SF_6 per year (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

Historically, SF_6 from aluminum activities has 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). Emissions are considered to be insignificant, given that 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).

Emissions of SF_6 from aluminum fluxing and degassing have not been estimated. Uncertainties exist as to the quantity of SF_6 used by the aluminum industry and its rate of destruction in its uses as a degassing agent or cover gas.

Recalculations Discussion

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, as well as measurements conducted at three U.S. aluminum smelters. The measurements were part of an EPA-funded study to determine facility-specific slope coefficients. Consequently, these coefficients were used instead of IPCC defaults to calculate smelter-specific emission factors. These data were provided in cooperation with participants in the VAIP program. The combination of these changes resulted in an average annual increase of less than 0.1 Tg CO_2 Eq. (0.2 percent) in PFC emissions from aluminum production for the period 1990 through 2002.

Carbon dioxide emission estimates from aluminum production for 2002 were updated to include aluminum production data from the USAA. Previous CO_2 emission estimates for 2002 were based on aluminum production data from the USGS. This change resulted in a decrease in CO_2 emissions from aluminum production of less than 0.1 Tg CO_2 Eq. (less than -0.1 percent) for 2002.

4.19. 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 a 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 2003, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 4.3 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-73 and Table 4-74 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 48 percent since 1990. The emissions growth rate began to slow after 1997, and emissions declined by 40 percent between 1999 and 2003. This decline is due both to a drop in production (with a continuing decline in silicon consumption) and to the initial implementation of PFC emission reduction methods such as process optimization.

Table 4-73: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CF_4	0.7		1.6	1.8	1.8	1.8	1.3	1.1	1.0
C_2F_6	1.5		3.2	3.6	3.7	3.0	2.1	2.2	2.1
C_3F_8	0.0		0.0	0.0	0.0	0.1	0.1	0.1	0.1
C_4F_8	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.1
HFC-23	0.2		0.4	0.4	0.4	0.3	0.2	0.2	0.2
SF_6	0.5		1.1	1.3	1.3	1.1	0.8	0.7	0.8
NF_3*	0.0		0.1	0.1	0.1	0.1	0.1	0.3	0.2
Total	**2.9**		**6.3**	**7.1**	**7.2**	**6.3**	**4.5**	**4.4**	**4.3**

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 4-74: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Year	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**

CF_4	115		245	277	281	281	202	175	161
C_2F_6	160		347	391	397	324	231	244	228
C_3F_8	0		0	0	0	17	14	9	13
C_4F_8	0		0	0	0	0	0	5	8
HFC-23	15		33	37	37	23	16	15	17
SF_6	22		48	54	55	46	31	28	35
NF_3	3		8	9	9	11	12	32	30

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 & Beizaie 2001).[17] 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 decreases as layers increase), and (2) product type (memory vs. logic). PEVM derives historical consumption of silicon (i.e., square centimeters) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI 2003a,b,c). 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 (International SEMATECH 1998-2003). 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 & Lieberman 2004). 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 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.

The U.S. estimate for the years 2000 through 2003—the period during which partners began the consequential application of PFC-reduction measures—used a different estimation method. The emissions reporting 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.

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

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[17] The most recent version of this model is v.3.1.0306.0304r, completed in March 2004.

manufacturers during this period and the application of IPCC default emission factors for each gas. For the 2000 through 2003 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 emissions for 2000 through 2003 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.

Partners estimate their emissions using a range of methods. For 2003, most participants cited a method at least as accurate as the IPCC's Tier 2c Methodology, recommended in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (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 International (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 to 2003). Estimates of silicon consumed by line-width from 1990 through 2003 were derived from information from VLSI Research (2003d), and the number of layers per line-width was obtained from International SEMATECH's *International Technology Roadmap: 1998 – 2003.*

Uncertainty

Quantitative uncertainty of this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique. Uncertainty is associated with the emission estimates reported by the Partners, with the estimated share of total layer-weighted silicon capacity in 2003 attributable to the Partners, and with the total U.S. PFC emissions estimate as determined by PEVM.

The Monte Carlo analysis presented below relied on estimates of uncertainty attributed to these three variables. 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 ±10 percent (representing a 95 percent confidence interval). This value accounts for uncertainty in partners' estimates of gas-volume usage, and was calculated using 2003 Partnership submittals. Through expert judgment and review of the emission reports submitted by companies under the Partnership agreement, the relative uncertainties were assumed to be the same for each submittal in 2003, equal to ±29 percent of the individual Partner's reported value. Under that assumption, uncertainty propagated across all Partners resulted in a combined relative uncertainty equal to about 10 percent of the aggregate emissions reports under the Partnership. For the second variable, the share of U.S. layer-weighted silicon capacity accounted for by non-Partners, an uncertainty of ±36 percent was estimated based on the variability of the share over the period 1995 through 2003.

For the third variable, the relative error associated with the PEVM estimate in 2003, EPA estimated an uncertainty of ±44 percent, using the calculus of error propagation and considering the aggregate average emission factor, world silicon consumption, the U.S. share of layer-weighted silicon capacity, and the number of layers. The uncertainty associated with the aggregate average emission factor was estimated to be 15 percent based on the variability exhibited by the emission factor from 1996 through 1999. The uncertainty associated with the U.S. share of capacity was estimated to be 10 percent based on information from the firm that compiled the database; the principal source of errors was determined to be incomplete e-mail and telephone surveys of manufacturers (SMA 2003). The uncertainty associated with silicon consumption data was estimated to be 10 percent, based on the reliability of industry surveys of world silicon consumption by technology node. Finally, the uncertainty associated with the number of layers was estimated to be 39 percent.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-75. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 3.7 and 5.7 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 20 percent below to 23 percent above the emissions estimate of 4.6 Tg CO_2 Eq. It should be noted that this range and the associated percentages apply to the estimate of total emissions rather than those of individual gases.

Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table 4-75: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Emission Estimate[a] (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[b]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Semiconductor Manufacture	HFC, PFC, and SF_6	4.6	3.7	5.7	-20%	+23%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-73.

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

Planned Improvements

The method by which non-partner related emissions are estimated (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.)

4.20. 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 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 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 3.0 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2003 (see Table 4-76). This represents a 12 percent increase from 2002. The increase is attributable to a 1.5 percent rise in production and casting levels and to a 10.5 percent increase in the weighted-average SF_6 usage rate at these facilities. There are no significant plans for expansion of primary magnesium production in the United States, but demand for magnesium metal by U.S. casting companies has grown as auto manufacturers design more lightweight magnesium parts into vehicle models. In the last ten years, the quantity of magnesium used in North American-produced vehicles has doubled (USGS 2004a). Foreign magnesium producers are expected to meet the growing U.S. demand for primary magnesium (USGS 2004a).

Table 4-76: 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
1997	6.3	0.3
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

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 over 80 percent of the casting sector (i.e., die, gravity, wrought, and anode casting). Emissions for 1999 through 2003 from primary production, some secondary production (i.e., recycling), and a large fraction of die casting were reported by participants. The 1999 through 2003 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 five major processes (other than primary production) that require SF_6 melt protection: 1) secondary production; 2) die casting; 3) gravity casting; 4) wrought products; and 5) anodes. The emission factors are provided below in Table 4-77. Because only one primary producer existed in the United States in 2003, the emission factor for primary production is withheld to protect production information. However, the emission factor has not risen above the 1995 value of 1.1 kg SF_6 per metric ton.

Die casting emissions for 1999 through 2003, 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 2003, 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, gravity, wrought, and anode casting) were based on discussions with industry representatives.

Table 4-77: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Secondary	Die Casting	Gravity	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

[a] The 1999 factor is 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 2003 were available from the USGS (USGS 2002, 2003, 2004b). 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 2002). The emission factors for the other processes (i.e., secondary production, and gravity, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-65.

Uncertainty

An uncertainty of 5 percent was assigned to the SF_6 emissions data reported by each participant in the SF_6 Emission Reduction Partnership. These data have low uncertainty since they are prepared through facility-specific tracking of SF_6 cylinder purchases, usage, and returns. 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. For example, to estimate 2003 emission factors, the average change in emission factor from 2002 to 2003 for reporting partners was applied to the 2002 emission factor of the non-reporting partner. The uncertainty associated with the extrapolated emission factor was assumed to be 25 percent. For production data, if estimates were unavailable for the current reporting year, data from the last reported year was applied.

For 2003, the uncertainty associated with this approach was assumed to be 30 percent. Between 1999 and 2003, 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 gravity, anode, and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and an estimated process-specific emission factor (see Table 4-78). The uncertainty associated with USGS-reported statistics and emission factors were assumed to be 25 percent and 75 percent, respectively. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Table 4-78: Simulated Variables for Tier 2 Uncertainty Analysis

Parameter	Probability Distribution	Uncertainty[a] (%)
Partner-Reported SF_6 Data (kg SF_6)	Normal	5
SF_6 Emission Factor for Non-Reporting Partners (kg SF_6/metric ton Mg)	Normal	25
Production Data for Non-Reporting Partners (metric ton Mg)	Normal	30
USGS Production Data for Gravity, Anode, Wrought Casting and Secondary Production (metric ton Mg)	Normal	25
SF_6 Emission Factor for Gravity, Anode, Wrought Casting and Secondary Production (kg SF_6/metric ton Mg)	Normal	75

[a] Reflects a 95 percent confidence interval.

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.

A Monte Carlo analysis was applied to estimate the overall uncertainty of the emission estimate for the U.S. magnesium industry. Random variables were selected from the probability density functions for each parameter, which were assumed to be characterized by normal distributions. In the cases of estimates developed from partners and non-reporting partners, probability density functions were applied to parameters (i.e., SF_6 emissions data, emission factors and production data) at the facility-specific level. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-79. Magnesium production and processing SF_6 emissions were estimated to be between 2.6 and 3.3 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 to 13 percent above the emission estimate of 3.0 Tg CO_2 Eq.

Table 4-79: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	Gas	2003 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2003 Emission Estimate[a]	
			(Tg CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production and Processing	SF_6	3.0	2.6	3.3	-11%	+13%

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

Recalculations Discussion

The emission estimates for 2000, 2001, and 2002 were adjusted upward slightly from the previously reported values. This revision reflects an update to historical data supplied by partnership participants and the USGS. The changes resulted in an average annual increase of less than 0.1 Tg CO_2 Eq. (4.1 percent) in SF_6 emissions from magnesium production and processing for the period 2000 through 2002.

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 2001) 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 gravity 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 4-80 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.[18] 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 2003, 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 4-80: 2003 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	181.0	99.5
Aluminum Production	-	3.8
HCFC-22 Production	-	12.3
Semiconductor Manufacture	6.6	4.3
Magnesium Production and Processing	3.0	3.0
Electrical Transmission and Distribution	21.8	14.1

- Not applicable.

[END BOX]

4.21. Industrial Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of ambient air pollutants. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 2003 are reported in Table 4-81.

Table 4-81: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
NO_x	**591**		**629**	**637**	**595**	**626**	**656**	**630**	**648**
Chemical & Allied Product Manufacturing	152		115	117	93	95	97	95	92
Metals Processing	88		81	81	78	81	86	76	83
Storage and Transport	3		15	15	13	14	15	14	14
Other Industrial Processes	343		417	424	409	434	457	442	457
Miscellaneous*	5		1	1	2	2	1	3	2
CO	**4,124**		**3,153**	**3,163**	**2,156**	**2,217**	**2,339**	**2,308**	**2,431**
Chemical & Allied Product Manufacturing	1,074		971	981	317	327	338	306	299
Metals Processing	2,395		1,551	1,544	1,138	1,175	1,252	1,174	1,290
Storage and Transport	69		64	65	148	154	162	195	219
Other Industrial Processes	487		528	535	518	538	558	576	575
Miscellaneous*	101		38	38	35	23	30	57	49

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[18] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

NMVOCs	**2,426**		**2,038**	**2,047**	**1,813**	**1,773**	**1,769**	**1,725**	**1,711**
Chemical & Allied Product Manufacturing	575		352	357	228	230	238	194	198
Metals Processing	111		71	71	60	61	65	62	65
Storage and Transport	1,356		1,205	1,204	1,122	1,067	1,082	1,093	1,069
Other Industrial Processes	364		397	402	398	412	381	369	374
Miscellaneous*	20		13	13	6	3	4	7	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 2004), 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.

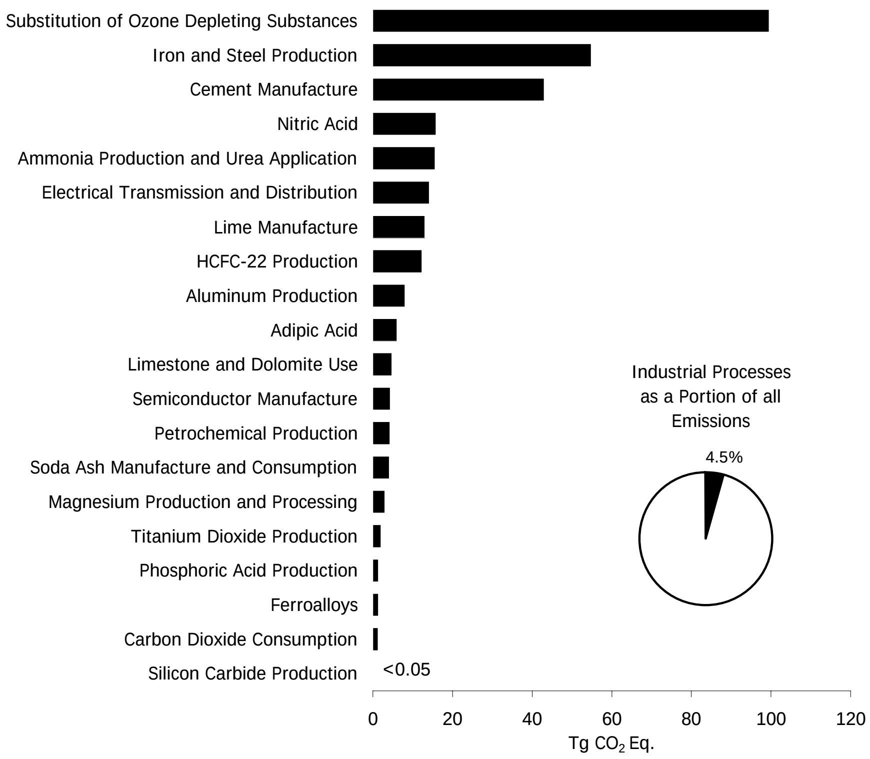

Figure 4-1: 2003 Industrial Processes Chapter Greenhouse Gas Sources

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 2003 (see Table 5-1). Ambient air pollutant emissions also result from solvent and other product use, and are presented in Table 5-2.

Table 5-1: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq. and Gg)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
Nitrous Oxide Product Usage								
Tg CO_2 Eq.	4.3	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Gg	13.9	15.4	15.4	15.4	15.4	15.4	15.4	15.4

Table 5-2: Ambient Air Pollutant Emissions from Solvent and Other Product Use (Gg)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
NO_x	**1**	**3**	**3**	**3**	**3**	**3**	**5**	**4**
CO	**4**	**1**	**1**	**46**	**46**	**45**	**46**	**65**
NMVOCs	**5,217**	**5,100**	**4,671**	**4,569**	**4,384**	**4,547**	**4,256**	**4,138**

5.1. *Nitrous Oxide Product Usage (IPCC Source Category 3D)*

Nitrous oxide is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. Nitrous oxide 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).

Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. 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 2003 was approximately 17 Gg. Nitrous oxide emissions were 4.8 Tg CO_2 Eq. (15.4 Gg) in 2003 (see Table 5-3). Production of N_2O has stabilized over the past decade because medical markets have found other substitutes for anesthetics, and more medical procedures are 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 Nitrous Oxide Product Usage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.3	13.9
1997	4.8	15.4
1998	4.8	15.4

1999	4.8	15.4
2000	4.8	15.4
2001	4.8	15.4
2002	4.8	15.4
2003	4.8	15.4

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:

> Nitrous Oxide Product Usage Emissions = $\sum_i$ [Total U.S. Production of Nitrous Oxide] × [Share of Total Quantity of N_2O Usage by Sector i] × [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 2002, and also assumed for 2003, 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 (Tupman 2002). 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. Once the N_2O is allocated across these subcategories, a usage emissions rate is then applied for each sector to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories are estimated to release emissions into the atmosphere, and therefore these subcategories are 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 is 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 is 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) was able to provide 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 2003 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 2003). Share of total quantity of N_2O usage data for 2003 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	16.3
1991	15.9
1992	15.0
1993	17.0
1994	17.0
1995	17.0
1996	17.0
1997	17.0
1998	17.0
1999	17.0
2000	17.0
2001	17.0
2002	17.0
2003	17.0

Uncertainty

Since plant-specific N_2O production data is confidential, emissions are based on national production statistics acquired as ranges through reports and interviews with industry experts Heydorn (1997) and Tupman (2002). Based on these ranges, the uncertainty associated with the production estimate that was used to develop industry emissions in 2003 was calculated. Information regarding the industry-specific use of N_2O is confidential. Thus, the predicted share of the total quantities of N_2O used by each subcategory is somewhat uncertain because they are also based on industry expert opinion.

While the level of certainty differs by industry, the minimum and maximum market shares, expressed as a percent of N_2O usage, are within 2 to 3 percentage points of the estimated market share. The emissions rate for the medical/dental industry, an estimate also based on industry opinion, carries an uncertainty level of 3 percent. Unquantified areas of uncertainty include the schedule of the market decline of sodium azide production.

An uncertainty analysis, based on the Tier 1 methods found in IPCC's *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories,* was conducted for all inputs to the N_2O Product Usage source category analysis, including activity data, subcategory shares of N_2O consumption, and emission factors. The results of the Tier 1 quantitative uncertainly analysis are summarized in Table 5-5. N_2O Product Usage N_2O emissions were estimated to be between 4.4 and 5.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 7 percent above and below the 2003 emission estimate of 4.8 Tg CO_2 Eq.

Table 5-5: Tier 1 Quantitative Uncertainty Estimates for N_2O Emissions from Nitrous Oxide Product Usage (Tg CO_2 Eq. and Percent)

IPCC Source Category	**Gas**	**Year 2003 Emissions (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
N_2O Product Usage	N_2O	4.8	7%	4.4	5.1

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. Ambient Air Pollutants from Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., ambient air pollutants).[1] Nonmethane 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 (NOx), are also reported with this source category. Surface coatings accounted for approximately 41 percent of NMVOC emissions from solvent use in 2003, while "non-industrial"[2] uses accounted for about 38 percent and degreasing applications for 7 percent. Overall, solvent use accounted for approximately 28 percent of total U.S. emissions of NMVOCs in 2003; NMVOC emissions from solvent use have decreased 21 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 2003 are reported in Table 5-6.

Table 5-6: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1997	1998	1999	2000	2001	2002	2003
NO_x	**1**	**3**	**3**	**3**	**3**	**3**	**5**	**4**
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	1	1	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+	+
Surface Coating	1	2	2	3	3	3	5	4
Other Industrial Processes[a]	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+	+
CO	**4**	**1**	**1**	**46**	**46**	**45**	**46**	**65**
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+	+
Surface Coating	+	1	1	46	46	45	46	65
Other Industrial Processes[a]	4	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+	+
NMVOCs	**5,217**	**5,100**	**4,671**	**4,569**	**4,384**	**4,547**	**4,256**	**4,138**
Degreasing	675	566	337	363	316	331	310	301
Graphic Arts	249	266	272	224	222	229	214	208
Dry Cleaning	195	148	151	267	265	272	254	247

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[1] Solvent usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in the Industrial Processes chapter.

[2] "Non-industrial" uses include cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Surface Coating	2,289		2,228	1,989	1,865	1,767	1,863	1,744	1,695
Other Industrial Processes[a]	85		100	101	95	98	103	97	94
Non-Industrial Processes[b]	1,724		1,790	1,818	1,714	1,676	1,707	1,598	1,554
Other	+		3	3	40	40	42	40	38

[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 2004), 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 Change and Forestry sector. Carbon dioxide emissions from on-farm energy use are accounted in the Energy chapter.

Figure 6-1: 2003 Agriculture Chapter Greenhouse Gas Emission Sources

In 2003, the agricultural sector was responsible for emissions of 433.3 Tg CO_2 Eq., or 6.3 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent about 21 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 crop 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 67 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2003, CH_4 emissions from agricultural activities increased by 3.2 percent while N_2O emissions increased by 0.7 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the ambient air pollutants carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**156.9**	**163.0**	**164.2**	**164.6**	**162.0**	**161.9**	**161.5**	**161.8**
Enteric Fermentation	117.9	118.3	116.7	116.8	115.6	114.5	114.6	115.0
Manure Management	31.2	36.4	38.8	38.8	38.1	38.9	39.3	39.1
Rice Cultivation	7.1	7.5	7.9	8.3	7.5	7.6	6.8	6.9
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.8
N_2O	**269.6**	**269.8**	**285.6**	**261.3**	**282.1**	**275.6**	**270.9**	**271.5**
Agricultural Soil Management	253.0	252.0	267.7	243.4	263.9	257.1	252.6	253.5
Manure Management	16.3	17.3	17.4	17.4	17.8	18.0	17.9	17.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.4	0.5	0.5	0.4	0.4
Total	**426.5**	**432.8**	**449.8**	**425.9**	**444.1**	**437.5**	**432.4**	**433.3**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**7,470**	**7,760**	**7,821**	**7,838**	**7,713**	**7,708**	**7,689**	**7,705**
Enteric Fermentation	5,612	5,634	5,557	5,561	5,505	5,454	5,458	5,475
Manure Management	1,485	1,733	1,850	1,846	1,813	1,853	1,873	1,864
Rice Cultivation	339	356	376	395	357	364	325	328
Field Burning of Agricultural Residues	33	37	38	37	38	37	34	38
N_2O	**870**	**870**	**921**	**843**	**910**	**889**	**874**	**876**

Agricultural Soil Management	816	813	864	785	851	829	815	818
Manure Management	52	56	56	56	57	58	58	57
Field Burning of Agricultural Residues	1	1	1	1	1	1	1	1
CO	**689**	**767**	**789**	**767**	**790**	**770**	**706**	**794**
NO_x	**28**	**34**	**35**	**34**	**35**	**35**	**33**	**33**

Note: Totals may not sum due to independent rounding.

6.1. Enteric Fermentation (IPCC Source Category 4A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a 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 affect 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.

Methane emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2003 were 115 Tg CO_2 Eq. (5,475 Gg), increasing very slightly since 2002 due to minor increases 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 72 percent in 2003. Emissions from dairy cattle in 2003 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2003, emissions from enteric fermentation have decreased by 2 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 and goats have also decreased, while horse populations increased and the populations of swine fluctuated.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Beef Cattle	83.2	86.6	85.0	84.9	83.4	82.4	82.3	82.5
Dairy Cattle	28.9	26.4	26.3	26.6	27.0	26.9	27.1	27.3
Horses	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.3	1.3	1.2	1.2	1.2	1.1	1.1
Swine	1.7	1.8	2.0	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**117.9**	**118.3**	**116.7**	**116.8**	**115.6**	**114.5**	**114.6**	**115.0**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Beef Cattle	3,961	4,124	4,047	4,045	3,973	3,923	3,919	3,930
Dairy Cattle	1,375	1,255	1,251	1,265	1,283	1,282	1,290	1,300
Horses	91	93	94	93	94	95	95	95
Sheep	91	64	63	58	56	56	53	50
Swine	81	88	93	90	88	88	90	90
Goats	13	10	10	10	10	10	10	10
Total	**5,612**	**5,634**	**5,557**	**5,561**	**5,505**	**5,454**	**5,458**	**5,475**

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., 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 emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.9. These variables include performance factors such as pregnancy and lactation, as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a,b, 1999a,c,d,f, 2000a,c,d,f, 2001a,c,d,f, 2002a,c,d,f, 2003a,c,d,f, 2004a,c,d,f).

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., calves, heifer replacements, cows, etc.), and production (i.e., pregnant, lactating, etc.) 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. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2003. 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, as well as feedlot placement information were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f, 2002a-f, 2003a-f, 2004a-f). Horse population data were obtained from the FAOSTAT database (FAO 2004), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained from the Census of Agriculture (USDA 1999g). Methane 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

Uncertainty estimates were developed for the emission estimates presented in EPA (2003). No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2003 activity data and emission factor input variables. Consequently, the EPA (2003) uncertainty estimates were directly applied to the 2003 emission estimates.

A total of 185 primary input variables (178 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. A triangular distribution was assigned for three input variables (specifically cow-birth ratios for the current and the past two years). 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 no larger in magnitude than plus or minus 10 percent. However, for many emission factor-related input variables, the lower- and/or upper-bound uncertainty estimates were over 20 percent. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-5. Enteric fermentation CH_4 emissions in 2003 were estimated to be between 102.3 and 135.7 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 11 percent below to 18 percent above the 2003 emission estimate of 115.0 Tg CO_2 Eq. Among the individual sub-source categories, beef cattle accounts for the largest amount of CH_4 emissions as well as the largest degree of uncertainty in the emission estimates. Consequently, the cattle sub-source categories together contribute to the largest degree of uncertainty to the estimates of CH_4 emissions from livestock enteric fermentation. Among non-cattle, horses account for the largest degree of uncertainty in the emission estimates.

Table 6-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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**
Enteric Fermentation	CH_4	115.0	102.3	135.7	-11%	+18%

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

QA/QC and Verification

In order to ensure the quality of the emission estimates 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 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 historical data. USDA published revised population estimates in 2004 for some cattle statistics; these include population, livestock placements, and slaughter statistics for 2000, 2001, and 2002. Emission estimates changed for these years for both beef and dairy cattle as a result of revised inputs that reflect USDA updates.

The rate of weight gain for growing steers and heifers was increased for the modeling of 2000 through 2003. The model uses the weight gain data to estimate the number of cattle (steers and heifers) available to be placed into feedlots (by weight class). These estimates were compared to the USDA statistics on actual feedlot placements (by weight class). The updated USDA data show increases in feedlot placements in the heavy weight classes, and required an increase in the rate of weight gain in the modeled population in order to match the observed statistics. Additionally, the distribution of cattle by weight at the start of the year was adjusted to reflect the larger portion of heavier animals.

In 2000, both beef and dairy cattle emissions changed less than 3 Gg (0.1 percent) as a result of the recalculations. In 2001, beef cattle CH_4 emissions increased 12 Gg (0.3 percent), while dairy cattle emissions decreased 1 Gg (0.1 percent). In 2002, beef cattle CH_4 emissions increased 8 Gg (0.2 percent), while dairy cattle emissions increased less than 1 Gg (0.03 percent). For other livestock types, a slight upward revision in the swine population for 2002 resulted in an increase in CH_4 emissions of less than 1 Gg (0.06 percent) in that year. Overall, the changes resulted in an average annual increase of less than 0.1 Tg CO_2 Eq. (0.04 percent) in CH_4 emissions from enteric fermentation for the period 1990 through 2002.

Planned Improvements

The revised and updated USDA data discussed above highlight the need to re-examine several model inputs. Although the enteric fermentation model was constructed to identify the imbalances mentioned in the recalculations discussion, the current inventory presents the first effort to address such differences by making adjustments to model inputs. The updates are based both on expert opinion and on equations published by the American Society of Agricultural Engineers (ASAE) that predict weight versus age statistics for steers and imply growth rates larger than those used in previous years (ASAE 1999). In addition, in 2001, USDA reported increased rates of gains for yearlings (USDA 2001g). While these two sources provide support for the updates, further research is necessary to verify the changes and to understand what changes over time may be necessary in future inventory analyses.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide 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 pits) 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) favor 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 2003 were 39.1 Tg CO_2 Eq. (1,864 Gg), 25 percent higher than in 1990. The majority of this increase was from swine and dairy cow manure, where emissions increased 30 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. Larger swine and dairy farms tend to use liquid 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 1999e). From 2002 to 2003, there was a 0.5 percent decrease 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 2003 were estimated to be 17.5 Tg CO_2 Eq. (57 Gg). The 8 percent increase in N_2O emissions from 1990 to 2003 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 2002, although swine populations periodically declined slightly throughout the time series. Nitrous oxide emissions showed a 2 percent decrease from 2002 to 2003, due to minor shifts in animal population.

The population of beef cattle in feedlots increased over the period of 1990 to 2003, resulting in increased N_2O emissions from this sub-category of cattle. Although dairy cow populations decreased overall for the period 1990 to 2003, 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 2003. 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CH_4	**31.2**	**36.4**	**38.8**	**38.8**	**38.1**	**38.9**	**39.3**	**39.1**
Dairy Cattle	11.4	13.4	13.9	14.7	14.5	15.0	15.2	15.7
Beef Cattle	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.1
Swine	13.1	16.4	18.4	17.6	17.1	17.4	17.7	17.0
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	2.7	2.7	2.7	2.6	2.6	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**	**17.3**	**17.4**	**17.4**	**17.8**	**18.0**	**17.9**	**17.5**
Dairy Cattle	4.3	4.0	3.9	4.0	4.0	3.9	3.9	3.9
Beef Cattle	4.9	5.4	5.5	5.5	5.9	6.1	5.9	5.6
Swine	0.4	0.4	0.5	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	6.4	7.2	7.2	7.2	7.2	7.3	7.4	7.3
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**47.4**	**53.7**	**56.2**	**56.2**	**55.9**	**57.0**	**57.3**	**56.7**

+ 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CH_4	**1,485**	**1,733**	**1,850**	**1,846**	**1,813**	**1,853**	**1,873**	**1,864**
Dairy Cattle	545	639	662	700	692	715	722	748
Beef Cattle	153	152	149	150	149	148	147	146
Swine	622	780	874	837	812	826	843	808
Sheep	9	6	6	6	5	5	5	5

Goats	1		1	1	1	1	1	1	1
Poultry	128		127	130	125	125	129	126	127
Horses	27		28	28	28	28	29	29	29
N_2O	**52**		**56**	**56**	**56**	**57**	**58**	**58**	**57**
Dairy Cattle	14		13	13	13	13	13	13	13
Beef Cattle	16		17	18	18	19	20	19	18
Swine	1		1	1	1	1	1	1	1
Sheep	+		+	+	+	+	+	+	+
Goats	+		+	+	+	+	+	+	+
Poultry	21		23	23	23	23	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 *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (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);
- Methane 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, 2000h) and EPA (ERG 2000a, EPA 2001a, 2001b). For beef cattle and poultry, manure management system usage data was not tied to farm size (ERG 2000a, USDA 2000i, 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 then weighted to incorporate the distribution of management systems used within each state and thereby 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.

Methane emissions were estimated using the volatile solids (VS) production for all livestock. For poultry and swine animal groups, for example, volatile solids production was calculated using a national average volatile solids 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 volatile solids production rates that are related to the diet of the animal for each year of the inventory were used (Lieberman et al., 2004). The resulting volatile solids for each animal group was then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state-specific CH_4 conversion factors.

Nitrous oxide 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 U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f, 2002a-f, 2003a-f, 2004a-f). Horse population data were obtained from the FAOSTAT database (FAO 2004), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained from the Census of Agriculture (USDA 1999d). 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 1999e).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000h) for small operations and from preliminary estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2001a, 2001b). 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 2000i). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2001a, 2001b). 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 (Poe et al. 1999). These organizations include state NRCS offices, state extension services, state universities, USDA National Agriculture Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, 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).

Methane conversion factors 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), and the county population data were calculated from state-level population data from NASS and county-state distribution data from the 1992 and 1997 Census data (USDA 1999e). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county

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[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

population distribution data for 1998 through 2003 were assumed to be the same as 1997; and county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

The maximum CH_4 producing capacity of the volatile solids, 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. Volatile solids 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, volatile solids production rates from Lieberman et al. (2004) were used for dairy and beef cows, heifers, and steer for each year of the inventory. Nitrous oxide emission factors and MCFs for dry systems were taken from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA (2003) 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 EPA (2003) 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 2003 were estimated to be between 32.1 and 47.0 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 2003 emission estimate of 39.1 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.7 and 21.7 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the 2003 emission estimate of 17.5 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	2003 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	39.1	32.1	47.0	-18%	+20%
Manure Management	N_2O	17.5	14.7	21.7	-16%	+24%

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

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 and 1997 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.

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (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 volatile solids 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 *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (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 volatile solids 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 2002 and 2003 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. Efforts also continue to transition various components of the manure management inventory into a database to facilitate current and future QA checks.

Recalculations Discussion

No changes have been incorporated into the overall methodology for the manure management emission estimates; however, changes were made to the calculation of CH_4 emissions from sheep, goats, and horses. Changes were also made to address errors and updates in the population and waste management system data from previous inventory submittals. Additionally the population distribution of horses and poultry were adjusted, the typical animal mass for sheep was adjusted, and the temperature estimations were changed to reflect a refined methodology. Each of these changes is described in detail below.

- Methane emission estimation from sheep, goats, and horses. The sheep, goats, and horses emission methodologies were changed to be consistent with the methodologies used for the other animal groups. Previously, the sheep, goat, and horse methane estimates were scaled based on population data and earlier estimates of methane emissions (EPA 1992).

- Population. All USDA data from 1998 through the present year underwent review pursuant to USDA NASS annual review procedures. The population data in these years reflect some adjustments due to this review. For horses, state-level populations were estimated using the national FAO population data and the state distributions from the 1992 and 1997 Census of Agriculture. For poultry, populations for states reporting non-disclosed populations were estimated by distributing population values attributed to “other” states.

- Waste management system. The waste management system data for poultry were adjusted based on more recent data. Previously, layers were estimated to be 99 percent managed (EPA 1992). More recent WMS data available from USDA's Animal Plant and Health Inspection Service Layers '99 study (USDA 2000i) and the United Egg Producers Study (UEP 1999) indicate that layers are 100 percent managed. Therefore, the layer WMS estimates have been updated accordingly. Also, the waste management system distribution for dairy cows was adjusted to correct rounding errors.

- Typical animal mass. The typical animal mass for sheep were reevaluated and adjusted. Typical animal mass of sheep was adjusted from 27 kg to 68.6 kg (see Annex 3.10 for details).

- Temperature data: Temperature data are not available for every county with animal populations. Previously, counties without temperature data were not accounted for in the estimate of average weighted temperature. This methodology was changed to use the state average temperature for counties without temperature data available.

The combination of these changes resulted in an average annual increase of 0.1 Tg CO_2 Eq. (0.3 percent) in CH_4 emissions and an average annual increase of 0.1 Tg CO_2 Eq. (0.4 percent) in N_2O emissions from manure management for the period 1990 through 2002.

Planned Improvements

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., “cool”). 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.

Although an effort was made to introduce the variability in volatile solids 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 volatile solids production would be useful in future inventory estimates.

The American Society of Agricultural Engineers is publishing new standards for manure production characteristics in 2004. These data will be investigated and evaluated for incorporation into future estimates.

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 estimates will attempt to reflect these updated data.

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.

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 2002 Census of Agriculture became available in mid-2004. These data will be used to update assumptions that previously relied on the 1992 and 1997 Census of Agriculture.

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, 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. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow 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 2003, CH_4 emissions from rice cultivation were 6.9 Tg CO_2 Eq. (328 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2003, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall decrease of 3 percent over the thirteen-year period, due to an overall decrease in ratoon 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, 2001). 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 2001). 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.)

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[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.

[3] The 11 percent decrease occurred between 1992 and 1993; the 17 percent increase happened between 1993 and 1994.

State	1990	1997	1998	1999	2000	2001	2002	2003
Primary	**5.1**	**5.6**	**5.8**	**6.3**	**5.5**	**5.9**	**5.7**	**5.4**
Arkansas	2.1	2.5	2.7	2.9	2.5	2.9	2.7	2.6
California	0.7	0.9	0.8	0.9	1.0	0.8	0.9	0.9
Florida	+	+	+	+	+	+	+	+
Louisiana	1.0	1.0	1.1	1.1	0.9	1.0	1.0	0.8
Mississippi	0.4	0.4	0.5	0.6	0.4	0.5	0.5	0.4
Missouri	0.1	0.2	0.3	0.3	0.3	0.4	0.3	0.3
Oklahoma	+	+	+	+	NA	+	+	+
Texas	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.3
Ratoon	**2.1**	**1.9**	**2.1**	**2.0**	**2.0**	**1.7**	**1.1**	**1.5**
Arkansas	+	+	+	+	+	+	+	+
Florida	+	0.1	0.1	0.1	0.1	+	+	+
Louisiana	1.1	1.2	1.2	1.2	1.3	1.1	0.5	1.0
Texas	0.9	0.7	0.8	0.7	0.7	0.6	0.5	0.5
Total	**7.1**	**7.5**	**7.9**	**8.3**	**7.5**	**7.6**	**6.8**	**6.9**

+ Less than 0.05 Tg CO_2 Eq.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg CH_4)

State	1990	1997	1998	1999	2000	2001	2002	2003
Primary	**241**	**265**	**279**	**300**	**260**	**283**	**274**	**255**
Arkansas	102	118	126	138	120	138	128	124
California	34	44	39	43	47	40	45	43
Florida	1	2	2	2	2	1	1	1
Louisiana	46	50	53	52	41	46	45	38
Mississippi	21	20	23	27	19	22	22	20
Missouri	7	10	12	16	14	18	15	15
Oklahoma	+	+	+	+	NA	+	+	+
Texas	30	22	24	22	18	18	18	15
Ratoon	**98**	**91**	**98**	**95**	**97**	**81**	**52**	**73**
Arkansas	+	+	+	+	+	+	+	+
Florida	2	3	3	4	2	2	2	2
Louisiana	52	55	59	58	61	52	25	50
Texas	45	33	36	33	34	27	24	22
Total	**339**	**356**	**376**	**395**	**357**	**364**	**325**	**328**

+ Less than 0.5 Gg
NA (Not Available)
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 and Uncertainty Management in National Greenhouse Gas Inventories* (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 2003 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), *Crop Production 2000 Summary* (USDA 2001), *Crop Production 2001 Summary* (USDA 2002), *Crop Production 2002 Summary* (USDA 2003), and *Crop Production 2003 Summary* (USDA 2004). 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), 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 (Lee 2003, 2004). 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). 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) and about 100 percent of the primary area in 2003 (Kirsetin 2004). 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, and rose to 35 percent in 2003 (Linscombe 1999a, 2001a, 2002, 2003, 2004 and 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 and in 2001, but increased to 50 percent in 2000 due to an early primary crop; it then decreased to 40 percent in 2001, 37 percent in 2002, and 38 percent in 2003 (Klosterboer 1999, 2000, 2001a, 2002, 2003, Stansel 2004).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1997	1998	1999	2000	2001	2002	2003
Arkansas								
Primary	485,633	562,525	600,971	657,628	570,619	656,010	608,256	588,830
Ratoon*	NO	NO	202	202	NO	NO	NO	NO
California	159,854	208,822	185,350	204,371	221,773	190,611	213,679	205,180
Florida								
Primary	4,978	7,689	8,094	7,229	7,801	4,562	5,077	2,315
Ratoon	2,489	3,845	4,047	4,673	3,193	2,752	2,734	2,315
Louisiana								
Primary	220,558	235,937	250,911	249,292	194,253	220,963	216,512	182,113
Ratoon	66,168	70,781	75,273	74,788	77,701	66,289	32,477	63,739
Mississippi	101,174	96,317	108,458	130,716	88,223	102,388	102,388	94,699
Missouri	32,376	47,349	57,871	74,464	68,393	83,772	73,654	69,203
Oklahoma	617	12	19	220	NA	265	274	53
Texas								
Primary	142,857	104,816	114,529	104,816	86,605	87,414	83,367	72,845
Ratoon	57,143	41,926	45,811	41,926	43,302	34,966	30,846	27,681
Total Primary	**1,148,047**	**1,263,468**	**1,326,203**	**1,428,736**	**1,237,668**	**1,345,984**	**1,303,206**	**1,215,237**
Total Ratoon	**125,799**	**116,552**	**125,334**	**121,589**	**124,197**	**104,006**	**66,056**	**93,735**
Total	**1,273,847**	**1,380,020**	**1,451,536**	**1,550,325**	**1,361,864**	**1,449,991**	**1,369,262**	**1,308,972**

* Arkansas ratooning occurred only in 1998 and 1999.
NO (Not Occurring)
NA (Not Available)
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 and 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.

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. From these ranges, an uncertainty for the emission factors of 109 percent for primary crops and 65 percent for ratoon was calculated. In order to perform a Tier 2 Monte Carlo uncertainty analysis, some information regarding the statistical distribution of the uncertainty is required. 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. The bounds of the distribution were set at 0 (indicating that CH_4 absorption was unlikely given this management system) and three times the emission factor.

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 triangular distribution of uncertainty was assumed about the mean for areas, which was bounded at half and one and a half times the estimated area.

Another source of uncertainty lies in the ratooned areas, which are not compiled regularly. Ratooning accounts for less than 8 percent of the total rice-cropped area, though it is responsible for a proportionately larger portion of emissions. Based on expert judgment, the uncertainty associated with ratooned areas is between 1 percent and 5 percent. A triangular distribution of uncertainty was assumed, and bound at half and one and a half times the estimated proportion of ratooned area.

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 representative conditions to account for this source or its associated uncertainty adequate for inclusion in the emission estimates or uncertainty evaluations presented here.

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[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).

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 2003 were estimated to be between 2.9 and 13.9 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 58 percent below to 101 percent above the 2003 emission estimate of 6.9 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**	**2003 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Rice Cultivation	CH_4	6.9	2.9	13.9	-58%	+101%

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

Planned Improvements

In performing a Monte Carlo-type uncertainty analysis, a higher level Tier 2 type emission mean is calculated incidentally. One would expect there to be a difference in the emission means calculated by these different methods, because under the IPCC default Tier 2 method used here to estimate CH_4 emissions, the statistical distribution of all parameters (i.e., activity data and emission factors) is implicitly considered to be normal. As described above, that is not the case with the uncertainty analysis, which allows for several asymmetrical statistical distributions. Here, the lower and upper bounds have been reported, directly from the Monte Carlo analysis. However, the percentages for the upper and lower bounds of the range have been calculated based on the reported emission mean rather than that mean calculated by the Monte Carlo software (as is the case with all reported Tier 2 analyses). Because that mean may represent an improvement to the current Tier 2 methodology, including the higher level Tier 2 estimate in future inventories is being investigated.

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 add nitrogen (N) to soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of nitrous oxide (N_2O) emitted. These activities may add N to soils either directly or indirectly (see Figure 6-2). Direct additions occur through various soil management practices and from the deposition of manure on soils by animals on pasture, range, and paddock (PRP) (i.e., by animals whose manure is not managed). Soil management practices that add N to soils include fertilizer use, application of managed livestock manure and sewage sludge, production of N-fixing crops and forages, retention of crop residues, and cultivation of histosols (i.e., soils with a high organic matter content, otherwise known as organic soils).[6] Only direct emissions from agricultural lands (i.e., croplands and grasslands), along with emissions from PRP manure are included in this section. The direct emissions from forest lands and settlements are presented within the LUCF sector. Indirect nitrous oxide emissions from all land use types resulting from N additions to croplands, grasslands, forestlands, and settlements are also included in this section. These indirect emissions occur through two

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[5] Nitrification and denitrification are two processes within the N cycle that are brought about by certain microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well understood mechanism (Nevison 2000).

[6] Cultivation of histosols does not, *per se*, “add” N to soils. Instead, the process of cultivation enhances mineralization of N-rich organic matter that is present in histosols, thereby enhancing N_2O emissions from histosols.

mechanisms: 1) volatilization and subsequent atmospheric deposition of applied N;[7] and 2) surface runoff and leaching of applied N into groundwater and surface water. Other agricultural soil management activities, such as irrigation, drainage, tillage practices, and fallowing of land, can affect fluxes of N_2O (as well as other greenhouse gases) to and from soils and are partially accounted for in the analysis.

Figure 6-2: Direct N_2O Emissions Pathways from Cropland and Grassland Soils, and Indirect N_2O Emissions Pathways from All Sources.

Agricultural soils are responsible for the majority of U.S. N_2O emissions. Estimated emissions from this source in 2003 were 253.5 Tg CO_2 Eq. (818 Gg N_2O) (see Table 6-13 and Table 6-14). Annual agricultural soil management N_2O emissions fluctuated between 1990 and 2003; however, overall emissions were 0.2% greater in 2003 than in 1990. Year-to-year fluctuations are largely a reflection of annual variations in climate, synthetic fertilizer consumption, and crop production.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

	1990	1997	1998	1999	2000	2001	2002	2003
Direct	**140.4**	**155.9**	**158.6**	**151.1**	**156.3**	**154.5**	**159.9**	**155.3**
Agricultural Soils	100.1	113.6	116.5	111.0	116.4	113.0	118.5	114.8
Pasture, Range & Paddock Livestock Manure	40.2	42.2	42.1	40.1	39.8	41.5	41.4	40.5
Indirect (All Land Use Types)*	**112.6**	**96.2**	**109.1**	**92.3**	**107.6**	**102.6**	**92.7**	**98.2**
Total	**253.0**	**252.0**	**267.7**	**243.4**	**263.9**	**257.1**	**252.6**	**253.5**

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)

	1990	1997	1998	1999	2000	2001	2002	2003
Direct	**453**	**503**	**512**	**487**	**504**	**498**	**516**	**501**
Agricultural Soils	323	367	376	358	376	365	382	370
Pasture, Range & Paddock Livestock Manure	130	136	136	129	129	134	134	131
Indirect (All Land Use Types)*	**363**	**310**	**352**	**298**	**347**	**331**	**299**	**317**
Total	**816**	**813**	**864**	**785**	**851**	**829**	**815**	**818**

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, Table 6-16, and Table 6-17.

Table 6-15: Direct N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Mineral Agricultural Soils	97.3	110.8	113.7	108.2	113.6	110.1	115.6	111.9
Histosol Cultivation	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.9

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[7] These processes entail volatilization of applied N as ammonia (NH_3) and oxides of N (NO_x), transformations 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 oxides of N.

Pasture, Range & Paddock Livestock Manure	40.2	42.2	42.1	40.1	39.8	41.5	41.4	40.5
Total	**140.4**	**155.9**	**158.6**	**151.1**	**156.3**	**154.5**	**159.9**	**155.3**

Note: Totals may not sum due to independent rounding. Excludes sewage sludge and livestock manure used as commercial fertilizers.

Table 6-16: Direct N_2O Emissions from PRP Livestock Manure (Tg CO_2 Eq.)

Animal Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Beef Cattle	34.9	37.8	37.6	35.7	35.5	37.1	37.0	36.1
Dairy Cows	1.9	1.4	1.4	1.3	1.3	1.3	1.3	1.3
Swine	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sheep	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2
Goats	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Poultry	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Total	**40.2**	**42.2**	**42.1**	**40.1**	**39.8**	**41.5**	**41.4**	**40.5**

Table 6-17: Indirect N_2O Emissions from all Land Use Types* (Tg CO_2 Eq.)

	1990	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Volatilization and Atm. Deposition	15.6	16.5	16.4	16.4	16.8	16.4	16.6	16.5
Surface Leaching & Run-Off	97.1	79.6	92.7	75.9	90.8	86.3	76.1	81.8
Total	**112.6**	**96.2**	**109.1**	**92.3**	**107.6**	**102.6**	**92.7**	**98.2**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land and settlements.

Methodology

The methodology used to estimate emissions from agricultural soil management is consistent with the Tier 3 approach of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) and *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2003). Current methods divide this N_2O source category into three components: 1) direct emissions from managed soils due to applied N and the cultivation of histosols; 2) direct emissions from soils due to the deposition of manure by livestock on PRP lands; and 3) indirect emissions from soils or water induced by additions of fertilizers, sewage sludge, and livestock manure (both managed and unmanaged) to soils of all land use types.

Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each of the components.

The methodology applied in this Inventory is a hybrid approach for estimating N_2O emissions from mineral agricultural soils. This involves using the process-based model DAYCENT to estimate emissions from major crops on mineral (i.e., non-histosol) soils, and the IPCC methodology for non-major crops on mineral soils, PRP manure, as well as all emissions from histosols.

Direct N_2O Emissions from Mineral Agricultural Soils

Different methodologies were used in quantifying direct N_2O emissions from mineral agricultural soils with major crop types and those with non-major crop types as described below.

Major Crop Types

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct soil N_2O emissions from mineral agricultural soils cropped with major crop types. DAYCENT has been parameterized to simulate most of the major cropping systems (corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton) in the United States. These cropping systems simulated by DAYCENT represent approximately 90 percent of total cropped land in the United States. DAYCENT simulates crop growth, soil organic matter decomposition, greenhouse gas fluxes, N deposited by grazing animals, and other biogeochemical processes using daily climate data, land management information, and soil physical properties as model inputs. The scale of DAYCENT simulations is dictated by the scale of available input data. Soil and climate inputs were available for every county with more than 100 acres of agricultural land. Therefore, a single parameter value (e.g., maximum temperature for a particular day) is applied at the county-level for those variables. Land management data (e.g., timing of planting, harvesting, applying fertilizer, intensity of cultivation, rate of fertilizer application) were available at the agricultural region level as defined by the Agricultural Sector Model (McCarl el al. 1993). There are 63 regions in the contiguous United States; most states correspond to one region, except for states that are divided into two or more regions if there is sufficient variability in cropping practices within the state. Although various cropping systems were simulated for each county, the parameters controlling management activities (e.g., when crops were planted/harvested, amount of fertilizer added), did not change within an agricultural region.

Nitrous oxide emissions estimated by DAYCENT account for N additions, crop type, irrigation, and other factors. However, because DAYCENT is a process-based model that simulates the N cycle, N_2O emissions cannot be partitioned into the contribution of N_2O from different N inputs (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those emissions resulting from manure applications). Therefore, it was not possible to separate out these individual contributors to N_2O flux, as is suggested in the IPCC *Guidelines*.

In addition to simulating N_2O emissions from mineral agricultural soils cropped with major crop types, a DAYCENT simulation was performed of those same areas as though they were covered by native vegetation, so that anthropogenic emissions could be isolated from natural background emissions. Emissions from managed agricultural lands are the result of complex and interactive processes, practices, and inputs arising from anthropogenic intervention. Because removing inputs alone would not reflect the full anthropogenic greenhouse gas signature, managed soil emissions have been compared to those soils under native vegetation as a means of identifying the anthropogenic contribution. The reported estimates of emissions from managed soils therefore represent the difference between simulated emissions from native vegetation and emissions from cropland soils. Estimates of direct N_2O emissions from N applications were based on the total amount of N applied to soils annually through the following practices: 1) the application of synthetic and organic commercial fertilizers, 2) the application of livestock manure through both daily spread operations and through the eventual application of manure that had been stored in manure management systems, 3) the application of sewage sludge, 4) the production of N-fixing crops and forages, and 5) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, annual N applications were obtained 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).

- Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safely (2000), USDA (1996, 1998d), and ASAE (1999); daily rates of N excretion from ASAE (1999) and USDA (1996). Comparisons of estimates of managed manure production (i.e. non-PRP manure) with estimates of the amount of manure actually consumed by soils showed that manure consumed by soils accounted for approximately one-third of managed manure production). Values for manure consumption (Kellogg et al. 2000; Edmonds et al. 2003) were subtracted from values of managed manure production. Only consumed manure N was applied to agricultural soils. The remainder was assumed to have volatized during storage and transport. In contrast to the IPCC methodology that only considers volatilization of manure that was applied to soils, the manure that was assumed to volatilize during transport and storage was included in the volatilization component of indirect N_2O emissions. 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 were internally calculated by the process-based model.

- Sewage sludge: Bastian (2002); USDA (1998a); EPA (1993, 1999); Metcalf and Eddy (1991).

- Nitrogen-fixing crops and forages and retention of crop residue. Using the IPCC approach, these are considered activity data. However, when using DAYCENT, they should not be considered activity data because they 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 (2004), USDA (2000h), 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), Holmes (1929), Hodges et al. (1930), Bonnen and Elliot (1931), Brenner et al. (2002, 2001), Smith et al. (2002).

Applied 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. These amounts were then applied in the calculation of indirect emissions as described below. The remaining applied soil N was then added to the applied N from N-fixing crops and crop residues to yield total soil N additions for the DAYCENT simulation of direct N_2O emissions from soils cropped with major crop types. Because the model is sensitive to actual interannual variability in those factors to which N_2O emissions are sensitive (e.g., climate), emissions vary through time rather than demonstrate a linear, monotonic response.

Non-Major Crop Types

For lands cropped with non-major crop types, the IPCC emission factor methodology was used to estimate N_2O emissions from mineral agricultural soils, as described below.

Estimates of direct N_2O emissions from N applications to non-major crop types were based on the amount of N applied to soils annually through the following practices: 1) the application of synthetic commercial fertilizers, 2) the production of N-fixing crops and forages, and 3) the retention of crop residues. No organics were considered here because 100 percent of these were assumed to be applied to crops simulated by DAYCENT. This assumption is reasonable because DAYCENT simulated the 6 major cropping systems (corn, hay, pasture, sorghum, soybean, wheat) that receive the vast majority (approximately 95 percent) of manure applications (Kellogg et al. 2000, Edmonds et al. 2003).

Yearly synthetic fertilizer N additions to non-major crop types were calculated by process of elimination. For each year, fertilizer accounted for by the cropping systems simulated by DAYCENT (approximately 75 percent of the U.S. total), fertilizer estimated to be applied to forests (less than 1 percent of the U.S. total), and fertilizer estimated to be applied in settlements (approximately 10 percent of the U.S. total) were summed and subtracted from total fertilizer used in the United States. This difference was assumed to be applied to non-major crop types and accounted for approximately 15 percent of total N fertilizer used in the United States. Non-major crop types include fruits, nuts, and vegetables, which account for approximately 5 percent of U.S. N fertilizer use (TFI 2000) and other crops not simulated by DAYCENT (barley, oats, tobacco, sugar cane, sugar beets, sunflower, millet, peanuts, etc.) which account for approximately 10 percent of total U.S. fertilizer use. The non-volatilized proportion was obtained by reducing total applications by the default IPCC volatilization fraction (IPCC 1997, 2000). In addition to synthetic fertilizer-N applied to non-major crop types, 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 retention was derived from information about which residues are typically left on the field, the fractions that remain, annual crop production, mass ratios of aboveground residue to crop product, and dry matter fractions and N contents of the residues. For each of these practices, annual N applications were obtained from the following sources:

- 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).

- Annual production statistics for crops whose residues are left on the field: USDA (1994a, 1998b, 2000i, 2001a, 2002a, 2003a), Schueneman (1999, 2001), Deren (2002), Schueneman and Deren (2002), Cantens (2004), Lee (2003, 2004).

- Aboveground residue to crop mass ratios, residue dry matter fractions, and residue N contents: Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), Barnard and Kristoferson (1985), Karkosh (2000).

The net amount of N remaining on the soil from applied fertilizer was added to the N from N-fixing crops and crop residues to yield total unvolatilized applied N, which was multiplied by the IPCC default emission factor to derive an estimate of cropland N_2O emissions from non-major crop types.

Total annual emissions from major crops and other crops were summed to obtain total emissions from cropped mineral soils (see Table 6-13 and Table 6-14).

Direct N_2O Emissions from Histosols

Estimates of annual N_2O emissions from histosol cultivation were based on estimates of the total U.S. acreage of histosols cultivated annually for each of two climatic zones: 1) temperate, and 2) sub-tropical. Histosol area was obtained from the Natural Resources Inventory (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002). To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions.

Total Direct N_2O Emissions from Nitrogen Applications to Agricultural Soils

Total annual N_2O emissions from N applications to mineral agricultural soils and annual N_2O emissions from histosol cultivation were then summed to estimate total direct N_2O emissions from agricultural soils.

Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

As with N_2O from major row crops, dual methodologies incorporating the process-based simulation model DAYCENT and IPCC methods were applied in tandem to estimate total emissions from PRP manure. For DAYCENT simulations, annual county-level pasture area data were not available so county-level pasture area estimates from Kellogg et al. (2000) and Edmonds et al. (2003) were used. DAYCENT does not simulate paddocks and no county level area data for rangeland were available so IPCC methodology was used to estimate emissions from these sources. Because DAYCENT simulated only pastures and not paddocks or rangeland, the amount of manure accounted for by DAYCENT (manure N added to soil is an output variable in DAYCENT) was subtracted from annual estimates of total PRP manure and assumed that this manure contributed to emissions from paddocks and rangeland.

Estimates of N_2O emissions from PRP livestock manure are based on the amount of N in the manure that is deposited annually on soils by livestock on PRP. Estimates of annual manure N from these livestock were derived from animal population and weight statistics; information on the fraction of the total population of each animal type that is on pasture, range, or paddock; and annual N excretion rates for each animal type. The amount of manure N from each animal type was summed over all animal types to yield total PRP manure N. Nitrous oxide emissions resulting from manure deposited on pastures by livestock was simulated by DAYCENT in each county. The emissions were obtained by multiplying DAYCENT emissions (in g $N_2O\text{-}N\ m^{-2}$) by the total reported pasture area for each county, and summing across all counties to achieve a nationwide value. All of the manure accounted for by

DAYCENT was assumed to come from cattle because DAYCENT has been parameterized to simulate cattle manure, and cattle are responsible for approximately 90 percent of total PRP manure. The PRP manure N from paddocks and rangeland not accounted for by DAYCENT in the pasture component was multiplied by the IPCC default emission factor to estimate N_2O emissions from paddock and rangeland manure deposition. Emissions from the three types of PRP manure were summed to provide total national emissions from PRP manure in the United States.

Indirect N_2O Emissions from Managed Soils of All Land Use Types

This section describes the method for estimating indirect N_2O emissions from managed soils of all land use types (i.e., cropland, grassland, forest land and settlements). Indirect emissions of N_2O are composed of two parts, which are estimated separately and then summed. These parts are 1) emissions resulting from volatilization of non-N_2O gases (i.e., NO_x and NH_3) from synthetic fertilizer and manure additions to managed soils and from managed manure during storage, treatment and transport that are subsequently deposited onto other areas and eventually emitted to the atmosphere as N_2O, and 2) leaching and runoff of N (in the form of NO_3^-) from all soils where N additions have been made that is eventually denitrified and emitted as N_2O from a water body. Regardless of the original source or eventual land use type where these indirect N_2O emissions actually occur, all indirect N_2O emissions are accounted for in this section of the Inventory.

A mix of approaches was used to obtain the necessary information required to estimate indirect N_2O emissions. While DAYCENT simulates NO_x and NH_3 volatilization as well as NO_3 leaching/runoff, it does not model their transport or subsequent off-site conversion to N_2O. Therefore, DAYCENT was used to simulate N volatilization and leaching/runoff losses for major crop types. Volatilized and leached/runoff N from non-major crops, settlements and forest lands were obtained by applying the IPCC default fractions to total fertilizer applications to those crops and/or land areas. The volatilization and leaching/runoff components of indirect emissions for PRP manure were obtained by using a combination of DAYCENT generated outputs for manure deposited on pasturelands and applying IPCC defaults to manure deposited on paddocks and rangelands. Manure from managed systems assumed to be volatilized during storage, treatment and transport was included in the indirect emission calculations as well. In contrast to the IPCC approach that has been used in the past, DAYCENT simulations for major crops, where all managed manure is assumed to be applied, do not assume that 100 percent of the N in managed manure is available to be applied to soils. According to data in Kellogg et al. (2000) and Edmonds et al. (2003), more than 50 percent of the N in managed manure is lost to volatilization, spillage and leaching/runoff during storage, treatment and transport. Consequently, manure N applied to soils, based on data from Kellogg et al. (2000) and Edmonds et al. (2003), is subtracted from total managed manure N and assumed to volatilize during storage, treatment, and transport where it is then included in the volatilization component of indirect emissions. Results from this mix of approaches described above were then summed for the appropriate indirect N_2O emission pathway as described below.

Voltilized Indirect Emissions

Volatilized N emissions for settlements, forest lands, PRP manure, major crops, non-major crops, and volatilized managed manure prior to land application were summed. The IPCC default emission factor for indirect N_2O was applied to the total to give total indirect N_2O emissions from N volatilization from soils of all land use types and volatilized managed manure.

Leaching/Runoff Indirect Emissions

The amounts of leached/runoff N from settlements, forest lands, PRP manure, major and non-major crop types were summed and multiplied by the IPCC default emission factor for leached/runoff N.

Total Indirect Emissions from Volatilization and Leaching/Runoff

Total indirect emissions from volatilization and from leaching/runoff were summed to estimate total indirect emissions of N_2O from croplands (Table 6-17).

Uncertainty

The DAYCENT biogeochemical ecosystem model was used to calculate N_2O emissions from major crop types. There are two broad classes of uncertainty in such analyses: that inherent in the activity data and emission factors, and structural uncertainty inherent to the model used to estimate emissions. Consistent with the United States' uncertainty management plan, uncertainty inherent to the DAYCENT model was not quantified as part of the IPCC Tier 1 approach described below.

Three types of approaches were taken for estimating different types of emissions in this chapter: 1) Direct emissions calculated by DAYCENT; 2) Direct emissions not calculated by DAYCENT; and 3) Indirect emissions. Uncertainty was estimated differently for each category.

For direct emissions calculated by DAYCENT (99.3 of the total direct 155.3 Tg CO_2 Eq.), uncertainty in national totals for N inputs and uncertainty in how N application rates change with crop type, year, and agricultural region contribute to total uncertainty in the N application activity data. Total uncertainty in N inputs was estimated at 20 percent (Mosier 2004). Other activity data include climate data, for which uncertainty was estimated to be 19 percent, and soil type, which was estimated to have an uncertainty of 12 percent (Del Grosso 2005a). Their combined uncertainty, according to the sum-of-squares method, is approximately 30.1 percent. To estimate the uncertainty associated with the effective emission factor, DAYCENT outputs were compared with N_2O measurements from various cropped soils over the annual cycle (Del Grosso et al. in press). Through this method, the uncertainty associated with the effective emission factor was estimated at 57 percent (Del Grosso 2005b). Through the calculus of error propagation, overall uncertainty for direct emissions calculated by DAYCENT was 64 percent.

Direct N_2O emissions not calculated by DAYCENT were assumed to maintain the 64 percent uncertainty.

Finally, indirect emissions were calculated according to the default IPCC methodology, as has been performed in past Inventories. Consequently, the maximum uncertainty calculated for last year's indirect N_2O emissions from agricultural soil management of 286 percent (U.S. EPA 2004) was applied to conservatively address the uncertainty in indirect emissions here.

The results of the Tier 1 quantitative uncertainty analysis are summarized in Table 6-18. Agricultural soil management N_2O emissions in 2003 were estimated to be between 45.2 and 461.8 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 82 percent above and below the 2003 emission estimate of 253.5 Tg CO_2 Eq.

Table 6-18: Tier 1 Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2003 (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	253.5	82%	45.2	461.8

Recalculations Discussion

Differences in the present report compared to previous years exist for two reasons: differences in sources and differences in methodologies. In previous Inventories, fertilizer applied to forests and settlements were included in the agricultural sector. For the current Inventory, for the direct emissions, these fertilizer additions were included in the LUCF sector, and therefore approximately 15 percent less synthetic fertilizer is counted in the agricultural sector than in previous Inventories. Also in previous Inventories, the default Tier 1 IPCC methodology was used to estimate emissions from this sector. That methodology relied solely on N inputs, and did not account for effects of climate, soil type, and other factors that influence N_2O emissions. To account for some of these additional factors and increase confidence in estimates, a Tier 3 method, the DAYCENT ecosystem model, was used to account for

N_2O emissions from major cropping systems. Overall, the changes resulted in an average annual decrease of 31.2 Tg CO_2 Eq. (11 percent) in N_2O emissions from agricultural soil management for the period 1990 through 2002.

The IPCC emission factor methodology is an example of a Tier 1 approach. This approach is activity driven, i.e., total N from different sources (e.g. synthetic fertilizer, manure, N fixation, etc.) is used to estimate N_2O from these sources. The Tier 3 approach in this case uses a process-based model (i.e., DAYCENT) and is area driven, i.e., it is necessary to know the annual area of major crop types and the N amendment rates for each of these crops. With the Tier 3 approach, emissions cannot be separated by N inputs because once N is in the plant/soil system, the model does not distinguish its source according to IPCC categorizations (e.g., whether the N_2O emitted was synthetic fertilizer-derived or derived from manure). Because the Tier 3 approach was used for approximately 90 percent of fertilized soils in the United States, N_2O emissions are not partitioned into the IPCC's N-input categories, as has been done in the past.

The Tier 3 approach requires some of the same activity data as the Tier 1 approach, plus additional information. Like the Tier 1 approach, the Tier 3 approach requires national totals for N amendments, but it also requires data on N amendment rates for different cropping systems. Consequently, the total amounts of N fertilizer and organic N additions were identical to previous years but assumptions regarding the fate of these amendments are different. For example, in previous years, 100 percent of managed manure was assumed to be applied to cropped soils, though here approximately 64 percent of manure N was lost to volatilization during transport and storage before it was applied to soil. This manure that was assumed to volatilize before soil application was included with indirect emissions, which is different than previous years. In addition to N amendments, the Tier 3 approach requires area data for different cropping systems. The Tier 3 approach distinguishes different cropping systems because crops vary in growth rates, fertilization rates, biomass N concentration, and timing for planting, harvesting, and cultivating. These crop system specific factors are important because they influence N availability in soil, which controls N_2O emissions.

An important difference between Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system in one year completely cycles 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 soil or biomass and be recycled and contribute to N_2O emission in subsequent years. In contrast, the process-based models used in the Tier 3 approach include legacy effects such that N added to the system in one year may be taken up by vegetation and returned to the soil in organic form during that year, then re-mineralized and emitted as N_2O during subsequent years. In addition to previous years' fertilizer additions, other long-term management practices that affect current soil organic matter (SOM) levels (e.g., intensive cultivation, summer fallow) also affect current N_2O emission, because in process based models, N from internal cycling (mineralization of SOM) contributes to N_2O emission. Thus, while Tier 1 estimates are influenced only by the current year's N inputs, Tier 3 emissions are also influenced by management in previous years.

Another difference in methodologies is that the Tier 1 method assumes that 10 percent of synthetic fertilizer and 20 percent of applied manure are volatilized, and 30 percent of applied N is leached or run-off. DAYCENT, however, calculates N volatilization and N leached and run-off internally based on specific climatic, environmental, and management conditions.

Consideration of N-fixation highlights another difference in the approaches. In the Tier 1 approach, a certain portion of aboveground fixed N is assumed to be emitted as direct soil N_2O. In the Tier 3 approach, N fixation is calculated by the model and fixed N can be harvested, lost as N_2O, lost in some other form (e.g., leached NO_3), or stored in the plant/soil system.

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, it can be cycled and lost thorough various pathways, regardless of its source. Similar to N fixation, N deposited on soil by pasture and range animals and N added to soils from crop residue are simulated by DAYCENT. More N from manure was assumed to volatilize before application to soils and hence less N from manure was available for leaching than previous years. However, total N volatilization and leaching/runoff were both still higher than previous years. This is because IPCC methodology considers only N from synthetic and organic fertilizer to contribute to indirect emissions whereas other sources of N (e.g., fixation, crop residue) contribute to volatilization and N leaching/runoff in DAYCENT.

The methodology used here estimated total N_2O emissions to be approximately 5 to 10 percent less than estimates based on the IPCC methodology due to changes in the calculation method, as well as accounting for N_2O from fertilization of forest and settlement soils within the LUCF sector. The current method estimates lower direct N_2O emissions Table 6-19, but higher indirect N_2O emissions (Table 6-20) than the IPCC method. Differences in total N_2O emissions are shown in Table 6-21. Direct emissions were lower because of different assumptions regarding the cycling of fixed N and lower manure N applications to the major crop types under the current methodology compared with that used in the past. Indirect emissions, on the other hand, were larger because more contributors to N volatilization and leaching/runoff are accommodated by the simulation (by including crop residue applications, for example). Mean direct emissions from non-N fixing crops differed by approximately one percent, whereas direct emissions from N fixing crops were approximately 30 percent less with hybrid than IPCC methodology. Interestingly, total N fixation with the hybrid approach was only approximately two percent lower than with IPCC methodology and the implied emission factor for direct N_2O emissions from fixation is approximately 0.9 percent using hybrid methodology; i.e., these DAYCENT simulations suggest that the 1.25 percent emissions factor used for direct N_2O emissions from N fixation is too high. This is consistent with field data showing that IPCC methodology may overestimate N_2O emissions from soybean and alfalfa cropping (Del Grosso et al. in press, Rochette et al. 2004).

Table 6-19. Comparison of Direct Soil N_2O Emission Estimates for IPCC versus Current Methodologies (Tg CO_2 Eq.).

Method	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
IPCC	191.2		214.9	216.1	213.9	213.0	213.2	210.1	205.8
Current Simulation*	146.0		162.3	165.1	157.7	162.6	160.7	166.3	161.7
Difference	**45.2**		**52.6**	**51.0**	**56.2**	**50.4**	**52.5**	**43.8**	**44.1**

* Unlike Table 6-13, emissions due to N applied to forest lands and settlements are included here, to be consistent with IPCC estimates used in previous reports.

Table 6-20. Comparison of Indirect Soil N_2O Emission Estimates for IPCC versus Current Methodologies (Tg CO_2 Eq.)

Method	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
IPCC	72.6		79.0	78.8	78.8	77.4	76.0	77.2	77.3
Current Simulation	112.6		96.2	109.1	92.3	107.6	102.6	92.7	98.2
Difference	**-40.0**		**-17.2**	**-30.3**	**-13.5**	**-30.2**	**-26.6**	**-15.5**	**-20.9**

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Table 6-21. Comparison of Total Soil N_2O Emission Estimates for IPCC versus Current Methodologies (Tg CO_2 Eq.)

Method	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
IPCC	263.8		293.9	294.9	292.8	290.4	289.2	287.2	283.1
Current Simulation*	258.6		258.4	274.2	250.0	270.2	263.3	259.0	259.9
Difference	**5.2**		**35.4**	**20.7**	**42.7**	**20.2**	**25.9**	**28.2**	**23.2**

* Unlike Table 6-13, emissions due to N applied to forest land and settlements are included here, to be consistent with IPCC estimates used in previous reports.

Compared with the IPCC methodology used in the past, the current methodology shows a smaller increase in total N_2O emissions from 1990 through 2003. The current methodology takes into account climate patterns as well as annual fluctuations in N additions. The linear regression between emissions estimated with the new method and time shows a trend toward increasing emissions of approximately 0.39 percent per year. During this time period, synthetic N fertilizer applications increased by nine percent, manure additions increased by 11 percent, and N fixation increased by about 17 percent. Soybean cropped area increased by 27 percent, corn area increased by six percent, and wheat area decreased by 20 percent. The increase in soybean area is largely responsible for the increase in fixation. Because total non-legume cropped area decreased and total fertilizer applied to major crops increased, the average rate of fertilizer applied to major crops increased by 32 percent from 1990 through 2003. The current method accounts for each of these variables plus the effects of climate variability, whereas the previous method accounted only for changes in fertilizer and manure additions. Climate interacts with N additions to control emissions with the new methodology. Total N additions from fertilizer are important with the IPCC methodology, while the current method accounts for total N additions, the area that receives the N are important, as well as environmental and management conditions. As a result, simulated N_2O emission estimates may increase or decrease non-linearly, whereas emissions always increase linearly with N applications when using the IPCC methodology.

Planned Improvements

The presented uncertainty estimate is incomplete in that uncertainty in model activity data besides N inputs (county level weather and soil type) was not included. Because county level soil and climate data are applied across the entire county, within which a great deal of variability may occur, there is inherent uncertainty in assuming that soil type and climate do not vary within a county. Future estimates of uncertainty will include sensitivity analyses so that the response of model N_2O output to variations in climate, soil type, and N inputs can be quantified. Also, a more appropriate methodology than Tier 1 will also be used in future uncertainty estimates. Future efforts at characterizing uncertainty will work toward the inclusion of all agricultural soil management subsource categories in a Monte Carlo style calculation.

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 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, or supplemental animal feed. 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; therefore, emissions from this source are minor. 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 2003 have remained relatively constant, averaging approximately 0.7 Tg CO_2 Eq. (35 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 737 Gg of CO, and 32 Gg of NO_x (see Table 6-22 and Table 6-23).

Table 6-22: Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CH_4	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.8**
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	0.3	0.4	0.3	0.3	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**	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**
Wheat	+	+	+	+	+	+	+	+

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[8] The fraction of rice straw burned each year is significantly higher than that for other crops (see “Methodology” discussion below).

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	0.3	0.2
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-23: Emissions from Field Burning of Agricultural Residues (Gg)*

Gas/Crop Type	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**33**	**37**	**38**	**37**	**38**	**37**	**34**	**38**
Wheat	7	6	6	5	5	5	4	6
Rice	4	3	3	4	4	4	3	5
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	16	17	16	17	16	15	17
Barley	1	1	1	+	1	+	+	0
Soybeans	7	10	10	10	10	11	10	9
Peanuts	+	+	+	+	+	+	+	0
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**689**	**767**	**789**	**767**	**790**	**770**	**706**	**794**
Wheat	137	124	128	115	112	98	81	117
Rice	86	72	65	76	76	77	60	96
Sugarcane	18	21	22	23	24	23	23	23
Corn	282	328	347	336	353	338	320	360
Barley	16	13	13	10	12	9	8	10
Soybeans	148	207	211	204	212	222	211	186
Peanuts	2	2	2	2	2	3	2	3
NO_x	**28**	**34**	**35**	**34**	**35**	**35**	**33**	**33**
Wheat	4	3	3	3	3	3	2	3
Rice	3	3	2	3	3	3	2	3
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	8	8	8	8	8	8	9
Barley	1	+	+	+	+	+	+	+
Soybeans	14	20	20	19	20	21	20	18
Peanuts	+	+	+	+	+	+	+	+

* Full molecular weight basis.

+ Does not exceed 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* (USDA 1994, 1998), *Crop Production 1999 Summary* (USDA 2000), *Crop Production 2000 Summary* (USDA 2001), *Crop Production 2001 Summary* (USDA 2002), *Crop Production 2002 Summary* (USDA 2003) and *Crop Production 2003 Summary* (USDA 2004). 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) and Oklahoma acreages[12] (Lee 2003, 2004). The production data for the crop types whose residues are burned are presented in Table 6-24.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each state and reports of the California Air Resources Board (CARB) (Bollich 2000; Deren 2002; Guethle 1999, 2000, 2001, 2002, 2003, 2004; Fife 1999; California Air Resources Board 1999, 2001;

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[9] The IPCC Good Practice Guidance (IPCC 2000) provided no updates 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 Florida values are used as a proxy.

Klosterboer 1999a, 1999b, 2000, 2001, 2002, 2003; Lindberg 2002, 2003, 2004; Linscombe 1999a, 1999b, 2001, 2002, 2003, 2004; Mutters 2002, 2003; Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Slaton 1999a, 1999b, 2000; Stansel 2004; Street 1999a, 1999b, 2000, 2001, 2002, 2003; Walker 2004; Wilson 2001, 2002, 2003, 2004) (see Table 6-25 and Table 6-26). The estimates provided for Florida remained constant over the entire 1990 through 2003 period, while the estimates for all other states varied over the time series. For California, the annual percents 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 2003 because of a legislated reduction in rice straw burning (Lindberg 2002) (see Table 6-26).

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 6-27. 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 6-28) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-24: Agricultural Crop Production (Gg of Product)

Crop	1990		1997	1998	1999	2000	2001	2002	2003
Wheat	74,292		67,534	69,327	62,569	60,758	53,262	43,992	63,590
Rice	7,113		8,346	8,578	9,391	8,703	9,794	9,601	9,050
Sugarcane	25,525		28,766	30,896	32,023	32,762	31,377	32,597	31,178
Corn*	201,534		233,864	247,882	239,549	251,854	241,485	228,805	256,905
Barley	9,192		7,835	7,667	6,103	6,939	5,430	4,940	6,011
Soybeans	52,416		73,176	74,598	72,223	75,055	78,671	74,291	65,795
Peanuts	1,635		1,605	1,798	1,737	1,481	1,940	1,506	1,880

*Corn for grain (i.e., excludes corn for silage).

Table 6-25: Percentage of Rice Area Burned by State

State	Percent Burned 1990-1998	Percent Burned 1999	Percent Burned 2000	Percent Burned 2001	Percent Burned 2002	Percent Burned 2003
Arkansas	13	13	13	13	16	22
California	variable[a]	27	27	23	13	14
Florida[b]	0	0	0	0	0	0
Louisiana	6	0	5	4	3	3
Mississippi	10	40	40	40	8	65
Missouri	5	5	8	5	5	4
Oklahoma	3	3	3	3	3	0
Texas	1	2	0	0	0	0

[a] Values provided in Table 6-26.

[b] Although rice is cultivated in Florida, crop residue burning is illegal. Therefore, emissions remain 0 throughout the time series.

Table 6-26: Percentage of Rice Area Burned in California

Year	California
1990	75
1991	75
1992	66
1993	60

1994	69
1995	59
1996	63
1997	34
1998	33

Table 6-27: 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 6-28: 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

One 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 1994), 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 (2000). The uncertainty estimated for the CH_4 emission ratio was 40 percent based on the range of ratios reported in IPCC (2000).

The results of the Tier 1 quantitative uncertainty analysis are summarized in Table 6-29. Field burning of agricultural residues CH_4 emissions in 2003 were estimated to be between 0.2 and 1.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 69 percent above and below the 2003 emission estimate of 0.8 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to between 0.1 and 0.7 Tg CO_2 Eq. (or approximately 68 percent above and below the 2003 emission estimate of 0.4 Tg CO_2 Eq.).

Table 6-29: Tier 1 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
Field Burning of Agricultural Residues	CH_4	0.8	69%	0.2	1.3
Field Burning of Agricultural Residues	N_2O	0.4	68%	0.1	0.7

Recalculations Discussion

For the current Inventory, a transcription error was fixed for the 1998 rice production data for California from the USDA 2000 Crop Production Summary Report (2001). The change resulted in increases of less than 0.1 Tg CO_2 Eq. (0.1 percent) in CH_4 and N_2O emissions from the field burning of agricultural residues for 1998. Additionally, the 2002 rice production data was updated from the USDA 2003 Crop Production Summary Report (2004). The change resulted in increases of less than 0.1 Tg CO_2 Eq. (0.2 and 0.4 percent, respectively) in CH_4 and N_2O emissions from the field burning of agricultural residues for that year.

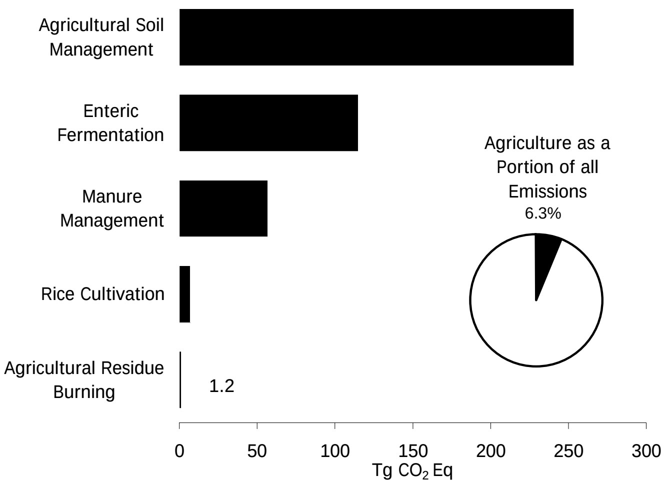
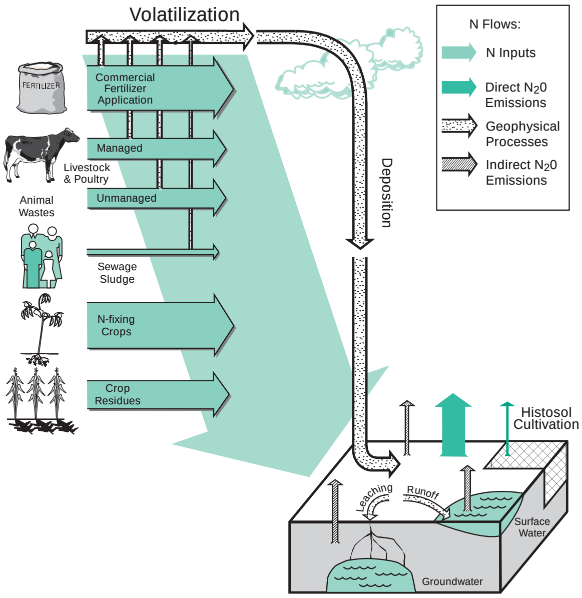


Figure 6-1: 2003 Agriculture Chapter GHG Sources

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 respresented 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 Change and Forestry

This chapter provides an assessment of the net greenhouse gas flux[1] resulting from forest lands, croplands, and settlements. IPCC *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2003) recommends reporting fluxes according to changes within and conversions between these land use types, as well as grassland and wetlands. However, consistent datasets are not available for the entire United States to allow results to be partitioned in this way. Therefore, greenhouse gas flux has been estimated for the following categories: 1) forest land remaining forest land 2) croplands remaining croplands, and 3) settlements remaining settlements. This categorization provides additional sources of information regarding N_2O emissions by major land use type.

It should be noted that other land-use and land-use change activities result in fluxes of non-CO_2 greenhouse gases to and from soils that are not comprehensively accounted for currently. These fluxes include emissions of CH_4 from managed forest soils, as well as CH_4 emissions from artificially flooded lands, which result from activities such as dam construction. Aerobic (i.e., non-flooded) soils are a sink for CH_4, so soil drainage can result in soils changing from a CH_4 source to a CH_4 sink, but if the drained soils are used for agriculture, fertilization and tillage disturbance can reduce the ability of soils to oxidize CH_4. The non-CO_2 emissions and sinks from these other land use and land-use change activities were not assessed due to scientific uncertainties about the greenhouse gas fluxes that result from these activities.

The greenhouse gas flux from forest land remaining forest land is reported using estimates of changes in forest carbon stocks and the application of nitrous oxide (N_2O) fertilizers to forest soils. Seven components of forest carbon stocks are analyzed: aboveground biomass, belowground biomass, dead wood, litter, soil organic carbon, harvested wood products in use, and harvested wood products in landfills. The estimated carbon dioxide (CO_2) flux from each of these forest components was derived from U.S. forest inventory data, using methodologies that are consistent with *LULUCF Good Practice Guidance* (IPCC 2003) and the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). In addition, this year, according to the new *LULUCF Good Practice Guidance* (IPCC 2003), N_2O emissions from fertilized forest soils are accounted for utilizing a default methodology.

Croplands remaining croplands emission estimates are a reflection of the changes in agricultural soil carbon stocks on both cropland and grazing land since the necessary datasets were not available to separate cropland and grassland fluxes. Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to use and management of cropland and grazing land, and emissions of CO_2 due to the application of crushed limestone and dolomite to agricultural soils (i.e., soil liming). The methods used to estimate all three components of flux in agricultural soil carbon stocks are consistent with the *Revised 1996 IPCC Guidelines* and the *LULUCF Good Practice Guidance (IPCC 2003).*

Fluxes resulting from settlements remaining settlements include landfilled yard trimmings and food scraps, urban trees, and soil N_2O emissions from fertilization. Changes in yard trimming and food scrap carbon stocks in landfills are estimated using analysis of life-cycle greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). Changes in carbon stocks in urban trees are estimated based on field measurements in ten U.S. cities and data on national urban tree cover, using a methodology consistent with the *LULUCF Good Practice Guidance* (IPCC 2003). Finally, this year, according to the new *LULUCF Good Practice Guidance* (IPCC 2003), N_2O emissions from fertilized settlement soils are accounted for according to a default methodology. Note that the chapter title "Land-Use Change and Forestry" has been used here to maintain consistency with the IPCC reporting structure for national greenhouse gas inventories; however, the chapter covers land-use activities, in addition to land-use change and forestry activities. Therefore, except in table titles, the term "land use, land-use change, and forestry" will be used in the remainder of this chapter.

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[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."

Unlike the assessments in other sectors, which are based on annual activity data, the flux estimates in this chapter, with the exception of those from wood products, urban trees, liming, and settlement and forest N_2O emissions, are based on periodic activity data 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. Because state surveys are collected at different times, using this data structure, the estimated CO_2 fluxes from forest carbon stocks differ at the national level from year to year. Agricultural soil carbon flux calculations are constant over multi-year intervals, with large discontinuities between intervals; however, fluxes after 1997 are inconsistent due to the method of accounting for the application of manure and sewage sludge amendments to mineral soils after 1997. 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 2003, the estimates of CO_2 flux from forests, agricultural soils, and landfilled yard trimmings and food scraps are based in part on modeled projections or 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.

Land use, land-use change, and forestry activities in 2003 resulted in a net carbon sequestration of 828 Tg CO_2 Eq. (226 Tg C) (Table 7-1and Table 7-2). This represents an offset of approximately 14 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net carbon sequestration declined by approximately 21 percent between 1990 and 2003. 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, as did annual carbon accumulation in agricultural soils. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for 1990 through 1999).

Table 7-1: Net CO_2 Flux from Land-Use Change and Forestry (Tg CO_2 Eq.)

Sink Category	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest Land Remaining Forest Land	**(949.3)**	**(851.0)**	**(805.5)**	**(751.7)**	**(747.9)**	**(750.9)**	**(751.5)**	**(752.7)**
Changes in Forest Carbon Stocks	(949.3)	(851.0)	(805.5)	(751.7)	(747.9)	(750.9)	(751.5)	(752.7)
Cropland Remaining Cropland	**(8.1)**	**(7.4)**	**(4.3)**	**(4.3)**	**(5.7)**	**(7.1)**	**(6.2)**	**(6.6)**
Changes in Agricultural Soil Carbon Stocks	(8.1)	(7.4)	(4.3)	(4.3)	(5.7)	(7.1)	(6.2)	(6.6)
Settlements Remaining Settlements	**(84.7)**	**(71.6)**	**(71.2)**	**(70.0)**	**(68.9)**	**(68.9)**	**(68.8)**	**(68.7)**
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Landfilled Yard Trimmings and Food Scraps	(26.0)	(12.9)	(12.5)	(11.4)	(10.2)	(10.3)	(10.2)	(10.1)
Total	**(1042.0)**	**(930.0)**	**(881.0)**	**(826.1)**	**(822.4)**	**(826.9)**	**(826.5)**	**(828.0)**

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

Table 7-2: Net CO_2 Flux from Land-Use Change and Forestry (Tg C)

Sink Category	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest Land Remaining Forest Land	**(259)**	**(232)**	**(220)**	**(205)**	**(204)**	**(205)**	**(205)**	**(205)**
Changes in Forest Carbon Stocks	(259)	(232)	(220)	(205)	(204)	(205)	(205)	(205)
Cropland Remaining Cropland	**(2)**	**(2)**	**(1)**	**(1)**	**(2)**	**(2)**	**(2)**	**(2)**
Changes in Agricultural Soil Carbon Stocks	(2)	(2)	(1)	(1)	(2)	(2)	(2)	(2)
Settlements Remaining Settlements	**(23)**	**(20)**	**(19)**	**(19)**	**(19)**	**(19)**	**(19)**	**(19)**
Urban Trees	(16)	(16)	(16)	(16)	(16)	(16)	(16)	(16)
Landfilled Yard Trimmings and Food Scraps	(7)	(4)	(3)	(3)	(3)	(3)	(3)	(3)
Total	**(284)**	**(254)**	**(240)**	**(225)**	**(224)**	**(226)**	**(225)**	**(226)**

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Land use, land-use change, and forestry activities in 2003 resulted in a net flux of 6.4 Tg CO_2 Eq. of N_2O (20.7 Gg) (Table 7-3 and Table 7-4). Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 14 percent between 1990 and 2003.

Table 7-3: Net N_2O Emissions from Land-Use Change and Forestry (Tg CO_2 Eq.)

Sink Category	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest Land Remaining Forest Land	**0.1**	**0.3**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
N_2O Fluxes from Soils	0.1	0.3	0.4	0.5	0.4	0.4	0.4	0.4
Settlements Remaining Settlements	**5.5**	**6.1**	**6.1**	**6.2**	**6.0**	**5.8**	**6.0**	**6.0**
N_2O Fluxes from Soils	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0
Total	**5.6**	**6.4**	**6.5**	**6.6**	**6.3**	**6.2**	**6.4**	**6.4**

Note: Totals may not sum due to independent rounding.

Table 7-4: Net N_2O Emissions from Land-Use Change and Forestry (Gg)

Sink Category	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest Land Remaining Forest Land	**0.2**	**1.0**	**1.1**	**1.5**	**1.1**	**1.3**	**1.3**	**1.3**
N_2O Fluxes from Soils	0.2	1.0	1.1	1.5	1.1	1.3	1.3	1.3
Settlements Remaining Settlements	**17.9**	**19.8**	**19.8**	**19.9**	**19.3**	**18.7**	**19.4**	**19.4**
N_2O Fluxes from Soils	17.9	19.8	19.8	19.9	19.3	18.7	19.4	19.4
Total	**18.1**	**20.7**	**20.9**	**21.4**	**20.4**	**20.0**	**20.7**	**20.7**

Note: Totals may not sum due to independent rounding.

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, all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, including all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, including 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 above 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 landfill.

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 *LULUCF Good Practice Guidance* (IPCC 2003) recommends reporting C stocks according to several land use types and conversions, specifically forest land remaining forest land, nonforest land becoming forest, and forest becoming non-forest. 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.

Note: Boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere.

Approximately 33 percent (303 million hectares) of the U.S. land area is forested (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 lands 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

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[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 about 50 percent carbon by weight.

through 2003. 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 832 Tg CO_2 Eq. (227 Tg C) over the period 1990 through 2003 (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 21 percent between 1990 and 2003. This decline was primarily due to a decline in the estimated rate of sequestration in forest soils. Inventory derived estimates of soil C stocks are based solely on forest area and type. Thus, changes in soil C over time are directly the result of changes in total forest area or changes in forest type from forest inventory data.

Table 7-5. Net Annual Changes in Carbon Stocks (Tg CO_2 Eq. yr^{-1}) in Forest and Harvested Wood Pools

Carbon Pool	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest	**(739)**	**(638)**	**(599)**	**(537)**	**(537)**	**(537)**	**(537)**	**(537)**
Aboveground Biomass	(396)	(457)	(437)	(400)	(400)	(400)	(400)	(400)
Belowground Biomass	(77)	(89)	(85)	(78)	(78)	(78)	(78)	(78)
Dead Wood	(74)	(53)	(51)	(45)	(45)	(45)	(45)	(45)
Litter	(67)	(31)	(28)	(26)	(26)	(26)	(26)	(26)
Soil Organic Carbon	(125)	(8)	1	12	12	12	12	12
Harvested Wood	**(210)**	**(213)**	**(206)**	**(215)**	**(211)**	**(214)**	**(214)**	**(216)**
Wood Products	(48)	(58)	(52)	(62)	(59)	(59)	(59)	(60)
Landfilled Wood	(162)	(155)	(154)	(153)	(152)	(155)	(155)	(155)
Total Net Flux	**(949)**	**(851)**	**(806)**	**(752)**	**(748)**	**(751)**	**(751)**	**(753)**

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^{-1}) in Forest and Harvested Wood Pools

Carbon Pool	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Forest	**(202)**	**(174)**	**(163)**	**(146)**	**(146)**	**(146)**	**(146)**	**(146)**
Aboveground Biomass	(108)	(125)	(119)	(109)	(109)	(109)	(109)	(109)
Belowground Biomass	(21)	(24)	(23)	(21)	(21)	(21)	(21)	(21)
Dead Wood	(20)	(14)	(14)	(12)	(12)	(12)	(12)	(12)
Litter	(18)	(9)	(8)	(7)	(7)	(7)	(7)	(7)

Soil Organic Carbon	(34)	(2)	0	3	3	3	3	3
Harvested Wood	**(57)**	**(58)**	**(56)**	**(59)**	**(57)**	**(58)**	**(58)**	**(59)**
Wood Products	(13)	(16)	(14)	(17)	(16)	(16)	(16)	(16)
Landfilled Wood	(44)	(42)	(42)	(42)	(41)	(42)	(42)	(42)
Total Net Flux	**(259)**	**(232)**	**(220)**	**(205)**	**(204)**	**(205)**	**(205)**	**(205)**

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 the average carbon density in forests by state, estimated for 2004.

Table 7-7. Carbon Stocks (Tg C) in Forest and Harvested Wood Pools

Carbon Pool	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Forest	**39,498**	**40,812**	**40,986**	**41,149**	**41,296**	**41,442**	**41,589**	**41,735**	**41,882**
Aboveground Biomass	14,114	14,928	15,053	15,172	15,281	15,390	15,499	15,608	15,717
Belowground Biomass	2,805	2,963	2,987	3,011	3,032	3,053	3,074	3,095	3,117
Dead Wood	2,444	2,572	2,587	2,600	2,613	2,625	2,638	2,650	2,662
Litter	4,496	4,598	4,606	4,614	4,621	4,628	4,636	4,643	4,650
Soil Organic Carbon	15,640	15,750	15,752	15,752	15,749	15,745	15,742	15,738	15,735
Harvested Wood	**1,915**	**2,307**	**2,365**	**2,421**	**2,480**	**2,537**	**2,595**	**2,654**	**2,713**
Wood Products	1,134	1,232	1,248	1,262	1,279	1,295	1,311	1,327	1,344
Landfilled Wood	781	1,074	1,117	1,159	1,200	1,242	1,284	1,327	1,369
Total Carbon Stock	**41,414**	**43,119**	**43,351**	**43,570**	**43,775**	**43,979**	**44,184**	**44,389**	**44,594**

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 2003 requires estimates of C stocks for 2003 and 2004.

Figure 7-2: Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools (Tg C yr^{-1})

Note: Estimates for harvested wood are based on the same methodology and data as the previous U.S. Inventory (EPA 2004). Estimates for all pools are based on measured forest inventory data as described in the text. Total Net includes all forest pools: biomass, dead wood, litter, forest soils, wood products, and landfilled wood.

Figure 7-3: Average Carbon Density in the Forest Tree Pool in the Conterminous U.S. During 2004.

Methodology

The methodology described herein is consistent with *LULUCF Good Practice Guidance* (IPCC 2003) and the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates of net C flux from Land-Use Change and Forestry, including all pools except harvested wood, 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 inventory 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]). However, over time individual state surveys gradually started to include reserved and less productive forest lands. 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 (Miles et al. 2001, Alerich et al. 2004), 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 each 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 forestlands, including reserved and less productive lands. Inventories are assumed to represent stocks as of January 1 of the inventory year.

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 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 volume-to-biomass conversion factors for different types of forests as presented in 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).

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[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 U.S. 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 U.S., which represented 79 percent of all forest lands over the same area (Smith et al. 2004b).

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 lands 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. Thus, the number of separate stock estimates for each state was one less than the number of available inventories. 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. Note that inventories are assumed to represent stocks as of January 1 of the inventory year; thus, stocks in 1989 and 1993 can be used to estimate flux for 1989 through 1992, for example. 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) and 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 2003, 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 of forest land (Miles et al. 2001). For larger areas, the uncertainty in area is concomitantly smaller. For volume data, the accuracy is targeted to be 5 percent for each 28,300 m^3 at the same confidence level. An analysis of uncertainty in growing stock volume data for timber producing lands was undertaken for five states: Florida, Georgia, North Carolina, South Carolina, and Virginia (Phillips et al. 2000). Nearly all of the uncertainty was found to be 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). Based on these accuracy guidelines and these results for the Southeastern United States, forest area and volume data for the conterminous United States are expected to be reasonably accurate, although estimates of small changes in growing stock volume may have substantial uncertainty.

In addition to uncertainty in growing stock volume, there is uncertainty associated with the estimates of C stocks in other ecosystem pools. 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, for example 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 (2000b) 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).

Recent studies have begun to quantify the uncertainty in national-level forest C budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000a) report on an uncertainty analysis they conducted on C sequestration in privately owned timberlands throughout the conterminous United States. These studies are not directly comparable to the estimates in this chapter because they used an older version of the FORCARB model and are based on older data. However, the relative magnitudes of the uncertainties are informative. For the period 1990 through 1999, the true mean C flux was estimated to be within 15 percent of the reported mean at the 80 percent confidence level. The corresponding true mean C stock estimate for 2000 was within approximately 5 percent of the reported mean value at the 80 percent confidence level. The relatively greater uncertainty in flux estimates compared to stock estimates is roughly similar to that found for estimates of growing stock volume discussed above (Phillips et al. 2000). In both analyses, there are greater relative uncertainties associated with smaller estimates of flux. Uncertainty in the estimates presented in this inventory may be greater than those presented by Heath and Smith (2000a) for several reasons. Most importantly, their analysis did not include uncertainty in growing stock volume data or uncertainties in stocks and fluxes of C from harvested wood.

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 2003 flux estimate for forest C stocks is estimated to be between (1,120.5) and (383.5) Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 49 percent below to 49 percent above the 2003 flux estimate of (752.7) Tg CO_2 Eq.

Table 7-8: Tier 2 Quantitative Uncertainty Estimates for CO_2 Net Flux from Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 Flux Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to 2003 Estimate**[a] **(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Forests Remaining Forests: Changes in Forest Carbon Stocks	CO_2	(752.7)	(1,120.5)	(383.5)	-49%	+49%

[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 USDA Forest Service Forest Inventory and Analysis 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 Forest Inventory and Analysis 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 Forest Inventory and Analysis 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 Homepage).

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 Methods 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 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. Forest Inventory and Analysis data and some model projections are given in English units, but C stock estimates were developed using metric units. To avoid unit conversion errors, a standard conversion table in electronic form was used (Appendix B of Smith et al. 2001). Finally, C stock estimates were compared with previous inventory report estimates to assure 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 2003). Methods for estimating soil organic carbon are new for the current Inventory; differences are in the interpretation of STATSGO data and their relationship with FIA survey data as described by Amichev and Galbraith (2004)—see Annex 3.12 for additional information. Similar to that reported in the previous Inventory, estimates of forest C stocks and fluxes are based on forest inventory data from individual states rather than regions, and the data collected in states were assigned an average survey inventory plot date rather than simply assigned the year for which the database was compiled. However, the selection and compilation of survey data was implemented differently for the current Inventory, and there were some important differences in the underlying data.

Three differences in methods can affect the non-soil forest C estimates. First, the selection of the datasets representing individual state surveys was independent of last year's selections. Both RPA and the newer FIADB datasets were considered, whereas last year only RPA data were used. The RPA data represent specific compilations of survey data and include some older data not currently available in the FIADB. Using both ensured the most recent data were used, yet older data were available as needed. Inventory data—even older surveys—are occasionally modified so that RPA and FIADB data of ostensibly the same survey may have some slight differences that can affect the C estimates. This is likely to have a very minor effect on recalculation of C stocks. Another minor change in method is that fluxes were separately determined from the original survey data for each state for each pool; in contrast, last year stocks were interpolated and summed to a national total for each year before flux was calculated. Finally, separate stocks and fluxes were determined for National Forest lands where, in the past, independent surveys were conducted at distinctly different times.

Pool definitions have changed for the current Inventory, as suggested by IPCC *LULUCF Good Practice Guidance* (IPCC 2003). In previous Inventories, the pools were trees, understory, forest floor, down dead wood, and forest soils. The forest soil pool is now soil organic carbon; forest floor is called litter. The previous tree pool included both above- and belowground biomass and mass of standing dead trees. The mass of standing dead trees was added to the down dead wood pool and is called dead wood. The remainder of the tree pool, live biomass, as well as the understory pool, was split into above- and belowground portions. The aboveground tree and understory pools were summed into the aboveground biomass pool; the belowground portions of these pools were added to create the belowground biomass pools.

Two changes in the use of data are also likely to affect the recalculation of C. The equations used to estimate tree C from forest inventory data have been revised slightly; the net effect is that total tree C (live plus standing dead trees, which are part of both the biomass and dead wood pools as summarized here) calculated for the 2002 RPA database (Smith et al. 2004b) was 0.3 percent greater with the new set of equations relative to those used last year. Perhaps the largest effect on C recalculations is that for the previous Inventory the final C stocks were modeled. This year, however, values are simply extrapolated. The principal reason for eliminating the projections was the difficulty in establishing projections consistent with the available forest inventory data.

Overall, these changes resulted in an average annual increase of 103.3 Tg CO_2 Eq. (16 percent) in forest carbon stocks for the period 1990 through 2002.

Planned Improvements

The Forest Inventory and Analysis program has adopted a new annualized design, such that a portion of each state will be surveyed each year (Gillespie 1999). The annualized survey also includes measuring attributes that are needed to estimate C in various pools, such as soil C and forest floor C, on a subset of the plots. During the next several years, the use of annual data, including new data on soil and forest floor C stocks, and new data on non-timberlands, will improve the precision and accuracy of estimates of forest C stocks and fluxes.

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.

N_2O Fluxes from Soils (IPCC Source Category 5.A.1)

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 2003 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 2003 forest soil N_2O emissions are roughly equivalent to 3.3 percent of the total forest soil carbon flux, and 0.07 percent of the total sequestration in standing forests, and are summarized in Table 7-9.

Table 7-9. N_2O Fluxes from Soils in Forests Remaining Forests (Tg CO_2 Eq. and Gg)

Forests Remaining Forests: N_2O Fluxes	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**

from Soils									
Tg CO_2 Eq.	0.06		0.30	0.35	0.47	0.35	0.39	0.39	0.39
Gg	0.19		0.96	1.14	1.50	1.14	1.26	1.26	1.26

Methodology

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 and 2003, 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 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 2003 emission estimate of 0.4 Tg CO_2 Eq.

Table 7-10: Tier 1 Quantitative Uncertainty Estimates of N_2O Fluxes from Forest Soils (Tg CO_2 Eq. and Percent)

IPCC Source Category	Gas	Year 2003 Emissions (Tg CO_2 Eq.)	Uncertainty (%)	Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)

				Lower Bound	**Upper Bound**
Forests Remaining Forests: N_2O Fluxes from Soils	N_2O	0.4	96 to 483%	0.01	2.3

Recalculations Discussion

The current Inventory reports N_2O emissions from soils in forested areas separately for the first time. In previous Inventories, N_2O emissions from this source were implicitly included with N_2O emissions from agricultural soils. The net effect of separating forest soils from agricultural soils for the current Inventory is to reduce emissions reported from the agricultural sector by a very small amount. However, because the methods for reporting that source have changed significantly this year, it is impossible to isolate the magnitude of change caused by this recalculation alone on the overall differences in N_2O emissions from agricultural soils. The 2003 direct emission estimate for N_2O from forest soils amounts to an offset of total forest carbon sequestration of approximately 0.5 percent (including standing forests and wood products).

7.2. Land Converted to Forest Land (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 lands are 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 quantify CO_2 or N_2O fluxes from land converted to forest land at this time.

7.3. Croplands Remaining Croplands

Changes in Agricultural Soil Carbon Stocks (IPCC Source Category 5B1)

Soils contain both organic and inorganic forms of carbon (C) that contribute to the total soil carbon stock. It is the organic soil carbon (SOC) stocks in mineral and organic soils that may respond to management practices by producing or sequestering greenhouse gases. The IPCC methodology for estimating impacts of agricultural practices on soil C stocks (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: 1) agricultural land-use and land-management activities on mineral soils; 2) agricultural land-use and land-management activities on organic soils; and 3) liming of soils. Nitrous oxide emissions from agricultural soils are presented within the Agriculture sector.

Mineral soils contain comparatively low amounts of organic C, much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic C (by weight), although some mineral soils that experience long-term saturation during the year may contain significantly more C (NRCS 1999). Mineral subsoils contain even lower amounts of organic C (NRCS 1999, Brady and Weil 1999). When mineral soils undergo conversion from their native state to agricultural use, as much as half the SOC can be lost to the atmosphere. The rate and ultimate magnitude of C loss will depend on native vegetation, 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. Eventually, the soil will reach a new equilibrium that reflects a balance between C accumulation from plant biomass and C loss through oxidation. Any changes in land-use or management practices that result in increased organic inputs or decreased oxidation of organic C (e.g., improved crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of SOC until a new equilibrium is achieved.

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 is also typically extremely deep. Organic soils form under waterlogged conditions, in which minimal decomposition of plant residue occurs. When organic soils are cultivated, they are first drained which, together with tilling or mixing of the soil, aerates the soil, and thereby accelerates the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layers, C loss from cultivated organic soils can continue over long periods of time.

When organic soils are disturbed for cultivation purposes, which invariably include drainage, the rate at which organic matter decomposes and CO_2 emissions are generated, is determined primarily by climate, composition (i.e., decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for annual crop production results in greater C loss than conversion to pasture or forests, due to deeper drainage and more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

The last category of the IPCC methodology addresses emissions from lime (in the form of crushed limestone ($CaCO_3$)) and dolomite ($CaMg(CO_3)_2$) additions 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. Complete degradation of applied limestone and dolomite could take several years, but it could also take significantly less time, depending on the soil conditions and the type of mineral applied.

The estimates in this section include management impacts on mineral and organic soil C stocks for croplands and grasslands. Due to limited data availability, it is impossible to differentiate between the stock changes resulting from management practices on croplands or grasslands and those resulting from conversions between the two (i.e., statistics have been developed in a manner that only net changes in conversions are determined with no tracking of the total amount of land converted between cropland and grassland uses).

Total SOC stock depends on the balance between inputs of organic material (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and loss of C through decomposition. 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. 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.

Of the three activities (those associated with mineral soils, organic soils, and liming of soils) land use and management of mineral soils was the most important component of total flux during the 1990 through 2003 period. C sequestration in mineral soils in 2003 was estimated to be approximately 51.7 Tg CO_2 Eq. (14 Tg C), while emissions from organic soils were estimated to be 35.6 Tg CO_2 Eq. (10 Tg C), and emissions from the practice of liming were estimated at 9.5 Tg CO_2 Eq. (3 Tg C). Together, the three activities accounted for net sequestration of approximately 6.6 Tg CO_2 Eq. (2 Tg C) in 2003. Total annual net CO_2 flux was negative (i.e., net sequestration occurred) each year over the inventory period, although the net C storage in soils did decline by 18 percent between 1990 and 2003. Net sequestration was largely due to annual cropland enrolled in the Conservation Reserve Program, cropland converted to permanent pastures and hay production, a reduction in the frequency of summer-fallow use in semi-arid areas, and some increase in the adoption of conservation tillage (i.e., reduced and no till practices). The decline in net sequestration was attributed to two management practices. First, the amount of organic soils that were drained for agricultural production increased during the time period, thus leading to higher emissions. Second, manure production declined over the inventory period, particularly during the last few years, and this decline reduced the amount of crop and grazing lands receiving organic amendments, and thus there was a small decline in C sequestration attributed to this activity.

The spatial variability in annual CO_2 flux for mineral and organic soils is displayed in Figure 7-4 through Figure 7-7. The highest rates of sequestration occur mostly in the southern and northern Great Plains, southern portions of the corn-belt in the Midwest, and the lower Mississippi River Valley. Sequestration rates are also relatively high in the southeastern United States. These regions either have high Conservation Reserve Program enrollment (particularly the Great Plains region), and/or have adopted conservation tillage at a higher rate than other regions of the country. The greatest organic soil emission rates are from drained peatlands 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.

Table 7-11: Net CO_2 Flux from Agricultural Soils (Tg CO_2 Eq.)

Soil Type	1990		1997	1998	1999	2000	2001	2002	2003
Mineral Soils	(52.4)		(51.7)	(49.5)	(48.9)	(50.0)	(51.6)	(51.9)	(51.7)
Organic Soils	34.8		35.6	35.6	35.6	35.6	35.6	35.6	35.6
Liming of Soils	9.5		8.7	9.6	9.1	8.8	9.0	10.1	9.5

Total Net Flux	**(8.1)**		**(7.4)**	**(4.3)**	**(4.3)**	**(5.7)**	**(7.1)**	**(6.2)**	**(6.6)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Estimates include the change in C storage resulting from the annual application of sewage sludge and the change in manure amendments or Conservation Reserve Program enrollment after 1997.

Table 7-12: Net Carbon Flux from Agricultural Soils (Tg C)

Soil Type	**1990**		**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Mineral Soils	(14.3)		(14.1)	(13.5)	(13.3)	(13.6)	(14.1)	(14.1)	(14.1)
Organic Soils	9.5		9.7	9.7	9.7	9.7	9.7	9.7	9.7
Liming of Soils	2.6		2.4	2.6	2.5	2.4	2.4	2.8	2.6
Total Net Flux	**(2.2)**		**(2.0)**	**(1.2)**	**(1.2)**	**(1.5)**	**(1.9)**	**(1.7)**	**(1.8)**

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. Estimates include the change in C storage resulting from the annual application of sewage sludge and the change in manure amendments or Conservation Reserve Program enrollment after 1997.

Figure 7-4: Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1990-1992

Figure 7-5: Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1993-2003

Figure 7-6: Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agricultural Management, 1990-1992

Figure 7-7: Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agricultural Management, 1993-2003

The flux estimates presented here are restricted to CO_2 fluxes 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.[5]

Methodology

The methodologies used to calculate net CO_2 flux from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997, Ogle et al. 2002, Ogle et al. 2003), except where noted below. Additional details on the methodology and data used to estimate flux from mineral and organic soils are described in Annex 3.13.

Mineral and Organic Soils

Mineral SOC stocks were estimated for 1982, 1992, and 1997, as well as CO_2 emissions from organic soils, for the conterminous United States and Hawaii using U.S. data on climate, soil types, land use and land management activity data, reference C stocks (for agricultural soils rather than native soils) and field studies addressing management effects on SOC storage. National-scale data on land-use and management changes over time were obtained from the *1997 National Resources Inventory* (USDA-NRCS 2000). The *1997 National Resources Inventory* provides land use/management data and soils information for more than 400,000 locations in U.S. agricultural lands. Two other sources were used to supplement the land-use information from the *1997 National*

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[5] Nitrous oxide emissions from agricultural soils and methane emissions from rice fields are addressed under the Agricultural Soil Management and Rice Cultivation sections, respectively, of the Agriculture sector.

Resources Inventory. The Conservation Technology Information Center (CTIC 1998) provided data on tillage activity, with adjustments for long-term adoption of no-till agriculture (Towery 2001), and Euliss and Gleason (2002) provided activity data on wetland restoration of Conservation Reserve Program Lands. Manure N production was derived from USDA livestock population data (USDA 1994a,b; 1995a,b; 1998a,b; 1999a-e; 2000a-g; 2001a-f; 2002a-f; 2003a-f), the FAOSTAT database (FAO 2003), and Lange (2000). Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safley (2000), USDA (1996, 1998c), and ASAE (1999); daily rates of N excretion from ASAE (1999) and USDA (1996); and information about the fraction of poultry litter used as a feed supplement from Carpenter (1992).

For estimating the emissions from both mineral and organic soils, Major Land Resource Areas were used as 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).[6] Major Land Resource Areas were classified into climate zones according to the IPCC categories using the Parameter-Evaluation Regressions on Independent Slopes Model (PRISM) climate-mapping program of Daly et al. (1994).

For mineral soils, 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* (IPCC/UNEP/OECD/IEA 1997). 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. management factors[7] were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, land-use change between cultivated and uncultivated conditions, as well as C loss rates associated with drainage of organic soils under agricultural management (Ogle et al. 2003, Ogle et al. in review). U.S. management factors associated with organic matter amendments and improving grazing lands were not estimated because of few studies analyzing those impacts. Instead, IPCC factors from *LULUCF Good Practice Guidance* (IPCC 2003) formed the basis for quantifying the effect of those activities. Euliss and Gleason (2002) provided the data for computing the change in SOC storage resulting from restoration of Conservation Reserve Program lands (Olness et al. in press, Euliss et al. in prep).

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 density functions for U.S.-specific management factors, reference C stocks, and land-use activity data (Ogle et al. 2003, Ogle et al. 2002). 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 2003 was determined by calculating the annual change in stocks between 1992 and 1997. Annual C flux estimates for mineral soils between 1990 and 2003 were adjusted to account for additional C sequestration from sewage sludge applications, as well as gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment and manure N production. For the entire inventory period, the amount of land amended with sewage sludge was estimated from N application data from the Soil Management section of the Agriculture chapter of this volume, and an assumed application rate derived from Kellogg et al. (2000). To estimate the impact of manure amendments after 1997, the change in manure N production was determined relative to the amount produced in 1997, and then similar to sewage sludge calculations, the production values were multiplied by the assumed application rate to determine the change in land area that was amended with manure. Carbon storage rate was estimated at 0.22 metric tons C per hectare per year for both the manure and sewage sludge amendments. To estimate the impact of enrollment in the Conservation Reserve

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[6] The polygons displayed in Figure 6-5 through Figure 6-8 are the Major Land Resource Areas.

[7] Management factors have been derived from published literature to reflect changes in tillage, cropping rotations and intensification, land-use change between cultivated and uncultivated conditions, as well as drainage of organic soils.

Program after 1997, the change in enrollment acreage relative to 1997 was derived based on Barbarika (2004), and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year.

Annual C emission estimates from organic soils between 1990 and 2002 were derived using *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), 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 land 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 2003.

Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied (see Table 7-13) by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite) (IPCC 2003).[8] These emission factors are based on the assumption that all of the C in these materials evolves as CO_2 in the same year in which the minerals are applied. 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, 2003, 2004; USGS 2002, 2003, 2004). 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).

To estimate the "unspecified" and "estimated" amounts of crushed limestone and dolomite applied to agricultural soils, the fractions of "unspecified" and "estimated" production that were applied to agricultural soils in a specific year were assumed to be equal to the fraction of "specified" production that was applied to agricultural soils in that same year. In addition, data were not available for 1990, 1992, and 2003 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 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).

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 *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: Quantities of Applied Minerals (Thousand Metric Tons)

Mineral	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**

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[8] The default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) and the *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) is incorrect. The value provided is 0.122 metric ton carbon/metric ton of dolomite; the correct value is 0.130 metric ton carbon/metric ton of dolomite.

Limestone	19,012	20,312	17,984	15,609	16,686	17,297	17,479	16,539	14,882	16,894	15,863	16,097	20,449	19,163
Dolomite	2,360	2,618	2,232	1,740	2,264	2,769	2,499	2,989	6,389	3,420	3,812	3,951	2,353	2,205

Uncertainty

Uncertainties for mineral and organic soils were quantified using a Monte Carlo Approach by constructing probability distribution functions (PDF) for inputs to the IPCC equations, including management factors, C emission rates for organic soils, and land use and management activity data, and then simulating a range of values using the Monte Carlo framework (Ogle et al. 2003, Annex 3.13). Uncertainty estimates do not include sewage sludge impacts on SOC storage for any year in the inventory period, or contributions of changing manure management and enrollment in the Conservation Reserve Program after 1997. PDFs for management 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 National Resources Inventory (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 Conservation Technology and Information Center, 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 crop and grazing land area receiving manure amendments were based on the data sources given for manure amendments in the methodology section, and a statistical relationship between production and the amount of land area that is amended according to manure management information 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 Tier 2 quantitative uncertainty analysis are summarized in Table 7-14. CO_2 flux from mineral and organic agricultural soil carbon stocks in 2003 was estimated to be between -40.0 and +5.9 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 148 percent below to 136 percent above the 2003 flux estimate of -16.1 Tg CO_2 Eq.

Table 7-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Mineral and Organic Agricultural Soil Carbon Stocks (Tg CO_2 Eq. and Percent)

			Uncertainty Range Relative to Flux Estimate[a]			
			(Tg CO_2 Eq.)		**(%)**	
Source	**Gas**	**2003 Flux Estimate (Tg CO_2 Eq.)**	**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mineral and Organic Soil Uncertainty	CO_2	(16.1)	(40.0)	5.9	-148%	+136%

[a] Includes mineral and organic soils only; estimates do not include the change in C storage resulting from the annual application of sewage sludge, or the change in manure amendments or Conservation Reserve Program enrollment after 1997.

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

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 lands. In addition, the same management factors (i.e., emission factors) were used each year for calculating the impact of land use and management on SOC stocks. There is no evidence that changing management practices has a quantitatively different impact on SOC stocks over the inventory period. For example, changing from conventional to no-till management in 1990 is assumed to have the same impact on soil C stocks over the course of this first year as it is over the course of each year in the 20 year period following the management change.

Although the mineral and organic soil estimates have been improved during the last two years using a Monte Carlo approach with the incorporation of U.S.-specific reference C stocks management factor values, and a more comprehensive accounting of manure amendment impacts on SOC storage, several limitations remain in the analysis. First, minimal data exist on where and how much sewage sludge has been applied to U.S. agricultural lands and the accounting of this activity appears to be much more difficult than the related-activity of using manure to amend agricultural soils. Consequently, uncertainties have not been estimated for the change in SOC storage resulting from sludge applications. Second, due to the IPCC requirement that inventories include all land areas that are potentially subject to land-use change, the *1997 National Resources Inventory* dataset includes some points designated as non-agricultural land-uses if the points were once categorized as agricultural land use and their designation changed during the period from 1992 to 1997. The non-agricultural land uses are urban, water, and miscellaneous non-cropland (e.g., roads and barren areas). 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). Third, 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 the estimates of emissions from liming result from both the methodology and the activity data. The IPCC method assumes that all inorganic C in the applied minerals evolves to CO_2, and that this degradation occurs in the same year that the minerals are applied. However, recent research has shown that liming can either be a C source or a sink, depending upon weathering reactions, which are pH dependent (Hamilton et al. 2002). Moreover, it can take several years for agriculturally applied limestone and dolomite to degrade completely. However, application rates are fairly constant over the entire time series, so this latter assumption may not contribute significantly to overall uncertainty.

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 lime applications was estimated at 15 percent (Tepordei 2003). While IPCC provides no uncertainty values for the emission factor from this subsource, there is uncertainty stemming primarily from the inherent assumption that all applications are converted to CO_2 within the year of application. In fact, limestone may persist in the soil for 3 to 4 years following application (Nardozzi 2004), indicating that emissions may continue throughout that period of time. Taking this into account, the resulting uncertainty in the emission factor is estimated to be 75 percent. The preliminary results of the Tier 1 quantitative uncertainty analysis are summarized in Table 7-15. Liming of agricultural soils CO_2 emissions in 2003 were estimated to be between 2.2 and 10.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 76 percent above and below the 2003 emission estimate of 9.5 Tg CO_2 Eq.

Table 7-15: Tier 1 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

IPCC Source Category	**Gas**	**Year 2003 Emissions (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound***
Liming of Agricultural Soils	CO_2	9.5	76%	2.2	10.9

* Because the current Inventory methodology assumes that all of the limestone and dolomite decomposes in the year of application, the emission factors could be significantly lower, but could not be higher. Consequently, the emissions estimate may only be higher due to the uncertainty in the application data. Therefore, while normally, Tier 1 analyses generate a symmetrical distribution of uncertainty around the emission estimate, an asymmetrical distribution was necessarily imposed here.

It is not currently possible to combine the results of this Tier 1 uncertainty analysis with those of the Tier 2 uncertainty analyses for CO_2 fluxes from mineral soils and histosols.

Recalculations Discussion

The estimates of changes in agricultural SOC stocks have been modified in several ways. First, uncertainty in manure amendments was evaluated and incorporated into the general inventory calculations for agricultural soil C, using the Tier 2 IPCC methodology (IPCC/UNEP/OECD/IEA 1997). In previous Inventories, the change in SOC storage attributed to organic amendments was estimated as a post-analysis calculation using a simplistic activity-based approach. Incorporating amendment data into the IPCC analysis led to a decline in the estimated change for SOC storage attributed to manure management, relative to previous years. The activity-based approach assumed that all of the applied manure was leading to an increase in SOC, while the IPCC method only accounted for the changes in organic amendments from the baseline year to estimate the impact on SOC storage. In general, the IPCC approach assumes that impacts on SOC storage are manifested in the first 20 years following a management change, and consequently, this method does not account for smaller residual changes in SOC storage that can occur in later years. However, the activity-based approach also has limitations because it does not account for the possibility that a portion of the manure applied in a year is simply maintaining SOC storage from past applications. In fact, the production of manure has not changed to a large extent since 1982 according to USDA statistics (see Annex 3.13), and, therefore, many of the current amendments are only serving the purpose of maintaining past storage. Hence, incorporating manure management into the IPCC calculations has produced a more conservative estimate by reducing the potential for over-estimating the impact of longer-term manure amendments, but also does not capture the residual change in SOC storage occurring after the first 20 years.

Two additional revisions have been incorporated into the analysis since the previous Inventory. As part of the revision, management factors provided in the IPCC *LULUCF Good Practice Guidance* (IPCC 2003) now form the basis to estimate management impacts for which U.S.-specific factors have not been derived (i.e., improving grazing lands and organic amendments). Previously, defaults factor values from the *Revised 1996 IPCC Guidelines* formed the basis for these calculations using the IPCC method, but greater disaggregation of management factors by climate in the IPCC *LULUCF Good Practice Guidance* was assumed to produce more realistic estimates of those management impacts, compared to the single global values provided in the *Revised 1996 IPCC Guidelines*.

Lastly, emissions from organic soils have changed slightly from those reported in the previous inventory, as a result of revising the land area included in the emission calculation. In previous years, lands that were converted between agricultural and non-agricultural uses (i.e., urban, water, and miscellaneous non-cropland) were not included in the estimation of emissions from organic soils, and this led to a slight under-estimation of emissions from organic soils. Specifically, a small amount of land area under agricultural management in 1992 or 1997 was not included in the emission calculation because it had been converted from a non-agricultural use.

Estimates of CO_2 emissions from agricultural soil management have been revised due to methodological and historical data changes in the calculations of N from livestock that is applied to soils. These changes include corrections to: the typical animal mass value for beef cows and calves; the accounting of sheep in New England states; state broiler populations; and updated NASS animal population estimates for the years 1998 through 2001 (NASS 2000). Additionally, the factor for converting short tons to metric tons was revised to include another significant digit, and the percent residue applied for rice in the year 2001 was corrected. In combination, these changes resulted in a minor effect on the agricultural soil C estimates with a reduction in the CO_2 sink by less than 1 percent.

The quantity of applied minerals reported in the previous inventory for 2002 has been revised. Consequently, the reported emissions resulting from liming in 2002 have also changed. In the previous inventory, to estimate 2002 data, the previous year’s fractions were applied to a 2002 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2003* (USGS 2003). 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 2002. These values have replaced those used in the previous inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

Overall, these changes resulted in an average annual decrease of 14.2 Tg CO_2 Eq. (67 percent) in agricultural soil carbon stocks for the period 1990 through 2002.

Planned Improvements

A major planned improvement is currently underway that will enhance reporting of changes in agricultural soil C stocks and deals with an alternative inventory approach to better represent between-year variability in annual fluxes. This new annual activity-based inventory will use the Century ecosystem simulation model, which relies on actual climate, soil, and land use/management databases to estimate variation in fluxes. This inventory will provide a more robust accounting of C stock changes in U.S. agricultural lands than the more simplistic IPCC soil C accounting approach. This approach is likely to be used in the future for reporting of land use and management impacts on agricultural soil C stocks, and therefore a short description of this method compared to the IPCC approach is provided.

The Century ecosystem model has been widely tested and found to be successful in simulating those processes affecting SOC storage (Metherell et al. 1993, Parton et al. 1994). Simulation modeling differs from the IPCC approach in that annual changes are computed dynamically as a function of inputs of C and N to soil (e.g., crop residues, manure) and C emissions from organic matter decomposition, which are governed by climate and soil factors as well as management practices. The model distinguishes between all major field crops (maize, wheat and other small grains, soybean, sorghum, cotton) as well as hay and pasture (grass, alfalfa, clover). Management variables include tillage, fertilization, irrigation, drainage, and manure addition.

Input data are largely derived from the same sources as the IPCC-based method (i.e., climate variables come from the Parameter-Evaluation Regressions on Independent Slopes Models (PRISM) database; crop rotation, irrigation and soil characteristics from the National Resources Inventory (NRI); and tillage data from the Conservation Technology Information Center (CTIC)). In addition, the Century analysis uses detailed information on crop rotation-specific fertilization and tillage implements obtained from USDA's Economic Research Service. The main difference between the methods is that the climate, soil, and management data serve as driving variables in the Century simulation, whereas in the IPCC approach these data are more highly aggregated and are used for classification purposes. In the Century-based analysis, land areas having less than 5 percent of total area in crop production are excluded and several less-dominant crops (e.g., vegetables, sugar beets and sugar cane, potatoes, tobacco, orchards, and vineyards), for which the model has not yet been parameterized, are not included. Thus, the total area included in the Century analysis (149 million hectares) will be smaller than the corresponding area of cropland (165 million hectares) included in the IPCC estimates.

Preliminary results using the Century model suggest (as with the IPCC model) that U.S. cropland mineral soils (excluding organic soils) are currently acting as a C sink. The Century model estimates that U.S. cropland soils sequestered an average of approximately 77 Tg CO_2 Eq. annually (21 Tg C/year) for 1992 through 1997. Organic soils (which contribute large C losses) have not yet been simulated by Century.

As with the IPCC method, increases in mineral SOC stocks in the Century analysis are associated with reduced tillage, Conservation Reserve Program lands, reduced bare fallow and some increase in hay area. However, the Century analysis also includes the effect of a long-term trend in increasing residue inputs due to higher productivity on cropland in general, contributing to increasing SOC stocks. Work is underway to refine model input data and to estimate uncertainty for the dynamic model approach.

Potential advantages of a dynamic simulation-based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of soil C change. This would facilitate annual estimates of SOC stock changes and CO_2 emissions from soils that would better reflect interannual variability in cropland production and weather influences on C cycle processes.

7.4. Lands Converted to Croplands (Source Category 5B2)

Land-use change is constantly occurring, and areas under a number of differing land use types are converted to croplands each year, just as croplands are converted to other uses. However, while the C stocks for Land Converted to Cropland are included in the Croplands Remaining Croplands section, it is not possible to sub-divide it and determine the magnitude of the change at this time. Additionally, given the lack of available land use information relevant to this particular IPCC source category, it is not possible to quantify the N_2O flux from Lands Converted to Cropland at this time.

7.5. 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 2003). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 20 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 34 percent in 2003. There is considerably less centralized composting of food scraps; generation has grown by 26 percent since 1990, though the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 77 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 10.1 Tg CO_2 Eq. in 2003 from 26.0 Tg CO_2 Eq. in 1990 (Table 7-16 and Table 7-17).

Table 7-16: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	**1990**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Yard Trimmings	**(23.2)**	**(11.3)**	**(10.4)**	**(9.6)**	**(8.5)**	**(7.2)**	**(7.4)**	**(7.5)**	**(7.5)**
Grass	(2.5)	(1.0)	(0.9)	(0.8)	(0.7)	(0.6)	(0.7)	(0.7)	(0.7)
Leaves	(11.2)	(5.9)	(5.4)	(5.1)	(4.5)	(4.0)	(4.0)	(4.0)	(4.0)
Branches	(9.6)	(4.4)	(4.0)	(3.7)	(3.2)	(2.6)	(2.7)	(2.7)	(2.8)
Food Scraps	**(2.8)**	**(2.2)**	**(2.6)**	**(2.9)**	**(2.9)**	**(3.0)**	**(2.9)**	**(2.7)**	**(2.6)**
Total Net Flux	**(26.0)**	**(13.5)**	**(12.9)**	**(12.5)**	**(11.4)**	**(10.2)**	**(10.3)**	**(10.2)**	**(10.1)**

Note: Totals may not sum due to independent rounding.

Table 7-17: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	**1990**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Yard Trimmings	**(6.3)**	**(3.1)**	**(2.8)**	**(2.6)**	**(2.3)**	**(2.0)**	**(2.0)**	**(2.0)**	**(2.0)**
Grass	(0.7)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(3.0)	(1.6)	(1.5)	(1.4)	(1.2)	(1.1)	(1.1)	(1.1)	(1.1)
Branches	(2.6)	(1.2)	(1.1)	(1.0)	(0.9)	(0.7)	(0.7)	(0.7)	(0.8)
Food Scraps	**(0.8)**	**(0.6)**	**(0.7)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.7)**	**(0.7)**
Total Net Flux	**(7.1)**	**(3.7)**	**(3.5)**	**(3.4)**	**(3.1)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.7)**

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, 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 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 in the United States: 2001 Facts and Figures* (EPA 2003). That report provides data for 1960, 1970, 1980, 1990, 1995, and 1999 through 2001. 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: 2000 Facts and Figures* (EPA 2002)). Remaining years in the time series for which data were not provided were estimated using linear interpolation, except for 2002 and 2003, which was assumed to have the same discards as 2001. These 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 79 percent and 21 percent in 2001).

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) (Table 7-18).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate. According to Barlaz (1998), 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) 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 mass of carbon remaining, divided by the original dry weight of the material, was reported as the carbon storage factor (Table 7-18).

For purposes of simulating U.S. landfill carbon flows, the carbon storage factors are divided by the initial carbon content to determine the proportion of initial carbon that does not decompose. The remaining portion is assumed to degrade (and results in emissions of CH_4 and CO_2). For example, for branches Barlaz (1998) reported the carbon storage factor as 38 percent (of dry weight), and the initial carbon content as 49 percent (of dry weight). Thus, the proportion of initial carbon that does not decompose is 77 percent (i.e., 0.38/0.49). The remaining 23 percent degrades.

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:

$$LFC_{i,t} = \sum_{n} W_{i,n} * (1 - MC_i) * ICC_i \; * \{[CSF_i / ICC_i] + [(1 - (CSF_i / ICC_i)) * e^{-k*(t - n)}]\}$$

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*,
ICC_i = the initial carbon content of waste *i*,
CSF_i = the carbon storage factor 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 (2003). 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 tonnes (the persistent portion, plus the remaining half of the degradable portion).

Continuing the example, by 2003, 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 2003), the total landfill carbon from food scraps in 2003 was 29.3 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 2003, yielding a value of 241.6 million metric tons (as shown in Table 7-19). 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 7-17) 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 2003 shown in Table 7-17 (2.7 Tg C) is equal to the stock in 2003 (241.6 Tg C) minus the stock in 2002 (238.9 Tg C).

When applying the carbon storage factor data reported by Barlaz (1998), an adjustment was made to the reported value for leaves, because the carbon storage factor was higher than the initial carbon content. This anomalous result, probably due to errors in the laboratory measurements, was addressed by applying a mass balance calculation, and assuming that (a) the initial carbon content was correctly measured, and (b) the carbon storage factor was incorrect. The same experiment measured not only the persistence of carbon (i.e., the carbon storage factor), but also the yield of methane for each of the individual waste materials (Eleazer et al. 1997). The anaerobic decomposition process results in release of equal molar volumes of CH_4 and CO_2. Thus, to derive a more realistic estimate of the carbon storage factor for leaves, the carbon released in the form of methane during decomposition was multiplied by two (to include the loss of carbon through CO_2, which is generated in approximately equal molar amounts as CH_4), and then subtracted from the initial carbon content of the leaves. This estimate of carbon remaining was used to derive the carbon storage factor (0.46).

Table 7-18: 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
CSF (kg C sequestered / dry kg waste)	0.32	0.46[a]	0.38	0.08
Initial Carbon Content (%)	45	49	49	51
Proportion of initial carbon sequestered (%)	71	94	77	16
Half-life (years)	5	20	20	5

[a] Adjusted using CH_4 yields in Eleazer et al. (1997).

Table 7-19: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	**1990**		**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Yard Trimmings	**167.8**		**196.5**	**199.3**	**201.9**	**204.2**	**206.2**	**208.2**	**210.2**	**212.3**
Grass	18.8		21.7	21.9	22.2	22.4	22.5	22.7	22.9	23.1
Leaves	78.7		92.9	94.3	95.7	97.0	98.0	99.1	100.2	101.3
Branches	70.3		81.9	83.0	84.0	84.9	85.6	86.4	87.1	87.9
Food Scraps	**20.3**		**24.0**	**24.7**	**25.5**	**26.3**	**27.1**	**27.9**	**28.6**	**29.3**
Total Carbon Stocks	**188.1**		**220.5**	**224.0**	**227.4**	**230.5**	**233.3**	**236.1**	**238.9**	**241.6**

Note: Totals may not sum due to independent rounding.

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 by the addition of 20 percent or subtraction of 10 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 7-20. Total yard trimmings and food scraps CO_2 flux in 2003 was estimated to be between -17.5 and -7.0 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 73 percent below to 31 percent above the 2003 flux estimate of -10.1 Tg CO_2 Eq.

Table 7-20: 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**	**2003 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	CO_2	(7.5)	(11.3)	(4.4)	-51%	+41%
Food Scraps	CO_2	(2.6)	(8.9)	(1.2)	-246%	+54%
Total	**CO_2**	**(10.1)**	**(17.5)**	**(7.0)**	**-73%**	**+31%**

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Negative values indicate net carbon storage (positive values denote emissions).

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 the 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. Thus, the uncertainty analysis used asymmetrical values (up to 10 percent less storage, up to 20 percent more storage) as inputs.

Several of the planned improvements to the analysis, described later in this section, are intended to reduce the uncertainty associated with these factors.

Recalculations Discussion

While conducting quality control procedures, it was found that the 1994 value for the amount of discards that are landfilled (or disposed of by means other than combustion) had been incorrectly recorded. The error was corrected, resulting in reduced carbon storage values by less than 1.0 Tg C for the years 1994 through 2003. Overall, this change, in combination with historical data revisions, resulted in an average annual decrease of 0.2 Tg CO_2 Eq. (0.7 percent) in carbon sequestration from yard trimming and food scraps over the period 1990 through 2002.

Planned Improvements

As noted above, the estimates presented in this section are driven by a small carbon storage factor data set, and some of these measurements (especially for leaves) deserve close scrutiny. There are ongoing efforts to conduct a re-analysis of the leaves experiment, using the same techniques as in the original experiments cited, and 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), which cover 3.5 percent of the continental United States, are estimated to contain about 3.8 billion trees. 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 continental United States were estimated by Nowak and Crane (2002) to account for an average annual net sequestration of 58.7 Tg CO_2 Eq. (16 Tg C). These data were collected throughout the 1990s, and have been applied to the entire time series in this report (see Table 7-21). Annual estimates of CO_2 flux have not been developed, but are believed to be relatively constant from 1990 through 2003.

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 7-21: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(58.7)	(16)
1997	(58.7)	(16)
1998	(58.7)	(16)
1999	(58.7)	(16)
2000	(58.7)	(16)
2001	(58.7)	(16)
2002	(58.7)	(16)
2003	(58.7)	(16)

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 *LULUCF Good Practice Guidance* (IPCC 2003), although sufficient data are not yet available to determine interannual changes in carbon stocks in the living biomass of urban trees.

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).

Annual net carbon sequestration estimates were derived for seven of the ten cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[9] National annual net carbon sequestration by urban trees was estimated from the city estimates of gross and net sequestration, and urban area and urban tree cover data for the contiguous United States. The urban areas are based on 1990 U.S. Census data, which define "urban land" as areas having a population density greater than 1,000 people per square mile and adjacent urban places, with predefined political boundaries, having a population total greater than 2,500. Therefore, urban encompasses most cities, towns, and villages (i.e., it includes both urban and suburban 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 an estimate of national urban tree cover area (76,151 km^2) 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. The average of these ratios is 0.70. The urban tree cover area estimates for each of the 10 cities and the contiguous United States were obtained from Dwyer et al. (2000) and Nowak et al. (2001).

Table 7-22: 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

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[9] Three cities did not have net estimates.

Jersey City, NJ	19,300	800	600	11.5	0.18	0.13

NA = not analyzed

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 7-23. Net C flux from changes in C stocks in urban trees was estimated to be between -80.3 and -37.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 37 percent above and below the 2003 flux estimate of -58.7 Tg CO_2 Eq.

Table 7-23: 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	2003 Flux Estimate (Tg CO_2 Eq.)	Uncertainty (%)	Uncertainty Range Relative to 2003 Flux Estimate (Tg CO_2 Eq.)	
				Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(58.7)	37%	(80.3)	(37.0)

Note: Parentheses indicate 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).

Planned Improvements

Some sources indicate a reduction in urban tree coverage in the United States over the Inventory period of approximately 21 percent over the last 10 years (AF 2004). However, because the methods for making this assertion have not yet been made available and their definition of urban land is unclear, the veracity and potential application of this estimate cannot currently be established. Because the magnitude of the urban tree greenhouse gas sink in the United States is not insignificant, identifying changes in this sector is considered a priority and is being actively pursued for inclusion in future Inventories. Should this diminishment prove to be accurate, it could mean the urban tree sink estimates will need to be significantly revised.

Changes in Soil Carbon Stocks (IPCC Source Category 5E1)

Given the lack of available land use information relevant to this particular IPCC source category, it is not possible to quantify the CO_2 flux from soils in Settlements Remaining Settlements at this time.

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 2003, N_2O emissions from this source were 6.0 Tg CO_2 Eq. (19.4 Gg N_2O). There was an overall increase of 9 percent over the thirteen year period 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 in the United States.

Emissions from this source are summarized in Table 7-24.

Table 7-24: N_2O Fluxes from Soils in Settlements Remaining Settlements (Tg CO_2 Eq.)

Settlements Remaining Settlements: N_2O Fluxes from Soils	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Tg CO_2 Eq.	5.5	6.1	6.1	6.2	6.0	5.8	6.0	6.0
Gg	17.9	19.8	19.8	19.9	19.3	18.7	19.4	19.4

Methodology

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. 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) and a recent AAPFCO database (AAPFCO 2000a). Unvolatilized N applied to turf grass 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 factor of 10 percent and 30 percent, respectively, for synthetic fertilizers, 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. Furthermore, only synthetic fertilizers are captured, so applications of organic fertilizers are not accounted for here. 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 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 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 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 7-25. N_2O emissions from soils in settlements remaining settlements in 2003 were estimated to be between 0.3 and 35.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 94 percent below to 483 percent above the 2003 emission estimate of 6.0 Tg CO_2 Eq.

Table 7-25: Tier 1 Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (Tg CO_2 Eq. and Percent)

IPCC Source Category	Gas	Year 2003 Emissions (Tg CO_2 Eq.)	Uncertainty (%)	Uncertainty Range Relative to 2003 Emission Estimate (Tg CO_2 Eq.)	
				Lower Bound	Upper Bound
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	6.0	94 to 483%	0.3	35.1

Recalculations Discussion

The current Inventory presents N_2O emissions from soils in settlements separately for the first time. Previously, N_2O emissions from this source were included with N_2O emissions from agricultural soils. The net effect of separating this source from agricultural soils is to reduce emissions reported from that source. However, because the methods for reporting that source category have changed significantly this year, it is not possible to isolate the magnitude of change caused by this recalculation alone on the overall differences in N_2O emissions from agricultural soils.

Planned Improvements

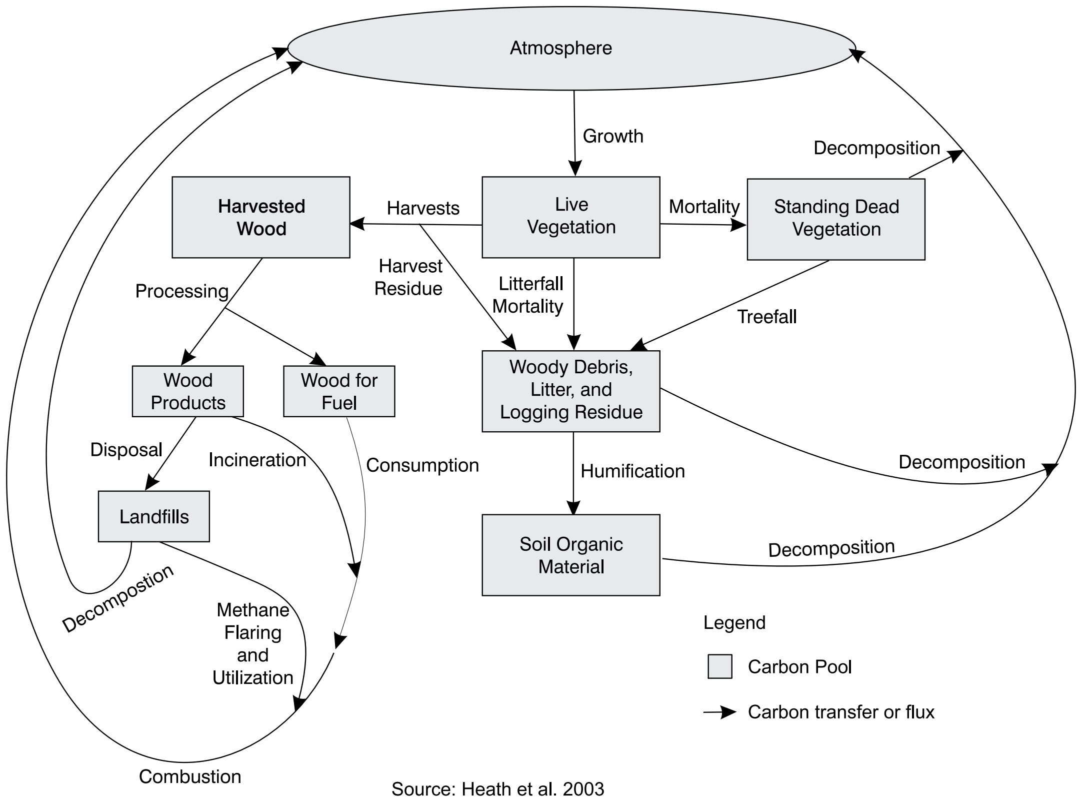
The process-based model DAYCENT, which was used to estimate N_2O emissions from cropped soils this year, could also be used to simulate emissions as well as volatilization and leaching/runoff from settlements. DAYCENT has been parameterized to simulate turf grass. State-level settlement area data is available from the National Resource Inventory. Future inventories will include DAYCENT simulations to estimate emissions from settlements.

7.6. Lands 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 quantify CO_2 or N_2O fluxes from lands converted to settlements at this time.

Figure 7-1

Forest Sector Carbon Pools and Flows



Source: Heath et al. 2003

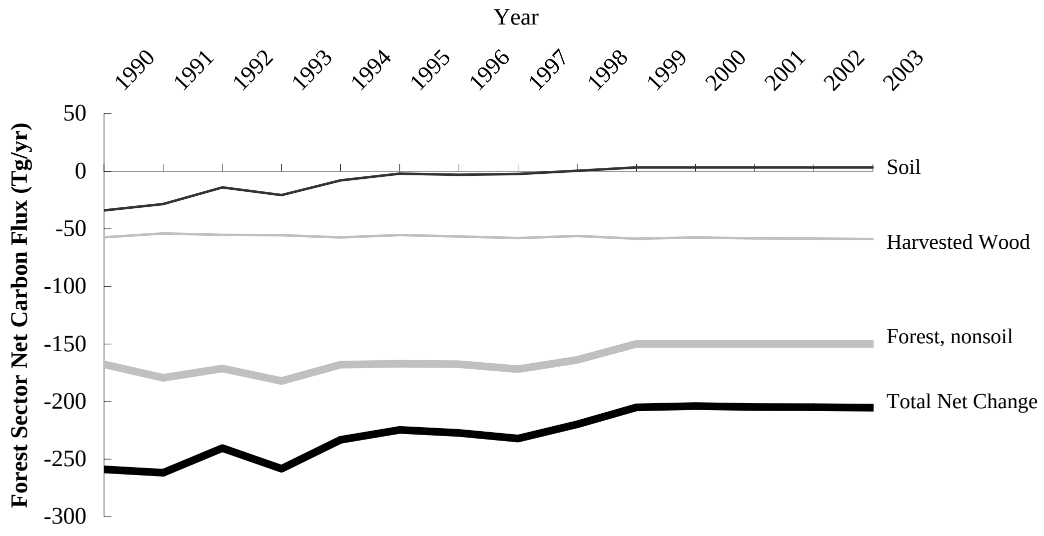
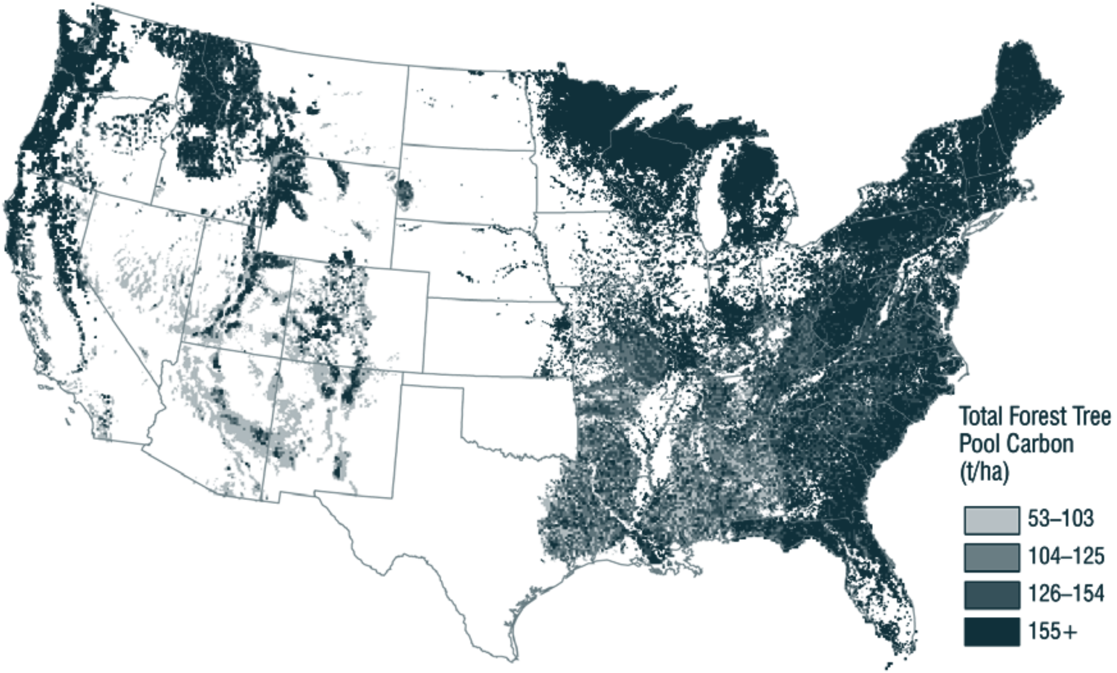


Figure 7-2: Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools

Figure 7-3

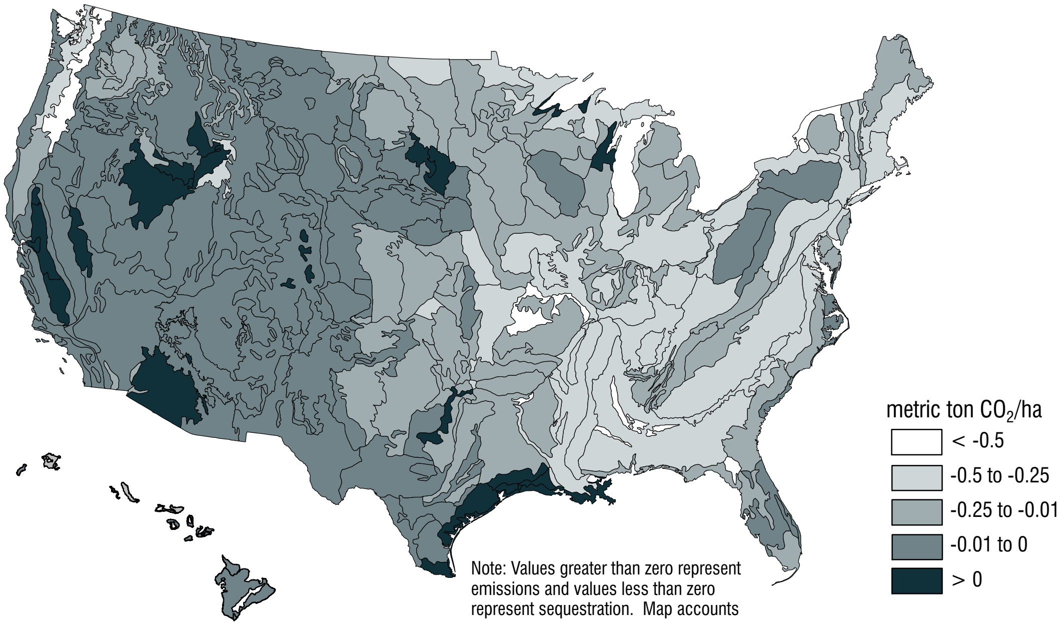
Average Carbon Density in the Forest Tree Pool in the Conterminous U.S. During 2004



Note: Estimates are based on forest inventory data as described in the text.

Figure 7-4

Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1990–1992

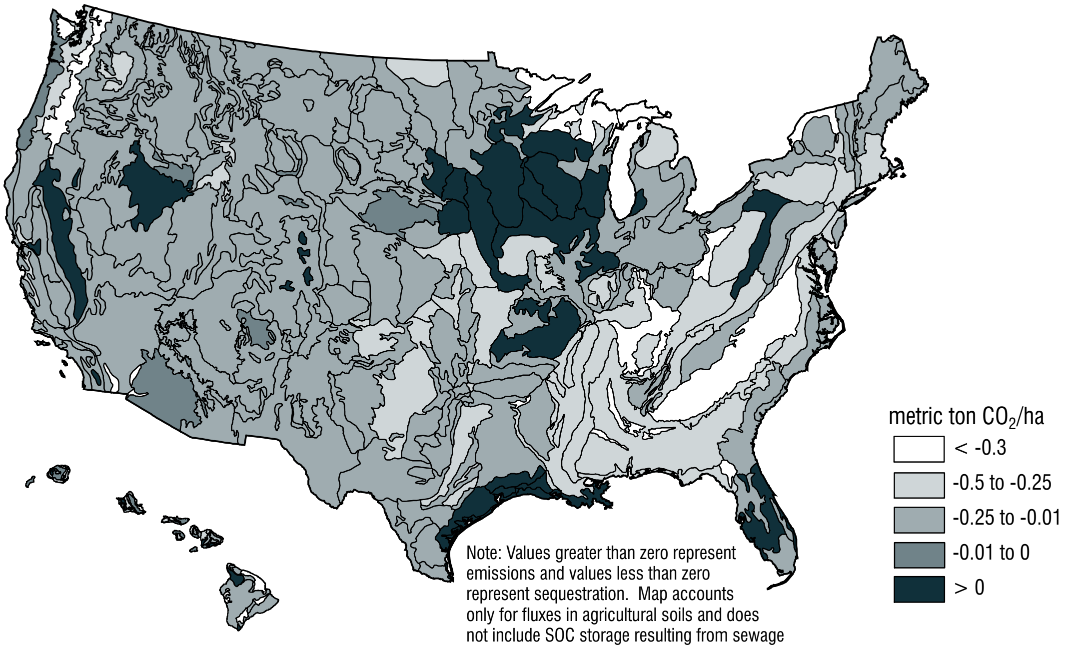


Note: Values greater than zero represent emissions and values less than zero represent sequestration. Map accounts only for fluxes in agricultural soils and does not include SOC storage resulting from sewage sludge amendments in any year.

This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1990 through 1992. The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 7-5

Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1993–2003

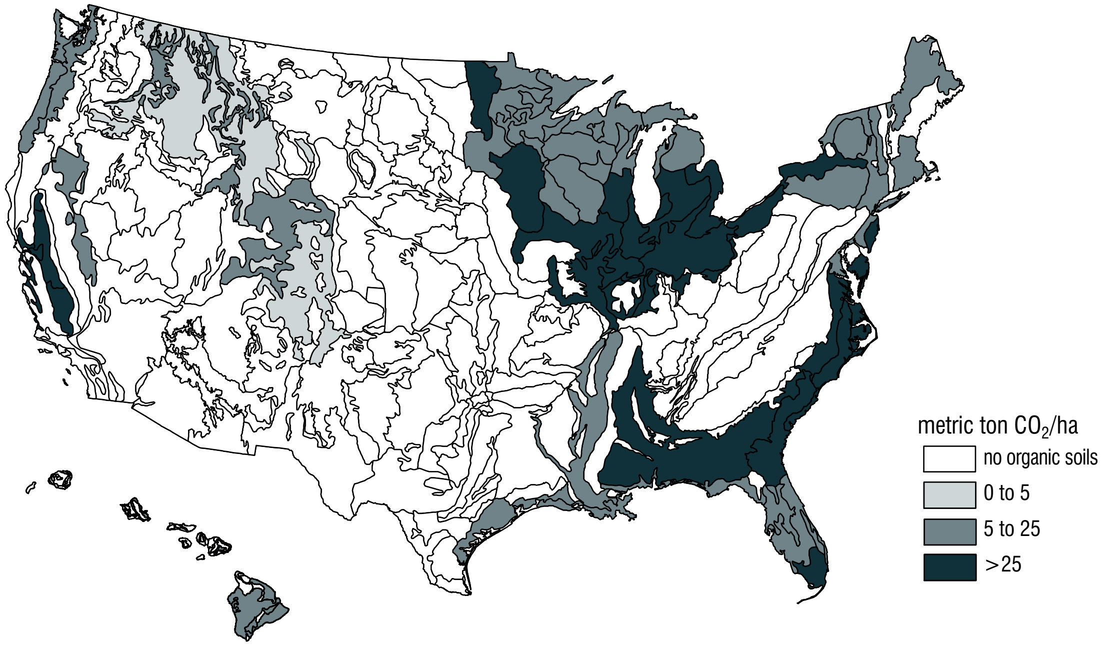


Note: Values greater than zero represent emissions and values less than zero represent sequestration. Map accounts only for fluxes in agricultural soils and does not include SOC storage resulting from sewage sludge amendments in any year, or CRP enrollment and manure management after 1997.

This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1993 through 2003. The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 7-6

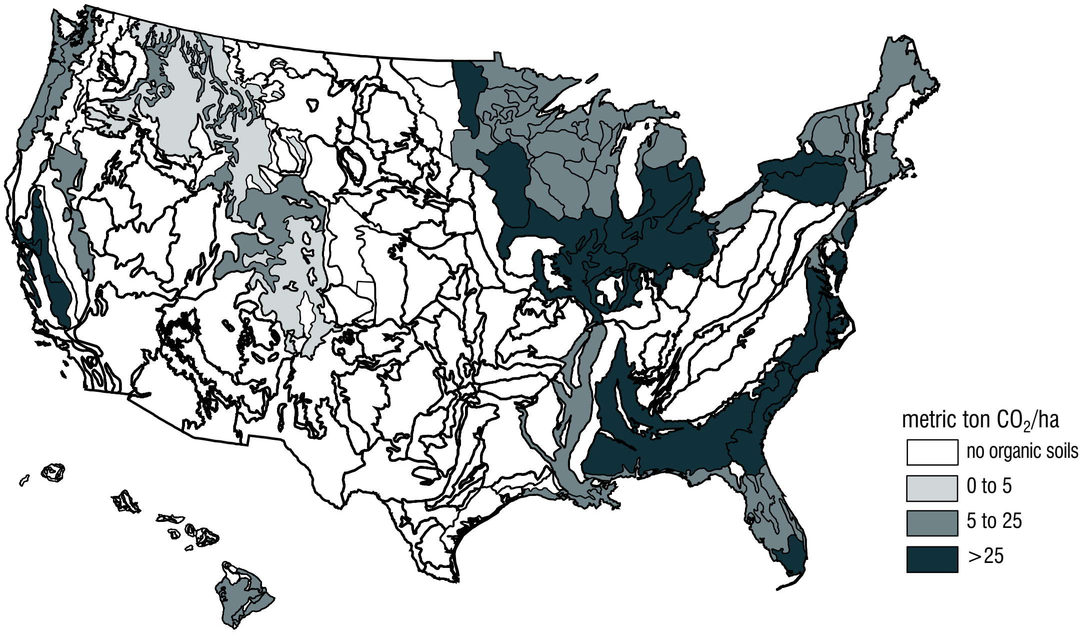
Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agricultural Management, 1990–1992



This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1990 through 1992.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

Figure 7-7

Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agricultural Management, 1993–2003



This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1993 through 2003.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

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 24 percent of total U.S. CH_4 emissions.[1] Smaller amounts of CH_4 are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide 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-methane 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 ambient air pollutant emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Figure 8-1: 2003 Waste Chapter Greenhouse Gas Sources

Overall, in 2003, waste activities generated emissions of 183.8 Tg CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**197.1**	**179.0**	**171.0**	**167.7**	**165.0**	**160.9**	**162.6**	**167.9**
Landfills	172.2	147.4	138.5	134.0	130.7	126.2	126.8	131.2
Wastewater Treatment	24.8	31.7	32.6	33.6	34.3	34.7	35.8	36.8
N_2O	**13.0**	**14.7**	**15.0**	**15.4**	**15.6**	**15.6**	**15.7**	**15.9**
Human Sewage	13.0	14.7	15.0	15.4	15.6	15.6	15.7	15.9
Total	**210.1**	**193.7**	**186.0**	**183.1**	**180.6**	**176.5**	**178.3**	**183.8**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1997	1998	1999	2000	2001	2002	2003
CH_4	**9,385**	**8,526**	**8,145**	**7,984**	**7,858**	**7,660**	**7,744**	**7,997**
Landfills	8,202	7,017	6,595	6,382	6,223	6,010	6,039	6,246
Wastewater Treatment	1,183	1,509	1,550	1,602	1,635	1,651	1,705	1,751
N_2O	**42**	**47**	**48**	**50**	**50**	**50**	**51**	**51**
Human Sewage	42	47	48	50	50	50	51	51
NO_x	**+**	**3**	**3**	**3**	**2**	**2**	**2**	**2**
CO	**1**	**5**	**5**	**13**	**8**	**8**	**8**	**8**
NMVOCs	**673**	**157**	**161**	**140**	**119**	**122**	**133**	**125**

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 2003, landfill CH_4 emissions were approximately 131 Tg CO_2 Eq. (6,246 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 1,800

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

operational landfills exist in the United States (BioCycle 2004), with the largest landfills receiving most of the waste and generating the majority of the CH_4.

After being placed in a landfill, biogenic waste (such as paper, food scraps, and yard trimmings) is initially digested by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which can 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. Methane-producing anaerobic bacteria convert these 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 may last from 10 to 60 years.

From 1990 to 2003, net CH_4 emissions from landfills decreased by approximately 24 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.

Methane 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 2003, 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 935 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2003, the estimated quantity of CH_4 recovered and combusted increased to 5,545 Gg.

Over the next several years, the total amount of municipal solid waste generated is expected to increase slightly. 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, as a result of a 1996 federal regulation that requires large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc 2002), 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
MSW Landfills	197.2	215.9	219.1	222.3	226.5	231.9	238.6	245.0
Industrial Landfills	13.8	15.1	15.3	15.6	15.9	16.2	16.7	17.2
Recovered								
Gas-to-Energy	(14.0)	(34.7)	(42.4)	(48.0)	(51.9)	(57.5)	(59.1)	(61.9)
Flared	(5.6)	(32.6)	(38.2)	(41.0)	(45.2)	(50.5)	(55.3)	(54.6)
Oxidized[a]	(19.1)	(16.4)	(15.4)	(14.9)	(14.5)	(14.0)	(14.1)	(14.6)
Total	**172.2**	**147.4**	**138.5**	**134.0**	**130.7**	**126.2**	**126.8**	**131.2**

Note: Totals may not sum due to independent rounding.

[a] Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH_4 Emissions from Landfills (Gg)

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of non-methane volatile organic compounds (NMVOCs).

Activity	1990	1997	1998	1999	2000	2001	2002	2003
MSW Landfills	9,391	10,279	10,435	10,588	10,785	11,045	11,364	11,669
Industrial Landfills	657	720	730	741	755	773	795	817
Recovered								
Gas-to-Energy	(669)	(1,652)	(2,018)	(2,287)	(2,472)	(2,738)	(2,814)	(2,946)
Flared	(266)	(1,551)	(1,821)	(1,951)	(2,154)	(2,403)	(2,635)	(2,599)
Oxidized[a]	(911)	(780)	(733)	(709)	(691)	(668)	(671)	(694)
Total	**8,202**	**7,017**	**6,595**	**6,382**	**6,223**	**6,010**	**6,039**	**6,246**

Note: Totals may not sum due to independent rounding.

[a] Includes oxidation at municipal and industrial landfills.

Methodology

Methane 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:

$$CH_{4,\text{Solid Waste}} = [(CH_{4,\text{MSW}} - R) + CH_{4,\text{ind}}] - Ox$$

Where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from municipal solid waste landfills,
R = CH_4 recovered and combusted,
$CH_{4,\text{ind}}$ = 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 IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and in a background paper prepared by Jensen and Papatti (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 2003 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 (2004) 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 methane 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), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2004). 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 2003 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 358 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 was likely to also have had 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.[3]

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 for the waste placed in every landfill for each year of its operation—a fundamental factor that affects CH_4 production. The heterogeneity of waste disposed in landfills is uncertain as well. 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 and reflects this heterogeneity. 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 efficiency.

The N_2O emissions from application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide 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 247 Gg total N between 1990 and 2002. The quantity of sewage sludge applied to landfills decreased from 28 to 11 percent from 1990 to 2001 (EPA 1993).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2003 were estimated to be between 84.0 and 152.2 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 2003 emission estimate of 131.2 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	2003 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]	
		(Tg CO_2 Eq.)	(Tg CO_2 Eq.)	(%)

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[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH_4	131.2	84.0	152.2	-36%	+16%

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

Recalculations Discussion

The estimates for the current inventory are based on the first order decay model rather than the linear regression model for 30-year waste in place used for previous inventories. The first order decay model was recommended by U.S. landfill and landfill gas experts and is the preferred approach in the IPCC guidance. Data are now available to develop reliable estimates of the two parameters needed for the first order decay model: CH_4 generation potential and the first order decay rate constant. In the past, these parameters were considered highly variable, thus making the first order decay methodology less desirable.

In addition to the change in method, improved estimates of the annual quantity of waste placed in landfills were developed, particularly for the time period of 1960 through 1988. These two methodological improvements resulted in a reduction in the estimate of CH_4 generation of approximately 20 percent for 1990 and 27 percent for 2002. About half of this reduction is due to the use of the first order decay model to estimate emissions, while the other half is due to the improved estimates of the annual quantity of waste placed in landfills.

Another revision was incorporating data from the EIA to improve estimates of emissions avoided by LFGTE projects and flaring. The use of the EIA data resulted in a decrease of about 11 percent in CH_4 emissions avoided (using 2002 as an example), primarily due to improved estimates for landfills with flares. Changes were also made to the LFGTE database used to estimate emissions avoided by these projects. The changes included corrections to megawatt capacity and gas flow rates, adding new projects that started in 2003, and accounting for projects that shut down. These changes had only a very small effect on emissions avoided by LFGTE projects. Overall, these changes resulted in an average annual decrease of 52.9 Tg CO_2 Eq. (26 percent) in CH_4 emissions from landfills for the period 1990 through 2002.

Planned Improvements

For the future inventories, 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.

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. 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 methane. 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), determines the methane 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 2003, CH_4 emissions from domestic wastewater treatment were estimated to be 19.8 Tg CO_2 Eq. (944 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. Industrial emission sources include wastewater from the pulp and paper, meat and poultry processing, and the vegetables, fruits and juices processing industry.[4] In 2003, CH_4 emissions from industrial wastewater treatment were estimated to be 16.9 Tg CO_2 Eq. (807 Gg). 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**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Domestic	11.4	15.8	16.5	17.1	17.8	18.5	19.2	19.8
Industrial*	13.5	15.9	16.1	16.5	16.5	16.2	16.7	16.9
Total	**24.8**	**31.7**	**32.6**	**33.6**	**34.3**	**34.7**	**35.8**	**36.8**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

Table 8-7: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Domestic	543	751	783	815	848	880	912	944
Industrial*	640	758	767	787	788	771	794	807
Total	**1,183**	**1,509**	**1,550**	**1,602**	**1,635**	**1,651**	**1,705**	**1,751**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology. National population data for 1990 to 2003, used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2004). For BOD_5 for domestic wastewater, two data points were available for 1991 and 2003 (Metcalf & Eddy 1990; Metcalf & Eddy 2003).[5] 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. 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 Wastewater BOD_5 Produced (Gg)

Year	**Population**	**BOD_5**
1990	254	5,566
1997	277	7,706
1998	280	8,032
1999	283	8,363
2000	287	8,695
2001	289	9,021
2002	292	9,351
2003	295	9,685

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[4] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter. Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles, however emissions from these sectors are considered to be insignificant.

[5] BOD_5 is the 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 2003).

Methane emissions estimates from industrial wastewater were developed according to the methodology described in the IPCC (2000). Industry categories that are likely to have significant CH_4 emissions from their wastewater treatment were identified. High volumes of wastewater generated and a high organic COD wastewater load were the main criteria. The top three industries that met these criteria included pulp and paper manufacturing, meat and poultry packing, and vegetables, fruits and juices processing.

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m^3/metric ton of output), the organics loading in the outflow (grams of organic BOD/m^3), the emission factor (grams CH_4/grams BOD), and the percentage of organic BOD assumed to degrade anaerobically. 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 pertinent industry-specific parameters are specified below.

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). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment).

In determining the percent that degraded 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. Approximately 42 percent of the BOD passes on to secondary treatment, which is less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades 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, WorldBank 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 wastewater flows into the anaerobic lagoons of 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, while 90 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	17.9	10.6	30.2
1991	129.2	18.5	11.2	31.3
1992	134.5	18.7	12.0	33.5
1993	134.1	18.9	12.3	34.1

1994	139.3	19.2	13.2	37.3
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	36.7
2003	140.0	21.8	17.6	34.4

Uncertainty

Significant uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loadings vary considerably for different plants and different sub-sectors (e.g., paper vs. board, poultry vs. beef, or baby food vs. juices). For pulp and paper industrial wastewater, five key variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 48 percent; BOD_5 concentration, with a standard deviation of 25 percent; percent anaerobically treated, with a standard deviation of 50 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent. For industrial wastewater from meat and poultry processing, five key variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 59 percent; BOD_5 concentration, with a standard deviation of 51 percent; percent anaerobically treated, with a standard deviation of 10 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent. For industrial wastewater from processing fruit and vegetables, five variables were simulated: material output, with a standard deviation of 10 percent; wastewater outflow, with a standard deviation of 55 percent; COD_5 concentration, with a standard deviation of 60 percent; percent anaerobically treated, with a standard deviation of 50 percent; and the BOD_5 IPCC methane emission factor, with a standard deviation of 30 percent.

In summary, uncertainties for outflows are approximately 50 percent for the different source categories and are based on a standard deviation calculation for meat and poultry, and on expert judgment and the literature for the pulp and paper and the vegetables, fruits, and juices category (Nemerow and Dasgupta 1991; World Bank 1999). Uncertainties for organic loadings are based on the same approach and are estimated at 25, 50, and 60 percent for pulp and paper, meat and poultry, and fruits, vegetables and juices, respectively. The uncertainty associated with the degree in which anaerobic degradation occurs in treatment systems is estimated at 50 percent for the pulp and paper and vegetables, fruits, and juices categories, while this factor for the meat and poultry industry is 10 percent, because the flow data are from the entrance of the anaerobic lagoons.

For domestic wastewater uncertainty, a normal probability distribution was assumed for the four key variables simulated: population, with a standard deviation of 5 percent; BOD_5, with a standard deviation of 30 percent; percent of wastewater treated anaerobically, with a standard deviation of 25 percent; and the BOD_5 IPCC CH_4 emission factor, with a standard deviation of 30 percent.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-10. Wastewater treatment CH_4 emissions in 2003 were estimated to be between 25.2 and 50.3 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 32 percent below to 37 percent above the 2003 emission estimate of 36.8 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**	**2003 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	36.8	25.2	50.3	-32%	+37%

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

Recalculations Discussion

Population estimates for the United States from 1990 through 2002 have been adjusted to include U.S. territories (i.e., American Samoa, Guam, Northern Mariana Islands, and the Virgin Islands). Emission estimates from previous years have only considered estimates of U.S. states and Puerto Rico. On average, updated U.S. population estimates increased total annual CH_4 emissions from wastewater treatment by less than one percent.

The time series for domestic wastewater has been updated due to an adjustment in the per capita BOD factor. The BOD factor changed from a constant value of 0.06 kg per capita per day to an increasing value from 0.06 in 1990 to 0.09 kg per capita per day in 2003. Compared to 2002 estimates, methane emissions from domestic wastewater increased 37 percent. The time series for industrial wastewater changed because more detailed field data became available for the meat and poultry industry (EPA 2002) that include new flow and organic loading data. As a result, estimates for the meat and poultry industrial subcategories have been separated. Organic matter loading calculations are also now based on BOD rather than COD estimates. The new flow data reflect field measurements at the anaerobic lagoon inlet, as opposed to more general plant outflow data. Industrial CH_4 emissions increased 14 percent compared to 2002 estimates, as a result of the more detailed meat and poultry data and a slight increase in pulp and paper production. The total 2002 CH_4 emissions from wastewater treatment increased by 25 percent compared to the emissions in the previous Inventory. Overall, these changes resulted in an average annual increase of 3.8 Tg CO_2 Eq. (14 percent) in CH_4 emissions from wastewater treatment for the period 1990 through 2002.

Planned Improvements Discussion

The Authors/Experts Meeting for the Preparation of 2006 IPCC National Greenhouse Gas Inventories Guidelines for the Wastewater Sector, held in November 2004, will likely generate improved methodological data. Improvements will be planned accordingly.

8.3. Human Sewage (Domestic Wastewater) (IPCC Source Category 6B)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc. and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater treatment system, or 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.

Nitrous oxide 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 via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3^-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide 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 2003 emissions of N_2O from wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (0.9 Gg) and 15.6 Tg CO_2 Eq. (50 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 15.9 Tg CO_2 Eq. (51 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	13.0	42
1997	14.7	47
1998	15.0	48
1999	15.4	50
2000	15.6	50
2001	15.6	50
2002	15.7	51
2003	15.9	51

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 the sewage sludge, which is land applied, incinerated or landfilled (N_{sludge}). The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.
    - The IPCC methodology uses annual, per capita protein consumption (kg/year). This number is 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.[6] 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.[7] 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 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

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[6] 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 US 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/year (6.6 kg N/year), leading to a factor of 1.4 (9.4/6.6).

[7] The type, composition, and quantity of this co-discharged wastewater will 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 footnote 1). Until better data become available, the amount of N in wastewater was increased by 10 mg/l to account for industrial co-discharge (factor of 1.25.)

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 N/(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 $[(US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) \times {}^{28}/_{44}]$ (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.

U.S. population data were taken from the U.S. Census Bureau (2003). 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 2004). Because data on protein intake were unavailable for 2003, 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
1997	277	40.9
1998	280	41.2
1999	283	42.0
2000	287	41.9
2001	289	41.8
2002	292	41.6
2003	295	41.8

Uncertainty

Nitrous oxide emissions from wastewater treatment are estimated to be substantially less than emissions from effluent-surface water. Thus, this wastewater treatment subcategory was not considered in the uncertainty analysis. A triangular distribution was used to simulate land application of sludge as defined for the agricultural soil management sector. The same distribution was assumed for landfilled sludge. The means for the distributions were the estimates used for the 2003 inventory estimate. Based on professional judgment, the standard deviation for population was 5 percent, the standard deviation for per capita protein consumption was 5 percent, the standard deviation of the fraction of nitrogen in protein ($Frac_{NPR}$) was 2 percent, and the standard deviation of the non-consumption protein in domestic wastewater was 25 percent based on professional judgment. The standard deviation emission factor for effluent is 80 percent based on the range provided in IPCC (1996). For the triangular distributions, the lower bound and upper estimates for the land applied and landfilled sludge were 50 percent below and above the respective estimates used for the 2003 inventory. A normal distribution was used to simulate five variables: population, per capita protein intake data, fraction of nitrogen in protein ($Frac_{NPR}$), non-consumption protein in domestic wastewater, and the IPCC emission factor.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-13. Human sewage N_2O emissions in 2003 were estimated to be between 4.2 and 29.9 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 74 percent below to 88 percent above the 2003 emission estimate of 15.9 Tg CO_2 Eq.

Table 8-13: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2003 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	15.9	4.2	29.9	-74%	+88%

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

QA/QC and Verification

An IPCC Tier 1 level QA/QC verification was performed. During the QA/QC process the values for Wastewater BOD produced per capita (kg/capita/day) were adjusted to be based on a calculated rather than estimated interpolated value between the reported 1990 and 2003 values. In addition, the documentation of references in the spreadsheets was improved.

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 Needs Survey (1996) and Metcalf & Eddy (1991). The uncertainty associated with this factor can likely be reduced incorporating more recent data.

Recalculations Discussion

Population estimates for the U.S. from 1990 through 2002 have been adjusted to include U.S. territories (i.e., American Samoa, Guam, Northern Mariana Islands, and the Virgin Islands). Emission estimates from previous years have only considered estimates of U.S. states and Puerto Rico. Overall, the change resulted in an average annual increase of 0.2 Tg CO_2 Eq. (1.7 percent) in N_2O emissions from wastewater treatment processes and effluent for the period 1990 through 2002.

8.4. Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of ambient air pollutant emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2003 are provided in Table 8-14.

Table 8-14: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
NO_x	**+**	**3**	**3**	**3**	**2**	**2**	**2**	**2**
Landfills	+	2	2	3	2	2	2	2

Wastewater Treatment	+		+	+	+	+	+	+	+
Miscellaneous[a]	+		1	1	+	+	+	+	+
CO	**1**		**5**	**5**	**13**	**8**	**8**	**8**	**8**
Landfills	1		5	5	12	7	7	7	7
Wastewater Treatment	+		+	+	1	1	1	1	1
Miscellaneous[a]	+		+	+	+	+	+	+	+
NMVOCs	**673**		**157**	**161**	**140**	**119**	**122**	**133**	**125**
Landfills	58		32	33	27	23	23	25	24
Wastewater Treatment	57		62	63	59	51	53	58	54
Miscellaneous[a]	558		64	65	54	46	46	51	47

[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 2004), 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.

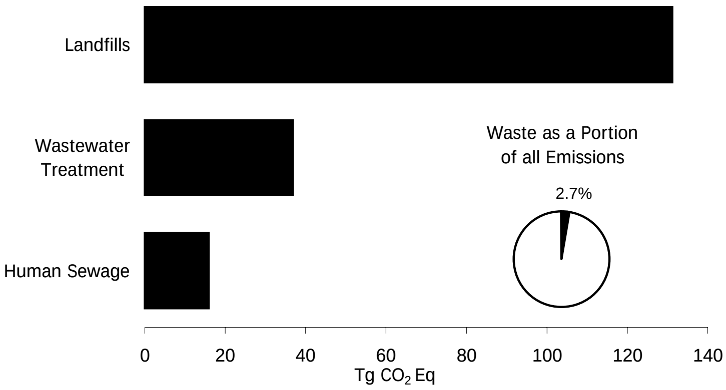

Figure 8-1: 2003 Waste Chapter Greenhouse Gas Sources

9. Other

The United States does not report any greenhouse gas emissions under the “other” 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 IPCC *Good Practice Guidance* (IPCC 2000), which states, regarding recalculations of the time series, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected (IPCC 2000)."

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 2002 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, four new sources—CO_2 emissions from non-energy use of fossil fuels and petrochemical production and N_2O emissions from settlements remaining settlements and forest land remaining forest land—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 2002) 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 2002, 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.

- *CO_2 from Fossil Fuel Combustion*. The most important change in the calculation was the revision that removed emissions from the non-energy use of fuels, which allowed them to be reported separately in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category. Overall, this change, along with several other alterations, resulted in an average annual decrease of 115.8 Tg CO_2 Eq. (2.2 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2002.

- *Land-Use Change and Forestry*. The most influential of the changes in the Land-Use Change and Forestry sector occurred in calculations for agricultural soil carbon stocks. These changes include: a new methodology for the evaluation and incorporation of uncertainty in manure amendments into the calculations for agricultural soil carbon, the use of new management factors provided in the IPCC *LULUCF Good Practice Guidance* (IPCC 2003), and revision of the land area included in the emission calculation for organic soils. Overall, these changes, in combination with adjustments in the other sources/sinks, resulted in an average annual decrease in net flux of CO_2 to the atmosphere from the land-use change and forestry sector of 89.0 Tg CO_2 Eq. (12.1 percent) for the period 1990 through 2002.

- *Landfills*. Revisions to the emissions calculation incorporated the use of a first order decay model rather than a linear regression model for 30-year waste in place figures, improved estimates of the annual quantity of waste placed in landfills, and more accurate estimates of emissions avoided by landfill gas to energy (LFGTE) projects and flaring. Overall, changes resulted in an average annual decrease in CH_4 emissions from landfills of 52.9 Tg CO_2 Eq. (26.0 percent) for the period 1990 through 2002.

- *Agricultural Soil Management*. The emissions calculation changed to incorporate the reallocation of emissions from fertilizer applied to forests and urban areas from the agricultural soil management source category within the Agriculture sector to the Land-Use Change and Forestry sector and the use of a Tier 3 methodology utilizing the DAYCENT ecosystem model rather than the Tier 1 methodology used in the past. Overall, changes resulted in an average annual decrease in N_2O emissions from agricultural soil management of 31.2 Tg CO_2 Eq. (11.0 percent) for the period 1990 through 2002.

- *Petroleum Systems*. The calculation of emissions was revised to incorporate a modified emission factor for CH_4 emissions from oil tanks in the production sector and new activity factor for offshore Gulf of Mexico platform venting in the production sector. Overall, changes resulted in an average annual decrease in CH_4 emissions from petroleum systems of 7.1 Tg CO_2 Eq. (27.4 percent) for the period 1990 through 2002.

- *Natural Gas Systems*. The emissions calculation was revised to incorporate new Gas STAR emissions reduction data and the addition of three new emission sources in the production sector: CH_4 from gas condensate stored in tanks, unconventional gas well fugitives, and flaring from offshore Gulf of Mexico operations. Overall, changes resulted in an average annual increase in CH_4 emissions from natural gas systems of 6.7 Tg CO_2 Eq. (5.3 percent) for the period 1990 through 2002.

- *Mobile Combustion*. The most significant changes to this source were revisions to the emission factors for CH_4 and N_2O from highway vehicles, which were generated from EPA-sponsored laboratory vehicle testing. Revisions to these emission factors resulted in lower emission estimates for both CH_4 and N_2O emissions from highway vehicles. Overall, changes resulted in an average annual decrease in N_2O emissions from mobile combustion of 6.2 Tg CO_2 Eq. (10.9 percent) and an average annual decrease in CH_4 emissions from mobile combustion of 0.6 Tg CO_2 Eq. (13.6 percent) for the period 1990 through 2002.

- *Wastewater Treatment*. The most influential changes in the calculation were the use of an adjusted per capita BOD factor in the domestic wastewater emissions calculations and the use of more detailed field data for the meat and poultry industry in the industrial wastewater emissions calculations. Overall, changes resulted in an average annual increase in CH_4 emissions from wastewater treatment of 3.8 Tg CO_2 Eq. (14.0 percent) for the period 1990 through 2002.

- *Abandoned Coal Mines*. The calculation of emissions was revised to incorporate an updated mine list, updated coal seam permeabilities, and revised closure dates for 43 of the mines. Overall, changes resulted in an average annual increase in CH_4 emissions from abandoned coal mines of 2.8 Tg CO_2 Eq. (64.5 percent) for the period 1990 through 2002.

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
CO_2	**7.2**	**2.3**	**4.7**	**1.7**	**(0.8)**	**13.0**	**14.4**
Fossil Fuel Combustion	(102.9)	(120.8)	(133.7)	(142.9)	(128.5)	(110.8)	(109.5)
Non-Energy Use of Fuels[a]	108.0	120.3	135.4	141.6	124.7	120.1	118.8
Natural Gas Flaring	+	NC	NC	NC	+	0.7	0.9
Cement Manufacture	NC	NC	NC	NC	NC	NC	NC
Lime Manufacture	NC	NC	NC	NC	NC	NC	NC
Limestone and Dolomite Use	NC	NC	NC	NC	NC	NC	+
Soda Ash Manufacture and Consumption	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	+	+	+	+	+	+	(0.3)
Waste Combustion	NC	NC	NC	NC	NC	NC	NC
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	NC	NC	NC	NC	+
Iron and Steel Production	+	+	+	+	+	(0.2)	0.7
Ferroalloys	NC	NC	NC	NC	NC	NC	NC
Ammonia Manufacture & Urea Application	NC	NC	NC	NC	+	0.5	0.9
Petrochemical Production[a]	NC	NC	NC	NC	NC	NC	+
Phosphoric Acid Production	2.2	2.9	3.0	3.1	3.0	2.8	2.9
Land-Use Change and Forestry (Sink)	(84.2)	(109.1)	(175.2)	(150.4)	(132.3)	(137.1)	(135.8)
International Bunker Fuels	(0.4)	+	(0.5)	+	+	+	2.6
Biomass Combustion	NC	NC	NC	NC	NC	(3.9)	0.2
CH_4	**(37.3)**	**(49.3)**	**(51.0)**	**(55.8)**	**(60.3)**	**(58.3)**	**(55.6)**
Stationary Sources	(0.4)	(0.4)	(0.3)	(0.4)	(0.4)	(0.6)	(0.5)

Mobile Sources	(0.2)	(0.6)	(0.7)	(0.9)	(1.0)	(1.2)	(1.3)
Coal Mining	+	NC	+	+	NC	+	0.2
Abandoned Coal Mines	2.7	2.5	2.4	2.9	3.3	2.7	2.2
Natural Gas Systems	6.3	7.5	7.3	6.5	6.4	6.9	8.8
Petroleum Systems	(8.9)	(6.7)	(6.5)	(5.9)	(5.9)	(6.0)	(6.1)
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production	+	+	+	+	+	+	+
Enteric Fermentation	+	+	+	0.2	(0.1)	0.2	0.2
Manure Management	0.2	0.1	0.1	0.1	0.1	0.1	(0.1)
Rice Cultivation	NC	NC	NC	NC	NC	NC	NC
Field Burning of Agricultural Residues	NC	NC	+	NC	NC	NC	+
Landfills	(37.7)	(56.0)	(58.1)	(63.8)	(68.6)	(67.0)	(66.2)
Wastewater Treatment	0.7	4.3	4.8	5.4	6.0	6.5	7.1
International Bunker Fuels	+	+	+	+	+	+	+
N_2O	**(11.2)**	**(40.0)**	**(24.4)**	**(46.2)**	**(23.9)**	**(31.4)**	**(35.3)**
Stationary Sources	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.5)
Mobile Sources	(6.9)	(5.1)	(4.2)	(4.0)	(4.2)	(6.1)	(7.3)
Adipic Acid	NC	NC	NC	NC	NC	NC	NC
Nitric Acid	NC	NC	NC	NC	NC	NC	0.5
Manure Management	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Agricultural Soil Management	(9.8)	(41.2)	(26.5)	(48.7)	(25.9)	(31.5)	(34.8)
Field Burning of Agricultural Residues	NC	NC	+	NC	NC	NC	+
Human Sewage	0.2	0.2	0.3	0.3	0.3	0.2	0.1
N_2O Product Usage	NC	NC	NC	NC	NC	NC	NC
Waste Combustion	NC	NC	NC	NC	NC	0.1	0.1
Settlements Remaining Settlements[a]	5.5	6.1	6.1	6.2	6.0	5.8	6.0
Forest Land Remaining Forest Land[a]	0.1	0.3	0.4	0.5	0.4	0.4	0.4
International Bunker Fuels	+	+	+	+	+	+	+
HFCs, PFCs, and SF_6	**0.3**	**0.1**	**+**	**+**	**(0.2)**	**(0.2)**	**+**
Substitution of Ozone Depleting Substances	0.1	0.1	+	+	(0.1)	(0.1)	(0.2)
Aluminum Production	0.2	+	+	+	0.1	+	+
HCFC-22 Production	NC	+	+	+	+	+	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Electrical Transmission and Distribution	+	+	+	+	(0.2)	(0.2)	(0.1)
Magnesium Production and Processing	NC	NC	NC	NC	+	+	0.2
Net Change in Total Emissions[b]	**(41.0)**	**(86.9)**	**(70.7)**	**(100.3)**	**(85.2)**	**(77.0)**	**(76.5)**
Percent Change	**(0.7%)**	**(1.3%)**	**(1.0%)**	**(1.5%)**	**(1.2%)**	**(1.1%)**	**(1.1%)**

+ 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 sinks from 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 Change and Forestry (Tg CO_2 Eq.)

Component	**1990**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Forest Land Remaining Forest Land	(102.7)	(120.9)	(187.7)	(163.3)	(145.6)	(150.7)	(150.7)
Cropland Remaining Cropland	18.5	11.9	12.6	13.0	13.4	13.6	15.0
Settlements Remaining Settlements	NC	(0.1)	(0.1)	(0.1)	(0.1)	+	+
Net Change in Total Flux	**(84.2)**	**(109.1)**	**(175.2)**	**(150.4)**	**(132.3)**	**(137.1)**	**(135.8)**
Percent Change	**(8.8%)**	**(13.3%)**	**(24.8%)**	**(22.2%)**	**(19.2%)**	**(19.9%)**	**(19.7%)**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.

NC (No Change)

Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere, or an increase in net sequestration.
Note: Totals may not sum due to independent rounding.

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