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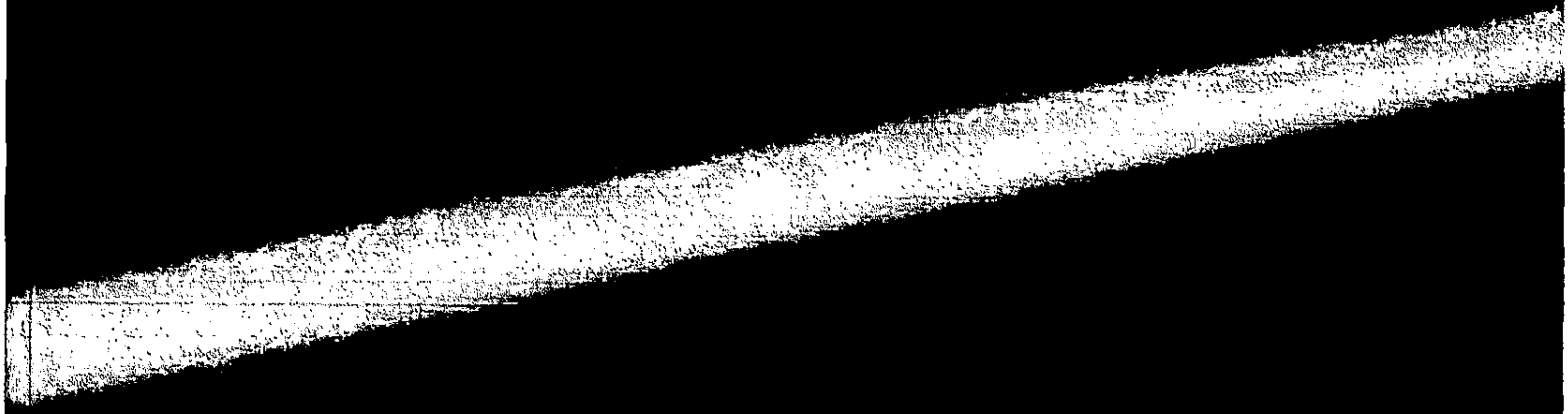
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993



Front Cover: Photograph obtained from NASA. The photograph was taken by STS 39 Crew of the Discovery (launched April 28, 1991 from Kennedy Space Center and completed on May 6, 1991) and depicts the atmosphere surrounding the Earth's surface. A sunset highlights the thin layers of gases and particles that shield the planet.

Photograph No. 91-H-433, 91-HC-376, S39-610-037

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

1990-1993

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF POLICY, PLANNING AND EVALUATION
WASHINGTON, D.C., U.S.A.

SEPTEMBER 1994

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EXECUTIVE SUMMARY

Central to any study of climate change is the development of and participation in an emission inventory process that identifies and quantifies a country's primary sources and sinks of greenhouse gases.[1] This process is important because: (1) it provides a basis for the ongoing development of a comprehensive and detailed methodology for estimating sources and sinks of greenhouse gases, and (2) it provides a common and consistent mechanism that enables all signatory countries to the United Nations' Framework Convention on Climate Change (FCCC) to estimate emissions and to compare the relative contribution of different emission sources and greenhouse gases to climate change. Moreover, systematically and consistently estimating emissions at the national and international levels is a prerequisite for evaluating the cost-effectiveness and feasibility of pursuing possible mitigation strategies and adopting emission-reduction technologies.

This document provides information on greenhouse gas sources and sinks, and estimates of emissions and removals for the United States for 1990-1993, as well as the methods used to calculate these estimates, and the uncertainties associated with them. Although estimates are provided for all four years, the 1990 estimates are considered the base year, since under the Framework Convention on Climate Change, countries are to submit inventories of greenhouse gas emissions for the year 1990.

The emission estimates presented here were calculated using the *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD, 1994) to ensure that the emission inventories submitted to the FCCC are consistent and comparable across sectors and between nations. In order to fully comply with the *IPCC Draft Guidelines*, the United States has provided a copy of the IPCC reporting tables in Annex D of this report. These tables include the data used to calculate emission estimates using the *IPCC Draft Guidelines*. The United States has followed these guidelines, except where more detailed data or methodologies were available for major U.S. sources of emissions. In such cases, the United States expanded on the IPCC guidelines to provide a more comprehensive and accurate account of U.S. emissions. These instances have been documented, and explanations have been provided for diverging from the *IPCC Guidelines* (IPCC/OECD, 1994).

The Greenhouse Gases and Photochemically Important Gases

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).[2] Chlorofluorocarbons (CFCs) (a family of human-made compounds), its substitute hydrofluorocarbons (HFCs), and other compounds such as perfluorinated carbons (PFCs), are also greenhouse gases. In addition, other photochemically important gases — such as carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs) — are not greenhouse gases, but contribute indirectly to the greenhouse effect (see Box ES-1 for explanation). These are commonly referred to as "tropospheric ozone precursors" because they influence the rate at which ozone and other gases are created and destroyed in the atmosphere. For convenience, all gases discussed in this summary are generically referred to as "greenhouse gases" (unless otherwise noted), although the reader should keep these distinctions in mind. In addition, emissions of sulfur dioxide (SO_2) are reported. Sulfur gases, primarily sulfur dioxide, are believed to contribute negatively to the greenhouse effect.

Recent Trends of U.S. Greenhouse Gas Emissions

Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, their recent atmospheric buildup appears to be largely the result of anthropogenic activities. This growth has altered the composition of the Earth's atmosphere, and may affect future global climate. Since 1800, atmospheric concentrations of carbon dioxide have increased by more than 25 percent, methane concentrations have more than doubled, and nitrous oxide concentrations have risen approximately 8 percent (IPCC, 1992). And, from the 1950s until the mid-1980s, the use of CFCs increased by nearly 10 percent per year. Now that CFCs are being phased out under the *Montreal Protocol on Substances that Deplete the Ozone Layer* (*Montreal Protocol*), the use of CFC substitutes is expected to grow significantly.

The current U.S. greenhouse gas inventory for 1990-93 is summarized in Table ES-1. For the 1990 base year, total U.S. emissions were 1,444 MMTCE. To be consistent with the IPCC-recommended guidelines, this estimate excludes emissions of 22.6 MMTCE from international transport. Changes in CO_2 emissions from fossil fuel consumption had the greatest impact on U.S. emissions from 1990 to 1993. While U.S. emissions of CO_2 in 1991 were approximately 1.2 percent lower than 1990 emission levels, in 1992 they were about 1.5 percent over 1991 levels, thus returning emissions to about 1990 levels. This trend is largely attributable to changes in total energy consumption resulting from the economic slowdown in the U.S. economy and the subsequent recovery. Based on preliminary data for 1993, the upward trend since 1991 has continued, with 1993 CO_2 emissions from fossil fuel combustion approximately 2.4 percent greater than 1990.

CH_4, N_2O, and HFCs and PFCs represent a much smaller portion of total emissions than CO_2. Overall, emissions of these gases remained relatively constant from 1990 to 1992. Methane emissions from coal mining declined slightly due to small decreases in coal production and increases in coalbed methane recovery. N_2O emissions remained relatively constant, while HFC emissions increased slightly, due to increased production of HCFC-22, which increased by-product emissions of HFC-23. Emissions of PFCs have remained constant over the period.

U.S. emissions were partly offset by an uptake of carbon in U.S. forests of 119 MMTCE. This increase was due to intensified forest management practices and the regeneration of forest land previously cleared for cropland and pasture.

Figure ES-1 illustrates the relative contribution of the primary greenhouse gases to total U.S. emissions in 1990. Due largely to fossil fuel consumption, CO_2 emissions accounted for the largest share of U.S. emissions -- 85 percent. These emissions were partially offset by the sequestration that occurred on forested lands. Methane accounted for 11 percent of total emissions, including contributions from landfills and agricultural activities, among others. The other gases were less important, with N_2O emissions com-

Box ES-1. The Global Warming Potential (GWP) Concept

As mentioned, gases can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas; indirect radiative forcing occurs when chemical transformation of the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of Global Warming Potential (GWP) has been developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide was chosen as the "reference" gas to be consistent with the 1993 U.S. *Climate Change Action Plan.* All gases in this report are presented in units of million metric tonnes of carbon-equivalent, or MMTCE. Carbon comprises 12/44 of carbon dioxide by weight.

The Global Warming Potential (GWP) of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one kilogram of a greenhouse gas to one kilogram of carbon dioxide over a period of time. While any time period can be selected, the 100-year GWPs recommended by the IPCC are used in this report.

Gas	GWP (100 Years)
Carbon dioxide	1
Methane	11/22*
Nitrous oxide	270
HFC-134a	1,200
HFC-23	10,000
HFC-152a	150
PFCs	5,400

* The direct GWP for methane is 11. The U.S. has accounted for both the direct and indirect effects of methane on radiative forcing. The indirect effects of methane are considered comparable in magnitude to the direct effects, therefore a GWP of 22 has been used (IPCC, 1992). Using a GWP of 22 for methane is also consistent with the GWP used in the U.S. *Climate Change Action Plan,* and follows the suggestion of the INC 9th Session that requests that indirect effects be included where applicable. The magnitude of the indirect effects of other gases are either zero or uncertain.

Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions: 1990 - 1993 (Million Metric Tonnes)

Gas/Source	Emissions (Full Molecular Weight)				Emissions (Direct and Indirect Effects; Carbon-Equivalent)			
	1990	1991	1992	1993	1990	1991	1992	1993
<u>Greenhouse Gases</u>								
Carbon Dioxide (CO_2)								
Fossil Fuel Combustion	4,895	4,835	4,908	5,013	1,335	1,319	1,339	1,367
Other	62	61	62	-	17	17	17	-
Total	4,956	4,896	4,970	-	1,352	1,336	1,356	-
Forests (sink)	(436)	(433)	(429)	-	(119)	(118)	(117)	-
Net Total	4,520	4,463	4,541	-	1,233	1,218	1,239	-
Methane (CH_4)								
Landfills	10.0	10.1	10.2	10.3	60	61	61	62
Agriculture	8.6	8.5	8.6	8.8	52	51	52	53
Coal Mining	4.4	4.2	4.0	-	26	26	24	-
Oil and Gas Systems	3.2	3.3	3.3	-	19	20	20	-
Other	0.8	0.8	0.8	-	5	5	5	-
Total	27.0	26.9	27.0	-	162	162	161	-
Nitrous Oxide (N_2O)								
Agriculture	0.2	0.2	0.2	-	14	14	14	-
Fossil Fuel Consumption	0.1	0.1	0.1	-	9	10	10	-
Industrial Processes	0.1	0.1	0.1	-	7	7	7	-
Total	0.4	0.4	0.4	-	30	32	32	-
HFCs and PFCs	+	+	+	-	19.2	19.6	20	-
<u>Photochemically Important Gases</u>								
Carbon Monoxide (CO)	82.7	81.4	78.1	-	-	-	-	-
Nitrogen Oxides (NO_x)	21.4	21.2	21	-	-	-	-	-
NMVOCs	19.1	18.7	17.9	-	-	-	-	-
NET U.S. EMISSIONS					1,444	1,432	1,452	-

\+ Total of these gases does not exceed 0.01 million metric tonnes.

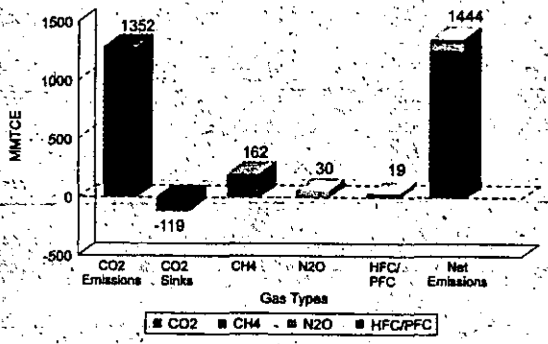
Note: *Totals presented in the summary tables in this chapter may not equal the sum of the individual source categories due to rounding.*

Since 1990, overall emissions of carbon dioxide have increased, while emissions of other greenhouse and photochemically important gases have remained relatively constant.

prising about 2 percent of total U.S. emissions, HFCs accounting for slightly over 1 percent, and PFCs about 0.3 percent. The emissions of the photochemically important gases CO, NO_x, NMVOCs, and SO_2 are not included in Figure ES-1 because there is no agreed upon method to estimate their contribution to climate change. These gases only affect radiative forcing indirectly. Also, any gases covered under the *Montreal Protocol* are not included in this figure because their use is being phased out, and the *IPCC Guidelines* (IPCC/OECD, 1994) recommend excluding gases covered by the *Montreal Protocol*.

The following sections present the anthropogenic sources of greenhouse gas emissions, briefly discuss the emission pathways, summarize the emission estimates, and explain the relative importance of emissions from each source category.

Figure ES-1
Total U.S. Greenhouse Gas Emissions: 1990



Largely because of fossil fuel consumption, CO2 emissions accounted for the largest share of U.S. emissions in 1990.

CARBON DIOXIDE EMISSIONS

The global carbon cycle is made up of large carbon flows and reservoirs. Hundreds of billions of tons of carbon in the form of CO_2 are absorbed by oceans, trees, soil, and vegetative cover and are emitted to the atmosphere annually through natural processes. When in equilibrium, carbon flows between the various reservoirs roughly balance each other. Since the Industrial Revolution, however, atmospheric concentrations of carbon dioxide have risen more than 25 percent, principally because of the combustion of fossil fuels (IPCC, 1992). While the combustion of fossil fuels accounts for 99 percent of total U.S. CO_2 emissions, CO_2 emissions also result directly from industrial processes. Changes in land use and forestry activities both emit carbon dioxide (*e.g.*, as a result of forest clearing) and can act as a sink for CO_2 (*e.g.*, as a result of improved forest management activities).

Table ES-2 summarizes U.S. emissions and uptake of carbon dioxide, while the remainder of this section presents detailed information on the various anthropogenic sources and sinks of carbon dioxide in the United States.

The Energy Sector

Approximately 88 percent of U.S. energy is produced through the combustion of fossil fuels. The remaining 12 percent comes from renewable or other energy sources such as hydropower, biomass, and

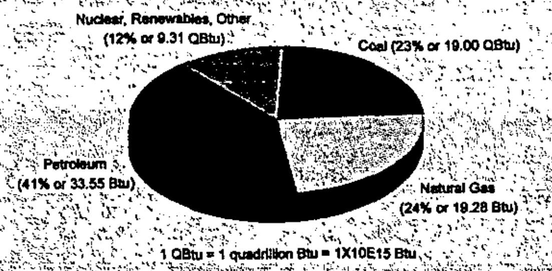
Table ES-2. Sources of CO_2 Emissions by Source: 1990
(Million Metric Tonnes)

Source/Sink	CO_2 Emissions (Molecular Basis)	CO_2 Emissions (Carbon-Equivalent)
Sources		
Fossil Fuel Consumption		
Residential	927	252.7
Commercial	757	206.4
Industrial	1,673	456.4
Transportation	1,505	410.5
U.S. Territories	33	9.1
Total	**4,895**	**1,335**
Fuel Production and Processing	6.6	1.8
Cement Production	32.7	8.9
Lime Production	11.9	3.2
Limestone Consumption	5.1	1.4
Soda Ash Production and Consumption	4.1	1.1
Carbon Dioxide Manufacture	0.2	0.3
Total -- All Sources	**4,956**	**1,352**
Sinks		
Forestry and Land Use	(436)	(119)
Total Net Emissions	**4,520**	**1,233**

Note: The totals provided here do not reflect emissions from bunker fuels used in international transport activities. The INC 9th Session instructed countries to report these emissions separately, and not include them in national totals. U.S. emissions from bunker fuels were approximately 22.6 MMTCE in 1990.

nuclear energy (see Figure ES-2). As they burn, fossil fuels emit carbon dioxide due to oxidation of the carbon contained in the fuel. The amount of carbon in fossil fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 20 percent less carbon than coal, and natural gas has about 45 percent less. The inventory includes carbon dioxide emissions from all fossil fuel consumption and oil and gas production and storage. Carbon dioxide emissions from biomass and biomass-based fuel consumption are reported on page 25, but are not included in the national total. This approach is consistent with the *IPCC Draft Guidelines* (IPCC/OECD, 1994).

Figure ES-2
Types of Energy Consumed in the U.S.: 1990



Approximately 88 percent of U.S. energy is produced through the combustion of fossil fuels.

Fossil Fuel Consumption. In 1990, the United States emitted a total of 1,335 MMTCE from fossil fuel combustion. (Bunker fuels, or fuels used in international transport, accounted for an additional 22.6 MMTCE.) The energy-related activities producing these emissions included heating in residential and commercial buildings, the generation of electricity, steam production for industrial processes, and gasoline consumption in automobiles and other vehicles. Petroleum products across all sectors of the economy accounted for about 44 percent of total U.S. energy-related carbon dioxide emissions; coal, 36 percent; and natural gas, 20 percent.

Industrial Sector

The industrial sector accounts for 34 percent of U.S. emissions from fossil fuel consumption, making it the largest end-use source of CO_2 emissions (see Figure ES-3). About two-thirds of these emissions result from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining one-third of industrial energy needs is met by electricity for such uses as motors, electric furnaces and ovens, and lighting.

The industrial sector is also the largest user of nonenergy applications of fossil fuels, which often store carbon. Fossil fuels used for producing fertilizers, plastics, asphalt, or lubricants can store carbon in products for very long periods. Asphalt used in road construction, for example, stores carbon indefinitely. Similarly, the fossil fuels used in the manufacture of materials like plastics also store carbon, releasing this carbon only if the product is incinerated.

Transportation Sector

The transportation sector is also a major source of CO_2, accounting for about 31 percent of U.S. emissions. Virtually all of the energy consumed in this sector comes from petroleum-based products. Nearly two-thirds of the emissions are the result of gasoline consumption in automobiles and other vehicles, with other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, accounting for the remainder.

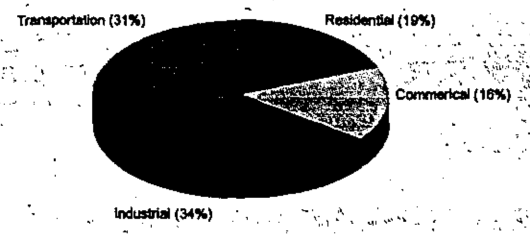
Residential and Commercial Sectors

The residential and commercial sectors account for about 19 and 16 percent, respectively, of CO_2 emissions from fuel consumption. Both sectors rely heavily on electricity for meeting energy needs, with about two-thirds to three-quarters of their emissions attributable to electricity consumption. End-use applications include lighting, heating, cooling, and operating appliances. The remaining emissions are largely due to the consumption of natural gas and oil, primarily for meeting heating and cooking needs.

Electric Utilities

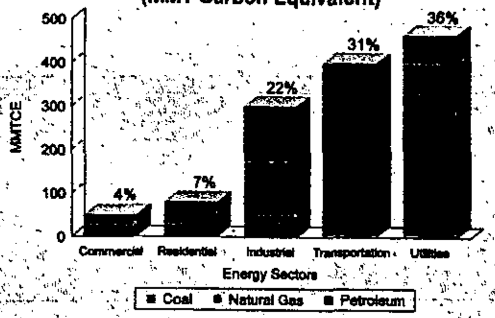
The U.S. relies on electricity to meet a significant portion of its energy requirements. In fact, as the largest consumers of fossil fuels, electric utilities are collectively the largest producers of U.S. CO_2 emissions (see Figure ES-4). Electric utilities generate electricity for such uses as lighting, heating, electric motors, and air conditioning. Some of this electricity is generated with the lowest CO_2-emitting energy technologies, particularly nonfossil options, such as nuclear energy, hydropower, or geothermal energy. However, electric utilities rely on coal for 55 percent of their total energy requirements and account for about 85 percent of all coal consumed in the United States.

Figure ES-3
Carbon Dioxide Emissions by End Use Sector: 1990



In this graph, emissions generated by electric utilities are allocated to each end-use sector according to each sector's share of electricity consumption;...

Figure ES-4
Carbon Dioxide Emissions from Fossil Fuel Combustion by Sector and Fuel Type: 1990
(MMT Carbon Equivalent)



......however, when the emissions attributable to electric utilities are pulled out of the various end-use sectors, as depicted in this graph, the reliance of the U.S. economy on electricity to meet its needs is evident.

Fuel Production and Processing. CO_2 is produced via flaring activities at natural gas systems and oil wells. Typically, the methane that is trapped in a natural gas system or oil well is flared to relieve the pressure building in the system or to dispose of small quantities of gas that are not commercially marketable. As a result, the carbon contained in the methane becomes oxidized and forms carbon dioxide. In 1990, the amount of CO_2 from the flared gas was approximately 1.8 MMTCE, or about 0.1 percent of total U.S. CO_2 emissions.

Biomass and Biomass-Based Fuel Consumption. Biomass fuel is used primarily by the industrial sector in the form of fuelwood and wood waste. Biomass-based fuel use, such as ethanol from corn or woody crops, occurs mainly in the transportation sector. Ethanol and ethanol blends, such as gasohol, are typically used to fuel public transport vehicles, such as buses or centrally fueled fleet vehicles.

Biomass, ethanol, and ethanol-blend fuels do release carbon dioxide. However, in the long run, the carbon dioxide they emit does not increase total atmospheric carbon dioxide because the biomass resources are consumed on a sustainable basis. For example, fuelwood burned one year but regrown the next only recycles carbon, rather than creating a net increase in total atmospheric carbon. As a result, carbon dioxide emissions from biomass have been estimated separately from fossil fuel-based emissions and, as recommended in the *IPCC Draft Guidelines*, are not included in national totals.

For 1990, CO_2 emissions from biomass consumption were approximately 48 MMTCE, with the industrial sector accounting for 73 percent of the emissions and the residential sector, 25 percent. Carbon dioxide emissions from ethanol use in the United States are generally declining, due to a combination of low gasoline prices and limited ethanol supply. In 1990, total U.S. CO_2 emissions from ethanol were estimated to be 1.2 MMTCE, and were emitted mostly in the South and Midwest, where the majority of ethanol is produced and consumed.

Industrial Processes

Emissions are often produced as a by-product of various nonenergy-related activities. For example, in the industrial sector raw materials are chemically transformed from one state to another. This transformation often releases such greenhouse gases as carbon dioxide. The production processes that emit CO_2 include cement production, lime production, limestone consumption (*e.g.*, in iron and steel making), soda ash production and use, and carbon dioxide manufacture. Total carbon dioxide emissions from these sources were approximately 15 MMTCE in 1990, accounting for 1 percent of total U.S. CO_2 emissions.

Cement Production (8.9 MMTCE). Carbon dioxide is produced primarily during the production of clinker, an intermediate product from which finished Portland and masonry cement are made. Specifically, carbon dioxide is created when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime and carbon dioxide. This lime combines with other materials to produce clinker, while the carbon dioxide is released into the atmosphere.

Lime Production (3.2 MMTCE). Lime is used in steel making, construction, pulp and paper manufacturing, and water and sewage treatment. It is manufactured by heating limestone (mostly calcium carbonate) in a kiln, creating calcium oxide (quicklime) and carbon dioxide, which is normally emitted to the atmosphere.

Limestone Consumption (1.4 MMTCE). Limestone is a basic raw material used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries. For example, limestone can be used as a purifier in refining metals, such as iron. In this case, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating carbon dioxide as a by-product. It is also used in flue gas desulfurization systems to remove sulfur dioxide from the exhaust gases.

Soda Ash Production and Consumption (1.1 MMTCE). Commercial soda ash (sodium carbonate) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of these products, natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which carbon dioxide is generated as a by-product. In addition, carbon dioxide is released when the soda ash is consumed. Of the two states that produce natural soda ash, only Wyoming has net emissions of carbon dioxide, because producers in California recover the CO_2 and use it in other stages of production. U.S. CO_2 emissions from soda ash *production* were approximately 0.4 MMTCE in 1990, while U.S. soda ash *consumption* generated about 0.7 MMTCE.

Carbon Dioxide Manufacture (0.3 MMTCE). Carbon dioxide is used in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil products, and a host of industrial and miscellaneous applications. For the most part, carbon dioxide used in these applications will eventually be released into the atmosphere.

Forests and Land Use Change

When humans use and alter the biosphere through changes in land use and forest-management activities, they alter the natural balance of trace gas emissions and uptake. These activities include clearing an area of forest to create cropland or pasture, restocking a logged forest, draining a wetland, or allowing a pasture to revert to a grassland or forest. Forests, which cover about 737 million acres of U.S. land (USFS, 1990), are a potentially important terrestrial sink for carbon dioxide. Because approximately half the dry weight of wood is carbon, as trees add mass to trunks, limbs, and roots, more carbon is stored in the trees than is released to the atmosphere through respiration and decay. Soils and other types of vegetative cover also provide a potential sink for carbon.

In the United States improved forest-management practices and the regeneration of previously cleared forest area have actually increased the amount of carbon stored on U.S. lands. This uptake of carbon is an ongoing result of land-use changes in previous decades. For example, because of improved agricultural productivity and the widespread use of tractors, the rate of clearing forest land for crop cultivation and pasture slowed greatly 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 brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The regeneration of forest land greatly increases carbon storage in both standing biomass and soils, and the impacts of these land-use changes are still affecting forest carbon fluxes in the East. In addition to land-use changes in the early part of this century, forest carbon fluxes in the East are affected by a trend toward managed growth on private land in recent decades, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (*e.g.*, the Forestry Incentive Program) and soil conservation programs (*e.g.*, the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber-management activities, combatting soil erosion, and converting marginal cropland to forests.

As a result of these activities, the net CO_2 flux from standing biomass and vegetative cover in 1990 was estimated to have been an uptake (sequestration) of 119 MMTCE. The Northeast, North Central, and South Central regions of the United States accounted for 99 percent of the uptake of carbon, largely due to high growth rates that are the result of intensified forest management practices and the regeneration of forest land previously cleared for cropland and pasture. Western states are responsible for a small net release of carbon, reflecting mature forests with a near balance between growth, mortality, and removals.

There are considerable uncertainties associated with the estimates provided for the net carbon flux from U.S. forests, however. Four major uncertainties are presented briefly below:

- *The impacts of forest management activities on soil carbon are quite uncertain.* Since forest soils contain over 50 percent of the total stored forest carbon in the U.S., this difference can have a large impact on flux estimates. However, because of uncertainties associated with soil carbon flux, this component is not included in the U.S. estimate at this time.
- *The U.S. has assumed that harvested timber effectively results in immediate carbon emissions.* This assumption is consistent with the methodology recommended by the IPCC (IPCC/OECD, 1994), however, studies that model the product pools in the U.S. estimate a net accumulation of carbon in forest product pools in 1990. This suggests that the estimates of carbon sequestration presented here may be too low.
- *The current estimate does not include forest land in Alaska and Hawaii or reserved timber land.* However, forests in these states are believed to be in equilibrium, so their inclusion would not significantly affect the flux estimates presented here.
- *Forest management activities may also result in fluxes of other greenhouse and photochemically important gases.* Dry soils are an important sink for CH_4 and source of N_2O, and both a source and a sink for CO, and vegetation is a source of several NMHCs (nonmethane hydrocarbons, a subset of NMVOCs). However, the effects of forestry activities on these gases are highly uncertain, and are therefore not included in the U.S. inventory at this time.

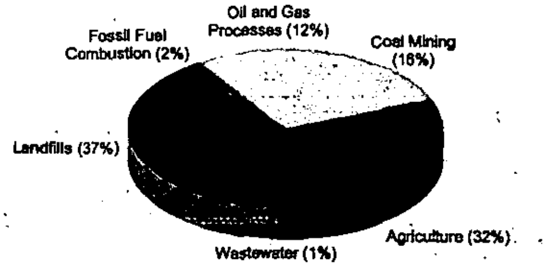
METHANE EMISSIONS

Atmospheric methane (CH_4) is second only to CO_2 as an anthropogenic source of the greenhouse effect. Methane's overall contribution to global warming is large because it is 22 times more effective at trapping heat in the atmosphere than carbon dioxide over a 100-year time horizon when both the direct and indirect effects are accounted for. Furthermore, methane's concentration in the atmosphere has more than doubled over the last two centuries. Scientists have concluded that these atmospheric increases are largely due to increasing emissions from anthropogenic sources, such as landfills, agricultural activities, coal mining, fossil fuel combustion, the production and processing of natural gas and oil, and wastewater treatment (see Table ES-3 and Figure ES-5).

Table ES-3. Sources of Methane Emissions: 1990
(Million Metric Tonnes)

Source	**CH_4 (Molecular Basis)**	**CH_4 (Carbon-Equivalent; GWP=11)**	**CH_4 (Carbon-Equivalent; GWP=22)**
Landfills	10.0	30.0	60.0
Agriculture	8.6	25.8	51.6
Coal Mining	4.4	13.2	26.4
Oil and Natural Gas Systems	3.2	9.7	19.4
Fossil Fuel Combustion	0.6	2.0	3.9
Wastewater Treatment	0.2	0.4	0.9
Total	**27.0**	**81.1**	**162.2**

Figure ES-5
Sources of Methane Emissions: 1990



Landfills and agriculture are the largest sources of atmospheric methane in the United States.

Landfills

Landfills are the largest single anthropogenic source of methane emissions in the United States. There are an estimated 6,000 landfills in the United States, with 1,300 of the largest landfills accounting for about half of the emissions.

In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, are decomposed by bacteria to produce methane, carbon dioxide, and stabilized organic materials (materials that cannot be decomposed further). Methane emissions from landfills are affected by such factors as waste composition, moisture, and landfill size.

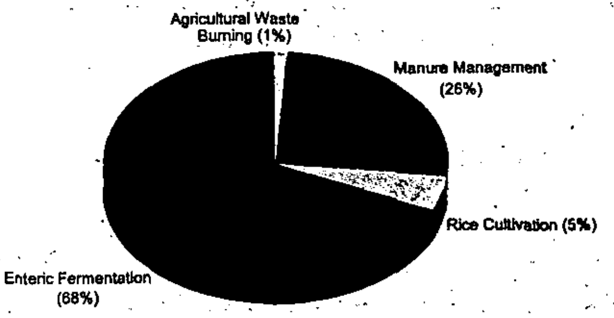
Methane emissions from U.S. landfills in 1990 were 60 MMTCE, or about 37 percent of total U.S. methane emissions. Emissions from U.S. municipal solid waste landfills, which received over 70 percent of the total solid waste generated in the United States, accounted for about 90 to 95 percent of total landfill emissions, while industrial landfills accounted for the remaining 5 to 10 percent. Currently, about 10 percent of the methane emitted is recovered for use as an energy source.

Agriculture

The agricultural sector accounted for approximately 32 percent of total U.S. methane emissions in 1990, with enteric fermentation in domestic livestock and manure management together accounting for the majority (see Figure ES-6). Other agricultural activities contributing to methane emissions include rice cultivation and field burning of agricultural crop wastes. Several other agricultural activities, such as irrigation and tillage practices, may contribute to methane emissions, but emissions from these sources are uncertain and are believed to be small; therefore, the United States has not included them in the current inventory. Details on the emission pathways included in the inventory are presented below.

Enteric Fermentation in Domestic Livestock (34.9 MMTCE). In 1990, enteric fermentation was the source of about 22 percent of total U.S. methane emissions, and about 68 percent of methane emissions from the agricultural sector. During animal digestion, methane is produced through enteric fermentation, a process in which microbes that reside in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest methane emissions among all animal types because they have a rumen, or large "fore-stomach," in which a significant amount of methane-producing fermentation occurs. Nonruminant domestic animals, such as pigs and horses, have much lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems. The amount of methane produced and excreted by an individual animal also depends upon the amount and type of feed it consumes.

Figure ES-6
Methane Emissions from Agriculture by Source: 1990



Manure Management (13.7 MMTCE). The decomposition of organic material in animal manure in an anaerobic environment produces methane. The most important factor affecting the amount of methane produced is how the manure is managed, since certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems (*e.g.*, lagoons, ponds, tanks, or pits) tend to produce a significant quantity of methane. However, when manure is handled as a solid or when it is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Higher temperatures and moist climate conditions also promote methane production.

Emissions from manure management were about 8 percent of total U.S. methane emissions in 1990, and about 27 percent of methane emissions from the agricultural sector. Liquid-based manure management systems accounted for over 80 percent of total emissions from animal wastes.

Rice Cultivation (2.6 MMTCE). 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 in the soils develop, and methane is produced through anaerobic decomposition of soil organic matter. Methane is released primarily through the rice plants, which act as conduits from the soil to the atmosphere.

Rice cultivation is a very small source of methane in the United States. In 1990, methane emissions from this source were less than 2 percent of total U.S. methane emissions, and about 5 percent of U.S. methane emissions from agricultural sources.

Field Burning of Agricultural Wastes (0.5 MMTCE). Large quantities of agricultural crop wastes are produced from farming systems. Disposal systems for these wastes include plowing them back into the field; composting, landfilling, or burning them in the field; using them as a biomass fuel; or selling them in supplemental feed markets. Burning crop residues releases a number of greenhouse gases, including carbon dioxide, methane, carbon monoxide, nitrous oxide, and oxides of nitrogen. Crop residue burning is not considered to be a net source of carbon dioxide emissions because the carbon dioxide released during burning is reabsorbed by crop regrowth during the next growing season. However, burning is a net source of emissions for the other gases. Because this practice is not common in the United States, it was responsible for only 0.3 percent of total U.S. methane emissions in 1990, and 0.9 percent of emissions from the agricultural sector.

Coal Mining

Coal mining and post-mining activities, such as coal processing, transportation, and consumption, are the third largest source of methane emissions in the United States. Estimates of methane emissions from coal mining for 1990 were 26.4 MMTCE, which accounted for about 16 percent of total U.S. methane emissions.

Produced millions of years ago during the formation of coal, methane is trapped within coal seams and surrounding rock strata. When coal is mined, methane is released to the atmosphere. The amount of methane released from a coal mine depends primarily upon the depth and type of coal, with deeper mines generally emitting more methane (U.S. EPA, 1993a). Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed.

Methane is hazardous in underground mines because it is explosive at concentrations of 5 to 15 percent in air. Therefore, all underground mines are required to remove methane by circulating large quantities of air through the mine and venting this air into the atmosphere. At some mines, more advanced methane-recovery systems may be used to supplement the ventilation systems and ensure mine safety. The practice of using the recovered methane as an energy source has been increasing in recent years.

Oil and Natural Gas Production and Processing

Methane is also a major component of natural gas. Any leakage or emission during the production, processing, transmission, and distribution of natural gas emits methane directly to the atmosphere. Because natural gas is often found in conjunction with oil, leakage during the production of commercial quantities of gas from oil wells 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 condition. Fugitive emissions can occur at all stages of extraction, processing, and distribution. In 1990, emissions from the U.S. natural gas system were estimated to be 17.8 MMTCE, accounting for approximately 11 percent of total U.S. methane emissions for 1990.

Methane is also released as a result of oil production and processing activities, such as crude oil production, crude oil refining, transportation, and storage, when commercial gas production is not warranted due to the small quantities present. Emissions from these activities are generally released as a result of system leaks, disruptions, or routine maintenance. For 1990, methane emissions from oil production and processing facilities were 1.6 MMTCE, accounting for about one percent of total U.S. methane emissions.

Other Sources

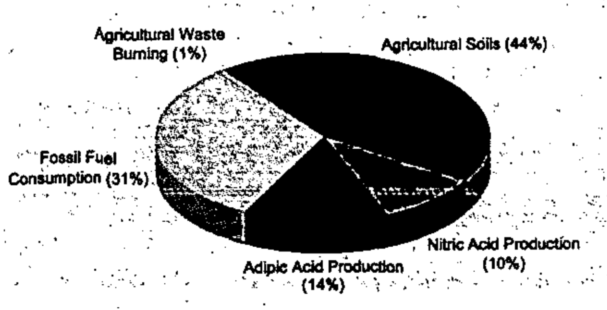
Methane is also produced from several other sources in the United States, including energy-related combustion activities, wastewater treatment, industrial processes, and changes in land use. The sources included in the U.S. inventory are fossil fuel combustion and wastewater treatment, which accounted for approximately 4.8 MMTCE in 1990, or about 3 percent of total U.S. methane emissions. Additional anthropogenic sources of methane in the United States, such as land use changes and ammonia, coke, iron, and steel production are not included because little information on methane emissions from these sources is currently available.

NITROUS OXIDE EMISSIONS

Nitrous oxide (N_2O) is a chemically and radiatively active greenhouse gas that is produced naturally from a wide variety of biological sources in soil and water. While actual emissions of N_2O are much smaller than CO_2 emissions, N_2O is approximately 270 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time horizon.

Over the past two centuries, human activities have raised atmospheric concentrations of nitrous oxide by approximately 8 percent. The main anthropogenic activities producing N_2O are soil management and fertilizer use for agriculture, fossil fuel combustion, adipic acid production, nitric acid production, and agricultural waste burning. The relative share of each of these activities to total U.S. nitrous oxide emissions is shown in Figure ES-7, and U.S. nitrous oxide emissions by source category for 1990 are provided in Table ES-4.

Figure ES-7
Sources of Nitrous Oxide Emissions: 1990



Agricultural Soil Management and Fertilizer Use

The primary sources of anthropogenic nitrous oxide emissions in the United States are fertilizer use and soil management activities. Synthetic nitrogen fertilizers and organic fertilizers add nitrogen to soils, and thereby increase emissions of nitrous oxide. Nitrous oxide emissions in 1990 due to consumption of synthetic and organic fertilizers were 13.5 MMTCE, or approximately 44 percent of total U.S. nitrous oxide emissions.

Other agricultural soil management practices, such as irrigation, tillage practices, or the fallowing of land, can also affect N_2O fluxes to and from the soil. However, because there is much uncertainty about the direction and magnitude of the effects of these other practices, only the emissions from fertilizer use and field burning of agricultural wastes are included in the U.S. inventory at this time.

Table ES-4: Sources of N_2O Emissions: 1990
(Million Metric Tonnes)

Source	N_2O (Molecular Basis)	N_2O (Carbon Equivalent; GWP=270)
Agricultural Soil Management and Fertilizer Use	0.2	13.5
Fossil Fuel Consumption	0.13	9.4
Adipic Acid Production	0.06	4.1
Nitric Acid Production	0.04	2.9
Agricultural Waste Burning	0.01	0.4
Total	0.41	30.3

Fossil Fuel Combustion

Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fossil fuel combustion. Both mobile and stationary sources emit nitrous oxide. Emissions from mobile sources are more significant and are better understood than those from stationary sources. The amount of nitrous oxide emitted varies, depending upon fuel, technology type, and pollution control device. Emissions also vary with the size and vintage of the combustion technology, as well as maintenance and operation practices.

For example, catalytic converters installed to reduce air pollution resulting from motor vehicles have been proven to promote the formation of nitrous oxide. As catalytic converter-equipped vehicles have increased in the U.S. motor vehicle fleet, emissions of nitrous oxide from this source have also increased (EIA, 1994g). Mobile emissions totalled 6.8 MMTCE in 1990 (22.4 percent of total N_2O emissions), with road transport accounting for approximately 95 percent of these N_2O emissions. Nitrous oxide emissions from stationary sources were 2.6 MMTCE in 1990.

Adipic Acid Production

Nitrous oxide is emitted as a by-product of the production of adipic acid. Ninety percent of all adipic acid produced in the United States is used to produce nylon 6,6. It is also used to produce some low-temperature lubricants, and to provide foods with a "tangy" flavor. In 1990, U.S. adipic acid production generated 4.1 MMTCE of nitrous oxide, or 13.7 percent of total U.S. N_2O emissions.

Nitric Acid Production

Production of nitric acid is another industrial source of N_2O emissions. Nitric acid is a raw material used primarily to make synthetic commercial fertilizer, and is also a major component in the production of adipic acid and explosives. Virtually all of the nitric acid that is manufactured commercially in the United States is obtained by the oxidation of ammonia. During this process, N_2O is formed and emitted to the atmosphere. Nitrous oxide emissions from this source were about 2.9 MMTCE in 1990, accounting for about 9.7 percent of total U.S. N_2O emissions.

Other Sources of N_2O

Other activities that emit N_2O include the burning of agricultural crop residues and changes in land use. Emissions from agricultural crop residue burning are extremely small relative to overall U.S. N_2O emissions. Nitrous oxide emissions in 1990 from this source were approximately 0.4 MMTCE, or about 1.2 percent of total U.S. nitrous oxide emissions.

Forestry activities may also result in fluxes of nitrous oxide, since dry soils are a source of N_2O emissions. However, the effects of forestry activities on fluxes of these gases are highly uncertain; therefore, they are not included in the inventory at this time. Similarly, the U.S. inventory does not account for several land-use changes because of uncertainties in their effects on trace gas fluxes, as well as poorly quantified land-use change statistics. These land-use changes include loss and reclamation of freshwater wetland areas, conversion of grasslands to pasture and cropland, and conversion of managed lands to grasslands.

EMISSIONS OF HFCS AND PFCS

Partially halogenated compounds (HFCs) and perfluorinated compounds (PFCs) were introduced as alternatives to the ozone-depleting substances (ODSs) being phased out under the *Montreal Protocol* and *Clean Air Act Amendments of 1990* (see Box ES-2). Because HFCs and PFCs are not directly harmful to the stratospheric ozone layer, they are not controlled by the *Montreal Protocol.* However, these compounds are powerful greenhouse gases and are, therefore, considered under the Framework Convention on Climate Change. For example, HFC-134a has an estimated direct GWP of 1,200, which makes the compound 1,200 times more heat absorbent than an equivalent amount by weight of CO_2 in the atmosphere. Therefore, emission estimates for these gases have been included in the U.S. inventory and are provided in Table ES-5.

In 1990, the use of CFC and HCFC substitutes was minimal. Thus, emissions of HFCs and PFCs were quite small, and were largely the result of by-product emissions from other production processes. For example, HFC-23 is a by-product emitted during the production of HCFC-22, and PFCs (CF_4 and C_2F_6)

are emitted during aluminum smelting. While the use of such ozone-depleting substances as methyl chloroform, CFC-12, and HCFC-22 is declining, consumption of HFCs is increasing markedly. Emissions of HFCs and PFCs should continue to rise as their use as replacements increases.

Box ES-2. Emissions of CFCs and Related Compounds

Chlorofluorocarbons (CFCs) and other halogenated fluorocarbons were emitted into the atmosphere for the first time this century. This family of man-made compounds includes chlorofluorocarbons, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and partially halogenated fluorocarbons (HCFCs). These substances are used in a variety of industrial applications, including foam production and refrigeration, air conditioning, solvent cleaning, sterilization, fire extinguishing, paints, coatings, other chemical intermediates, and miscellaneous uses (*e.g.*, aerosols, propellants, and other products).

Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone-depleting substances. In addition, they are important greenhouse gases because they block infrared radiation that would otherwise escape into space (IPCC, 1990).

Recognizing the harmful effects of these compounds on the atmosphere, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and consumption of a number of CFCs and other halogenated compounds. As of June 1994, 133 countries had signed the *Montreal Protocol*. The United States furthered its commitment to phase out these substances by signing and ratifying the *Copenhagen Amendments* to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to eliminating the production of all halons by January 1, 1994, and all CFCs by January 1, 1996.

The *IPCC Guidelines* do not include reporting emissions of CFCs and related compounds because their use is being phased out under the *Montreal Protocol*. The United States believes that no inventory is complete without these emissions; therefore, emission estimates for several Class I and Class II ozone-depleting substances are provided in the table below. Compounds are classified as "Class I" or "Class II" substances based on their ozone-depletion potential, and must adhere to a distinct set of phase-out requirements under the *Montreal Protocol*. Class I compounds are the primary ozone-depleting substances in use today; Class II compounds include partially halogenated chlorine compounds (known as HCFCs), which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere, and therefore pose only about one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs. Also, it should be noted that the effects of these compounds on radiative forcing are not provided here. Although CFCs and related compounds have very large direct GWPs, their indirect effects are believed to be negative and, therefore, could significantly reduce the magnitude of their direct effects (IPCC, 1992). Given the uncertainties surrounding the net effect of these gases, they are reported here on a full molecular basis only.

U.S. Emissions of Ozone-Depleting Substances and Related Compounds: 1990
(Million Metric Tonnes; Molecular Basis)

Compound	Emissions
Class I ODSs	
CFC-11	0.06
CFC-12	0.1
CFC-113	0.05
CFC-114	0.005
CFC-115	0.003
Carbon Tetrachloride	0.03
Methyl Chloroform	0.3
Halon-1211	0.001
Halon-1301	0.001
Class II ODSs	
HCFC-22	0.08
HCFC-141b	0.002
HCFC-124	0.003

Source: Estimates prepared by ICF Consulting Group for U.S. EPA, Office of Air and Radiation.

Table ES-5. Emissions of HFCs and PFCs: 1990
(Million Metric Tonnes)

Compound	Molecular Basis	GWP[a]	Carbon-Equivalent
HFCs			
HFC-23	0.00552	10,000	15.05
HFC-134a	0.0005	1,200	0.16
HFC-152a	0.0003	150	0.01
PFCs			
Total PFCs	0.003	5,400	3.98

[a] The GWP for HFC-23 was obtained from U.S. EPA's Office of Air and Radiation and is based on unpublished data from DuPont Chemical Company and others. The GWPs for the other compounds are from IPCC, 1992.

Source: U.S. EPA, 1994b

In 1990, the use of substitutes for ODSs was minimal. Thus, emissions of HFCs were quite small, and were largely the result of by-product emissions from the production of HCFC-22. PFC emission were the result of aluminum smelting activities.

EMISSIONS OF CRITERIA POLLUTANTS

Carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are commonly referred to in the United States as "criteria pollutants".[3] Carbon monoxide is created when carbon-containing fuels are burned incompletely; oxides of nitrogen, NO and NO_2, are created from lightning, biomass fires, fossil-fuel combustion, and in the stratosphere from nitrous oxide; nonmethane VOCs include compounds such as propane, butane, and ethane, and are emitted primarily from transportation and industrial processes, as well as biomass burning, and nonindustrial consumption of organic solvents (U.S. EPA, 1990a); sulfur dioxide can result from the combustion of fossil fuels, industrial processing (particularly in the metals industry), waste incineration, and biomass burning (U.S. EPA, 1993b). Because of their contribution to the formation of urban smog, they are regulated under the 1970 *Clean Air Act* and successive amendments. These gases also have an impact on global climate, although their impact is limited because their radiative effects are indirect (*i.e.*, they do not directly act as greenhouse gases but react with other chemical compounds in the atmosphere). It should be noted, however, that sulfur dioxide emitted into the atmosphere affects the Earth's radiative budget negatively; therefore, it is discussed separately from the other criteria pollutants in Box ES-3.

The most important of the indirect effects of the criteria pollutants — CO, NO_x, and NMVOCs — is their role as *precursors* of tropospheric ozone. In this role, they contribute to ozone formation and alter the atmospheric lifetimes of other greenhouse gases. For example, carbon monoxide interacts with the hydroxyl radical (OH) — the major atmospheric sink for methane — to form carbon dioxide. Therefore, increased atmospheric concentrations of CO limit the number of OH compounds available to destroy methane, thus increasing the atmospheric lifetime of methane.

Table ES-6. Emissions of CO, NO_x, and NMVOCs: 1990
(Million Metric Tonnes)

Source	CO	NO_x	NMVOCs
Fossil Fuel Combustion	73.65	20.36	8.94
Industrial Processes	4.35	0.72	3.49
Fossil Fuel Production, Distribution, and Storage	0.39	0.09	0.67
Waste Incineration	1.53	0.07	0.29
Agricultural Waste Burning	2.76	0.12	
Solvent Use	0.002	0.002	5.74
Total	**82.67**	**21.36**	**19.13**

Box ES-3. Sulfur Dioxide: Effects on Radiative Forcing and Sources of Emissions

Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through photochemical transformation into sulfate particles that (i) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (ii) possibly increase the number of cloud condensation nuclei, thereby potentially altering the physical characteristics of clouds, and (iii) affect atmospheric chemical composition, *e.g.* stratospheric O_3, by providing surfaces for heterogeneous chemical processes. As a result of these activities, the effect of these gases on radiative forcing may be negative (IPCC, 1992). Therefore, since their effects are uncertain and opposite from the other criteria pollutants, emissions of SO_2 have been presented separately below.

Emissions of Sulfur Dioxide: 1990
(Million Metric Tonnes)

Source	Emissions
Fossil Fuel Combustion	22.69
Industrial Processes	1.91
Solvent Use	0.001
Waste Incineration	0.04
Fossil Fuel Production, Distribution and Storage	0.51
Total	**25.15**

Source: U.S. EPA, 1993b

The major source of SO_2 emissions in the U.S. is the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also release significant quantities of SO_2. As a result, the largest contributor to overall U.S. emissions of SO_2 are electric utilities, accounting for about 70 percent. Coal combustion accounted for approximately 96 percent of SO_2 emissions from electric utilities. The second largest source is industrial fuel combustion, which produced about 14 percent of 1990 SO_2 emissions.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of SO_2 can cause significant increases in acute and chronic respiratory diseases. In addition, once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, as well as cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the U.S. has regulated the emissions of SO_2 in the *Clean Air Act* of 1970 and in its amendments of 1990. The U.S. EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Program, which protects air quality and public health on the local level; (2) the New Source Performance Standards, which set emission limits for new sources; (3) the New Source Review/Prevention of Significant Deterioration Program, which protects air quality from deteriorating, especially in clean areas; and (4) the Acid Rain Program, which addressees regional environmental problems often associated with long-range transport of SO_2 and other pollutants.

These criteria pollutants are generated through a variety of anthropogenic activities, including fossil fuel combustion, solid waste incineration, oil and gas production and processing, industrial processes and solvent use, and agricultural crop waste burning. Table ES-6 summarizes U.S. emissions from these sources for 1990. The United States has annually published estimates of criteria pollutants since 1970. Table ES-6 clearly shows that fuel consumption accounted for the majority of emissions of these gases. In fact, motor vehicles that burn fossil fuels comprise the single largest source of CO emissions in the United States, contributing about two-thirds of all U.S. CO emissions in 1990. Motor vehicles also emit about one-third of total U.S. NO_x and NMVOC emissions. Industrial processes, such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents are also major sources of CO, NO_x, and NMVOCs.

Endnotes

1. A "sink" is a process that destroys or absorbs greenhouse gases. The carbon cycle is composed of reservoirs of carbon (*e.g.*, the oceans, atmosphere, and biota), and of flows of carbon to and from these reservoirs. "Sinks" of carbon dioxide include absorption of atmospheric carbon dioxide by terrestrial biota (such as trees) and oceanic biota. The primary anthropogenic "sink" of carbon is tree planting and other forest management activities. The U.S. has estimated the enhancement of forests as a carbon sink.

2. Ozone exists in the stratosphere and troposphere. In the stratosphere (about 20 - 50 km above the Earth's surface), ozone provides a protective layer shielding the Earth from ultraviolet radiation and subsequent harmful health effects on humans and the environment. In the troposphere (from the Earth's surface to about 10 km above), ozone is a chemical oxidant and a major component of photochemical smog. Most ozone is found in the stratosphere, with some transport occurring to the troposphere (through the tropopause, *i.e.*, the transition zone separating the stratosphere and the troposphere) (IPCC, 1992).

3. The term "criteria pollutant" refers to those compounds for which attainment criteria have been established under the *Clean Air Act Amendments of 1970*. CO, NO_x, NMVOCs, and SO_2 all have air quality standards for which air quality criteria have been issued.

INTRODUCTION

Overview

The Earth absorbs radiation from the Sun, primarily at the surface, and reradiates this energy to space. A portion of this reradiated energy is absorbed or "trapped" by gases in the atmosphere. This "trapped" energy warms the Earth's surface and atmosphere, creating what is known as the "greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the Earth's temperature would average about 55° F lower than today.

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).[1] Chlorofluorocarbons (CFCs) and partially halogenated fluorocarbons (HCFCs), a family of human-made compounds, their substitutes hydrofluorocarbons (HFCs), and other compounds such as perfluorinated carbons (PFCs), are also greenhouse gases. In addition, there are photochemically important gases such as carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs) that, although not greenhouse gases, contribute indirectly to the greenhouse effect. These are commonly referred to as tropospheric ozone precursors because they influence the rate at which ozone and other gases are created and destroyed in the atmosphere. Box 1 contains a brief description of these gases, their sources, and their roles in the atmosphere.[2] In addition, emissions of sulfur dioxide (SO_2) are provided in Annex E of this report. Sulfur gases, primarily sulfur dioxide, are believed to contribute negatively to the greenhouse effect. Therefore, the U.S. has discussed these emissions separately.

Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, their recent atmospheric buildup appears to be largely the result of anthropogenic activities. This buildup has altered the composition of the Earth's atmosphere, and possibly will affect future global climate. Since 1800, atmospheric concentrations of carbon dioxide have increased more than 25 percent, methane concentrations have more than doubled, and nitrous oxide concentrations have risen approximately 8 percent (IPCC, 1992). And, from the 1950s until the mid-1980s, when international concern over CFCs grew, the use of these gases increased nearly 10 percent per year. The consumption of CFCs is declining quickly, however, as these gases are phased out under the *Montreal Protocol*. Use of CFC substitutes, in contrast, is expected to grow significantly.

The Inventory Process

Central to any study of climate change is the development of an emissions inventory that identifies and quantifies a country's primary sources and sinks of greenhouse gases. Developing and participating in the inventory process is important for two reasons: (1) it provides a basis for the ongoing development of a comprehensive and detailed methodology for estimating sources and sinks of greenhouse gases, and (2) it provides a common and consistent mechanism through which all signatory countries to the United Nations' Framework Convention on Climate Change (FCCC) can estimate emissions and compare the relative contribution of different emission sources and greenhouse gases to climate change. Moreover, systematically and consistently estimating emissions at the national and international levels is a prerequisite for

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[1] Ozone exists in the stratosphere and troposphere. In the stratosphere (about 20 - 50 km above the Earth's surface), ozone provides a protective layer shielding the Earth from ultraviolet radiation and subsequent harmful health effects on humans and the environment. In the troposphere (from the Earth's surface to about 10 km above), ozone is a chemical oxidant and major component of photochemical smog. Most ozone is found in the stratosphere, with some transport occurring to the troposphere (through the tropopause, i.e., the transition zone separating the stratosphere and the troposphere) (IPCC, 1992).

[2] For convenience, all gases discussed in this inventory are generically referred to as "greenhouse gases," although the reader should keep in mind the distinction between actual greenhouse gases and photochemically important trace gases.

Box 1. Greenhouse Gases and Photochemically Important Gases

The Greenhouse Gases

Carbon Dioxide (CO_2). The combustion of liquid, solid, and gaseous fossil fuels is the major anthropogenic source of carbon dioxide emissions. Some other non-energy production processes (*e.g.*, cement production) also emit notable quantities of carbon dioxide. CO_2 emissions are also a product of forest clearing and biomass burning. Atmospheric concentrations of carbon dioxide have been increasing at a rate of approximately 0.5 percent per year (IPCC, 1992), although recent measurements suggest that this rate of growth may be moderating (Kerr, 1994).

In nature, carbon dioxide is cycled between various atmospheric, oceanic, land biotic, and marine biotic reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. While there is a small net addition of CO_2 to the atmosphere (*i.e.*, a net source of CO_2) from equatorial regions, oceanic and terrestrial biota in the Northern Hemisphere, and to a lesser extent in the Southern Hemisphere, act as a net sink of CO_2 (*i.e.*, remove more CO_2 from the atmosphere than they release) (IPCC, 1992).

Methane (CH_4). Methane is 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 methane, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and oil, and is released as a by-product of coal production and incomplete fuel combustion. The atmospheric concentration of methane, which has been shown to be increasing at a rate of about 0.6 percent per year, may be stabilizing (Steele et al.,1992).

The major sink for methane is its interaction with the hydroxyl radical (OH) in the troposphere. This interaction results in the chemical destruction of the methane compound, as the hydrogen molecules in methane combine with the oxygen in OH to form water vapor (H_2O) and CH_3. After a number of other chemical interactions, the remaining CH_3 turns into CO which itself reacts with OH to produce carbon dioxide (CO_2) and hydrogen (H).

Halogenated Fluorocarbons, HFCs, and PFCs. Halogenated fluorocarbons are human-made compounds that include: chlorofluorocarbons (CFCs), halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). All of these compounds not only enhance the greenhouse effect, but also contribute to stratospheric ozone depletion. Under the *Montreal Protocol* and the *Copenhagen Amendments*, which control the production and consumption of these chemicals, the U.S. phased out the production and use of all halons by January 1, 1994 and will phase out CFCs, HCFCs, and other ozone-depleting substances by January 1, 1996. Perfluorinated carbons (PFCs) and hydrofluorocarbons (HFCs), a family of CFC and HCFC replacements not covered under the *Montreal Protocol*, are also powerful greenhouse gases.

Nitrous Oxide (N_2O). Anthropogenic sources of nitrous oxide emissions include soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, adipic (nylon) and nitric acid production, and biomass burning.

Ozone (O_3). Ozone is both produced and destroyed in the atmosphere through natural processes. Approximately 90 percent resides in the stratosphere, where it controls the absorption of solar ultraviolet radiation; the remaining 10 percent is found in the troposphere and could play a significant greenhouse role. Though ozone is not emitted directly by human activity, anthropogenic emissions of several gases influence its concentration in the stratosphere and troposphere. Chlorine and bromine-containing chemicals, such as CFCs, deplete stratospheric ozone. However, as previously stated, under the *Montreal Protocol* and *Copenhagen Amendments*, the U.S. phased out the production and use of all halons by January 1, 1994 and will phase out CFCs and other ozone-depleting substances by January 1, 1996.

Increased emissions of carbon monoxide, nonmethane volatile organic compounds, and oxides of nitrogen have contributed to the increased production of tropospheric ozone (otherwise known as urban smog). Emissions of these gases, known as criteria pollutants, are regulated under the *Clean Air Act of 1970* and subsequent amendments.

Photochemically Important Gases

Carbon Monoxide (CO). Carbon monoxide is created when carbon-containing fuels are burned incompletely. Carbon monoxide elevates concentrations of methane and tropospheric ozone through chemical reactions with atmospheric constituents (*e.g.*, the hydroxyl radical) that would otherwise assist in destroying methane and ozone. It eventually oxidizes to CO_2.

Oxides of Nitrogen (NO_x). Oxides of nitrogen, NO and NO_2, are created from lightning, biomass burning (both natural and anthropogenic fires), fossil fuel combustion, and in the stratosphere from nitrous oxide. They play an important role in climate change processes due to their contribution to the formation of ozone.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane VOCs include compounds such as propane, butane, and ethane. Volatile organic compounds participate along with nitrogen oxides in the formation of ground-level ozone and other photochemical oxidants. VOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents (U.S. EPA, 1990a).

evaluating the cost-effectiveness and feasibility of pursuing possible mitigation strategies and implementing emission reduction technologies.

This report presents estimates by the United States Government of U.S. greenhouse gas emissions and sinks for 1990-1993. A summary of these estimates is provided in Table 1 by gas and source category. The remainder of this document discusses the methods and data used to calculate these emission estimates. The emission estimates in Table 1 are presented on both a full molecular basis and on a carbon-equivalent basis in order to show the relative contribution of each gas to total radiative forcing (see Box 2 for an explanation of how the relative contribution of each gas was calculated).

The U.S. views this submission as an opportunity to fulfill its commitment under Article 4-1 of the FCCC, which came into force on March 21, 1994, following ratification. As decided at the Ninth Session of the International Negotiating Committee (INC), emission estimates are to be estimated and presented in accordance with the *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD, 1994) to ensure that the emission inventories submitted to the FCCC are consistent and comparable across sectors and among nations. The information provided in this inventory is presented in accordance with the *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD, 1994), unless otherwise noted.

Methodology and Data

Emissions of greenhouse gases from various sources are estimated using methodologies that are consistent with Volumes 1-3 of *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD, 1994).[3] To the extent possible, the present U.S. inventory relies directly on published activity and emission factor data.[4] Inventory emission estimates from energy consumption and production activities are based primarily on the latest official information from the Energy Information Administration of the Department of Energy (DOE/EIA). Emission estimates for oxides of nitrogen, carbon monoxide, and nonmethane volatile organic compounds are based directly on

Box 2: The Global Warming Potential (GWP) Concept

As mentioned, gases can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas; indirect radiative forcing occurs when chemical transformation of the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of Global Warming Potential (GWP) has been developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide was chosen as the "reference" gas to be consistent with the 1993 U.S. *Climate Change Action Plan*. All gases in this report are presented in units of million metric tonnes of carbon-equivalent, or MMTCE. Carbon comprises 12/44 of carbon dioxide by weight.

The Global Warming Potential (GWP) of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one kilogram of a greenhouse gas to one kilogram of carbon dioxide over a period of time. While any time period can be selected, the 100-year GWPs recommended by the IPCC are used in this report.

Gas	GWP (100 Years)
Carbon dioxide	1
Methane	11/22
Nitrous oxide	270
HFC-134a	1,200
HFC-23	10,000
HFC-152a	150
PFCs	5,400

The direct GWP for methane is 11. The U.S. has accounted for both the direct and indirect effects of methane on radiative forcing. The indirect effects of methane are considered comparable in magnitude to the direct effects, therefore a GWP of 22 has been used (IPCC, 1992). Using a GWP of 22 for methane is also consistent with the GWP used in the U.S. *Climate Change Action Plan*, and follows the suggestion of the INC 9th Session that requests that indirect effects be included where applicable. The magnitude of the indirect effects of other gases are either zero or uncertain.

Table 1: Summary of U.S. Greenhouse Gas Emissions: 1990 - 1993

(Million Metric Tonnes)

Gas/Source	Emissions (Full Molecular Weight)				Emissions (Direct and Indirect Effects; Carbon-Equivalent)			
	1990	1991	1992	1993	1990	1991	1992	1993
Greenhouse Gases								
Carbon Dioxide (CO_2)								
Fossil Fuel Combustion	4,895	4,835	4,908	5,013	1,335	1,319	1,339	1,367
Other	62	61	62	-	17	17	17	-
Total	4,956	4,896	4,970	-	1,352	1,336	1,356	-
Forests (sink)	(436)	(433)	(429)	-	(119)	(118)	(117)	-
Net Total	4,520	4,463	4,541	-	1,233	1,218	1,239	-
Methane (CH_4)								
Landfills	10.0	10.1	10.2	10.3	60	61	61	62
Agriculture	8.6	8.5	8.6	8.8	52	51	52	53
Coal Mining	4.4	4.2	4.0	-	26	26	24	-
Oil and Gas Systems	3.2	3.3	3.3	-	19	20	20	-
Other	0.8	0.8	0.8	-	5	5	5	-
Total	27.0	26.9	27.0	-	162	162	161	-
Nitrous Oxide (N_2O)								
Agriculture	0.2	0.2	0.2	-	14	14	14	-
Fossil Fuel Consumption	0.1	0.1	0.1	-	9	10	10	-
Industrial Processes	0.1	0.1	0.1	-	7	7	7	-
Total	0.4	0.4	0.4	-	30	32	32	-
HFCs and PFCs	+	+	+	-	19.2	19.6	20	-
Photochemically Important Gases								
Carbon Monoxide (CO)	82.7	81.4	78.1	-	-	-	-	-
Nitrogen Oxides (NO_x)	21.4	21.2	21	-	-	-	-	-
NMVOCs	19.1	18.7	17.9	-	-	-	-	-
NET U.S. EMISSIONS					1,444	1,432	1,452	-

\+ Total of these gases does not exceed 0.01 million metric tonnes.

Note: The "Totals" presented in the summary tables in this chapter may not equal the sum of the individual source categories due to rounding.

Changes in CO_2 emissions from fossil fuel consumption had the greatest impact on U.S. emissions from 1990 to 1993. U.S. emissions of CO_2 in 1991 were 1,319 MMTCE, about 1.2 percent lower than 1990 emission levels. Emissions for 1992 were 1,339 MMTCE, an increase of about 1.5 percent over 1991 levels, offsetting the decrease in 1991 and returning emissions to about 1990 levels. Based on preliminary data for 1993, the upward trend since 1991 has continued, with 1993 CO_2 emissions from fossil fuel about 2.4 percent greater than 1990. This trend is largely attributable to changes in total energy consumption resulting from the economic slowdown in the U.S. economy and the subsequent recovery.

CH_4, N_2O, and HFCs and PFCs represent a much smaller portion of total emissions than CO_2. Overall, emissions of these gases remained relatively constant over the period from 1990 to 1992. Methane emissions from coal mining declined slightly due to small decreases in coal production and increases in coalbed methane recovery. N_2O emissions remained relatively constant, while HFC emissions increased slightly, due to increased production of HCFC-22, which increased by-product emissions of HFC-23. PFC emissions remained constant over the period.

available U.S. Environmental Protection Agency (U.S. EPA) emissions data. These estimates are supplemented by calculations using the best available activity data from other agencies. Complete documentation of emission estimations can be found in the sources referenced throughout the text. In these supplementary calculations, attempts were made to adhere as closely as possible to IPCC methods. In many cases, the IPCC default methodologies have been followed. However, for emission sources considered to be *major* sources in the U.S., the IPCC default methodologies were expanded and more comprehensive methods used. These instances, including energy consumption, forest sinks, and some methane sources are documented in the text, along with the reasons for diverging from the IPCC default methodologies.[5]

The majority of 1990 U.S. methane emission estimates presented in this inventory were taken directly from the U.S. EPA report, *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (U.S. EPA, 1993a). That U.S. EPA report provided 1990 U.S. methane emissions for a variety of domestic sources, including natural gas systems, coal mining, landfills, domesticated livestock, manure management, rice cultivation, fuel combustion, and production and refining of petroleum liquids. The methodologies used to arrive at the emissions estimates in U.S. EPA (1993a) are conceptually similar to IPCC methodologies. Where the methodologies differ, information is provided in the text and/or annexes to ensure that the estimates presented are reproducible. Estimates for 1991, 1992, and 1993 have been developed using these same methodologies unless otherwise noted.

Emission estimates for NO_x, CO, and NMVOCs were taken directly, except where noted, from the U.S. EPA report, *National Air Pollutant Emission Trends 1900 - 1992* (U.S. EPA, 1993b), which is an annual U.S. EPA publication that provides the latest estimates of regional and national emissions for criteria pollutants.[6] Emissions of these pollutants are estimated by the U.S. EPA based on statistical information about each source category, emission factor, and control efficiency. While the U.S. EPA's estimation methodologies are conceptually similar to the IPCC-recommended methodologies and are discussed in detail below, the large number of sources EPA used in developing the estimates makes it difficult to reproduce the information from EPA (1993b) in this inventory document. In these instances, the sources containing the detailed documentation of the methods used are referenced for the interested reader.

Organization of the Inventory

In accordance with the IPCC guidelines for reporting contained in the *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD, 1994), this inventory is organized into six parts. These six parts correspond to the six major source categories below. In addition, annexes provide additional data on calculations which are not included in the main text. (Note: while the list below follows the IPCC's list of recommended source categories, emission sources that are not applicable to the U.S. are not included).

I. Part I covers emissions from all energy activities, including:
    A. Fuel Combustion Activities:
        1. Industry

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[3] Discussions of inventory methods can also be found in *Estimation of Greenhouse Gas Emissions and Sinks: Final Report from the OECD Experts Meeting, 18-21 February 1991* (August 1991). That report documents baseline inventory methodologies for a variety of source categories, which have subsequently been further refined based on recommendations provided at an IPCC-sponsored experts workshop held in Geneva, Switzerland in December 1991 and at an OECD/Netherlands-sponsored workshop in Amersfoort, Netherlands in February 1993. The proceedings from these meetings, the *Final Report* (OECD, 1991), as well as several other international meetings, form the basis for the current *IPCC Draft Guidelines*.

[4] Depending on the emission source category, *activity data* can include fuel consumption or deliveries, vehicle-miles travelled, raw material processed, etc.; *emission factors* are factors that relate the quantity of emissions to the activity.

[5] In order to fully comply with the *IPCC Draft Guidelines*, the United States has provided a copy of the IPCC reporting tables in Annex D.

[6] Criteria pollutants include: carbon monoxide (CO), lead (Pb), nitrogen oxides (NO_x), particulate matter less than ten microns (PM-10), sulfur gases (especially SO_2), total particulate matter (TP), and nonmethane volatile organic compounds (NMVOCs).

    2. Transportation
    3. Residential
    4. Commercial/Institutional
    5. Electric Utilities
    6. Biomass for energy
  - B. Fuel Production, Transmission, Storage, and Distribution:
    1. Crude oil and natural gas
    2. Coal mining

II. Part II covers emissions from other industrial production processes (nonenergy ISIC), including:
  - A. Chemicals
  - B. Non-Metallic Mineral Products
  - C. Other, including chlorofluorocarbons and other substances

III. Part III covers emissions from solvent use

IV. Part IV covers emissions from agriculture, including:
  - A. Enteric Fermentation (in domestic animals)
  - B. Manure Management (for domestic animals)
  - C. Rice Cultivation
  - D. Agricultural Soils
  - E. Agricultural Crop Waste Burning

V. Part V covers emissions resulting from land-use change and forestry

VI. Part VI covers emissions from wastes and waste-treatment processes, including:
  - A. Landfills
  - B. Wastewater Treatment
  - C. Waste Combustion

Uncertainty and Limitations of Emissions Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, it has several strengths and weaknesses. First of all, this report by itself does not provide a complete picture of past or future emissions in the U.S.; it only provides an inventory of U.S. emissions for the years 1990 - 1993. However, the U.S. believes that common and consistent inventories taken over a period of time can and will contribute to understanding future emission trends. The U.S. plans to update this comprehensive inventory of greenhouse gas emissions and sinks on an annual basis and to use the information gained to track progress of commitments made under the U.S. *Climate Change Action Plan*. The methodologies used to estimate emissions will be periodically updated as methods and information improve, and as further guidance is received from the IPCC and the INC. In order to maintain consistency as methodologies change over time, the U.S. will also include, as appendices to future updates, estimates of emissions using the methods described in this document.

Secondly, there are uncertainties associated with the emissions estimates. Some of the current estimates, such as those for CO_2 emissions from energy-related activities and cement processing, are considered accurate. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limit the scope or accuracy of the inventory. For certain categories, emission estimates are given as a specific range to reflect the associated uncertainty. Where applicable, specific factors affecting the accuracy of the estimates are also discussed in detail.

Finally, while the IPCC methodologies provided in the three volume IPCC/OECD report, *IPCC Draft Guidelines for National Greenhouse Gas Inventories*, represent baseline methodologies for a variety of source categories, many of these methodologies are still being refined. The current U.S. inventory uses the IPCC methodologies where possible, and supplements with other available methodologies and data where needed. The U.S. realizes that not only are the methodologies still evolving, but that additional efforts are necessary to improve methodologies and data collection procedures. Specific areas requiring further research include:

- Completing estimates for various source categories. Quantitative estimates of 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.
- Understanding the relationship between emissions and sources. This is a crucial step in completing and refining existing methodologies and in developing methodologies for emission source categories where none

currently exist. For example, a great deal of uncertainty exists in how nitrous oxide emissions are produced from energy-related activities and fertilizer consumption. As a consequence, the quality of emission factors and activity data for these categories are particularly weak.

- Improving the accuracy of emissions factors. A substantial amount of research is underway that could improve the accuracy of emission factors used to calculate estimates for a variety of sources. For example, the accuracy of current emission factors used to estimate emissions from surface coal mining is limited by a lack of available data. Emission factors for methane from landfills are also currently undergoing revision. To more accurately assess methane emissions from landfills, researchers are working to determine the relationship between moisture, climate, and waste composition and methane generation rates. Emission factors used to estimate greenhouse gas emissions from biomass burning and land use are also being revised.
- Providing appropriate activity data. Although methodologies exist for estimating emissions for some source categories, problems arise in obtaining data that are compatible with methodology requirements. For example, the ability to estimate emissions from oil and gas systems is constrained by a lack of information on compressor type, amount of leakage, and emission control technology. In the agricultural sector, estimating emissions of animal wastes using the IPCC methodology is arduous because of the complexity of the data required. Obtaining information on animal weights, waste management systems, and feeding practices by animal type is difficult. Efforts need to be made to collect activity data appropriate for use in the IPCC methodologies.

The uncertainties and limitations associated with calculating greenhouse gas emissions are both qualitative and quantitative. Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies and incomplete data. Efforts need to be made to improve existing methodologies and data collection activities, so that methodologies and data are consistent with one another and so that they allow both the U.S. and other countries to estimate emissions with greater ease, certainty, and consistency.

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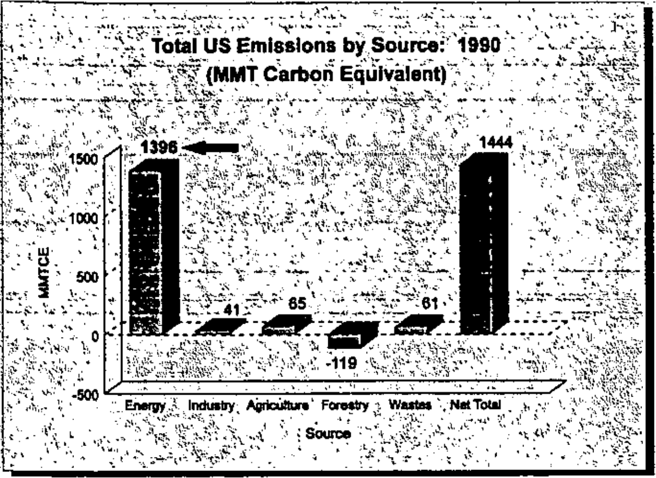
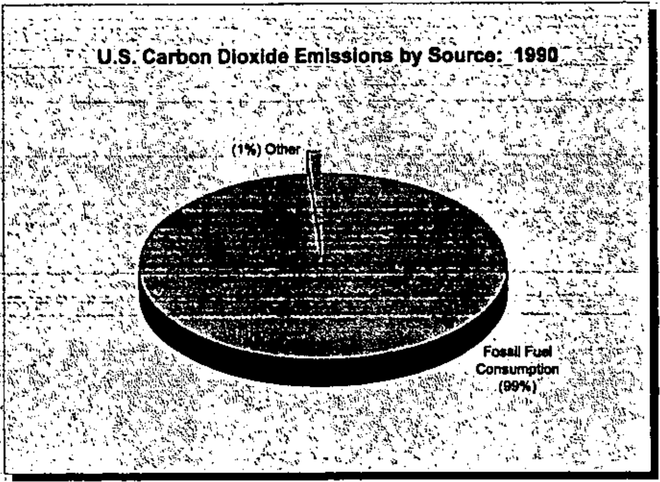
PART I. EMISSIONS FROM ENERGY





Energy-related activities are the most significant contributor to U.S. greenhouse gas emissions, accounting for 1,396 MMTCE, or 89 percent of U.S. emissions in 1990. Emissions from fossil fuel combustion comprise the vast majority of these energy-related emissions, with releases of CO_2 from fossil fuel combustion accounting for 1,335 MMTCE. Activities associated with the production, transmission, storage, and distribution of fossil fuels also emit greenhouse gases.[1] These are primarily fugitive emissions from natural gas systems, oil production and refining, and coal mining. The main gas emitted through these activities is methane, while smaller quantities of NMVOCs, CO_2, and CO can also be emitted. These gases represent a much smaller portion of total energy emissions than CO_2, but are nonetheless important. About 30 percent of the nation's CH_4 emissions and 31 percent of N_2O emissions come from energy-related activities. Additionally, the majority of criteria pollutants are emitted from energy activities, which account for 96, 90, and 50 percent of NO_x, CO, and NMVOC emissions, respectively.

The combustion of biomass and biomass-based fuels also emits greenhouse gases, although CO_2 emissions from these activities are not included in the U.S. total because biomass resources in the U.S. are used on a sustainable basis. That is, the carbon released when biomass is consumed is recycled as U.S. forests regenerate, causing no additional CO_2 to be added to the atmosphere.[1]

U.S. emissions of CO_2 from energy decreased over one percent in 1991 compared to 1990 levels, declining from 1,335 MMTCE to 1,319 MMTCE. Emissions for 1992 were 1,339 MMTCE, offsetting the decrease in 1991 and returning emissions to about 1990 levels. Based on preliminary data for 1993, the upward trend since 1991 has continued, with 1993 CO_2 emissions from fossil fuel combustion at 1,367 MMTCE, or about 2.4 percent greater than 1990. This trend is largely attributable to changes in total energy consumption resulting from the economic slowdown in the U.S. economy and the subsequent recovery. Methane emissions from coal mining did decline slightly over this period due to small decreases in coal production and increases in coalbed methane recovery. Emissions of the criteria pollutants CO, NO_x, and NMVOCs declined, continuing a downward trend in these gases over the past several years.

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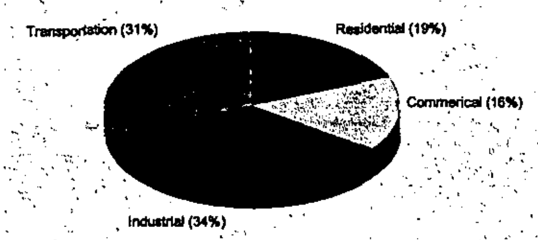
[1] Any emissions related to land use changes are discussed in Part V of this document.

A. EMISSIONS FROM FOSSIL FUEL CONSUMPTION

1. Carbon Dioxide Emissions from Fossil Fuel Consumption

The majority of energy in the United States, approximately 88 percent, is produced through the combustion of fossil fuels such as coal, natural gas, and petroleum. The remaining 12 percent consists of renewable or other energy sources such as hydropower, biomass, and nuclear energy.

Carbon Dioxide Emissions by End Use Sector: 1990

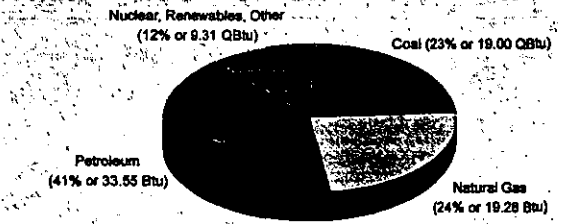


In this graph, emissions generated by electric utilities are allocated to each end-use sector according to each sector's share of electricity consumption.

In 1990 the U.S. emitted a total of 1,335 MMTCE as CO_2 from fossil fuel combustion, or about 99 percent of total U.S. emissions of CO_2 and 85 percent of all greenhouse gas emissions (fuels for international transport accounted for an additional 22.6 MMTCE, which is not included in the U.S. estimates)[2]. These emissions were produced from a variety of fossil fuel combustion activities, including heating in residential and commercial buildings, energy combustion to generate electricity, steam production for industrial processes, and gasoline consumption in automobiles and other vehicles.

As fossil fuels are combusted, the carbon stored in the fuels is emitted as carbon dioxide and smaller amounts of other gases, including CO, CH_4, and NMVOCs. These other gases are emitted as a by-product of incomplete fuel combustion. The amount of carbon in the fuel varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has about 80 percent of the carbon per unit of energy as compared to coal, and natural gas has only about 55 percent. Petroleum supplies the largest share of U.S. energy needs, accounting for over 40 percent of total energy consumption (see Figure I-1). As a result, uses of petroleum released approximately 581 MMTCE in 1990, or 43 percent of all CO_2 emissions from energy consumption (see Table I-1). The other fossil fuels, coal and natural gas, accounted for 36 and 21 percent, respectively.

Figure I-1
Types of Energy Consumed in the U.S.: 1990



1 QBtu = 1 quadrillion Btu = 1X10E15 Btu

Approximately 88 percent of U.S. energy is produced through the combustion of fossil fuels.

U.S. emissions of CO_2 from energy were estimated to be 1,335 MMTCE in 1990, declining to 1,319 MMTCE in 1991. 1992 emissions increased to 1,339 MMTCE. Based on preliminary data for 1993, CO_2 emissions from fossil fuel combustion were 1,367 MMTCE, or about 2.4 percent greater than 1990 (see Table I-1). This trend is largely due to the economic recession and subsequent recovery.

Industrial Sector

The industrial sector accounts for 34 percent of U.S. emissions from fossil fuel consumption, making it the largest end-use source of CO_2 emissions (see Figure I-2). About two-thirds of these emissions result from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining one-third of industrial energy needs is met by electricity for such uses as motors, electric furnaces and ovens, and lighting.

The industrial sector is also the largest user of non-energy applications of fossil fuels, which often store carbon. Fossil fuels used for producing fertilizers, plastics, asphalt, or lubricants can store carbon in products for very long periods. Asphalt used in road construction, for example, stores carbon indefinitely.

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[2] There is international disagreement as to which countries are responsible for emissions produced from international transport activities (fuels used in international transport are typically referred to as bunker fuels). The IPCC recommends that countries account separately for bunker fuel emissions and exclude them from national totals until an internationally recognized method is developed to allocate these emissions to specific countries. These emissions are therefore reported separately in the U.S. inventory and not included in the national total.

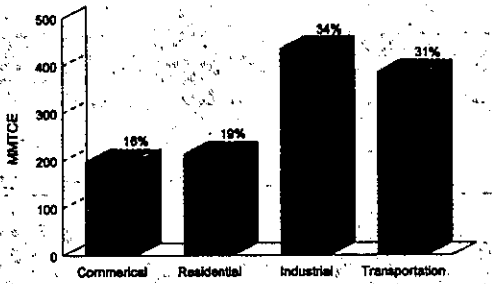
Table I-1. U.S. CO_2 Emissions from Energy Consumption by Sector and Fuel Type: 1990 - 1993
(Million Tonnes of Carbon-Equivalent)

Sector	1990	1991	1992	1993
Residential				
Coal	140.3	139.5	141.1	147.5
Petroleum	33.1	33.0	31.6	32.8
Gas	79.4	83.2	85.0	88.2
Total Residential	**252.7**	**255.7**	**257.7**	**268.4**
Commercial				
Coal	128.3	127.5	129.0	134.9
Petroleum	26.3	24.8	22.3	22.9
Gas	51.8	54.3	55.2	56.2
Total Commercial	**206.4**	**206.6**	**206.5**	**214.0**
Industrial				
Coal	210.3	205.9	205.6	212.5
Petroleum	112.8	99.4	108.8	105.9
Gas	133.3	138.5	143.2	145.3
Total Industrial	**456.4**	**443.8**	**457.7**	**463.8**
Transportation				
Coal	0.6	0.6	0.6	0.6
Petroleum	400.0	391.9	397.8	401.9
Gas	9.9	9.2	9.0	9.2
Total Transportation	**410.5**	**401.7**	**407.5**	**411.7**
U.S. Territories				
Coal	0.1	0.2	0.2	0.2
Petroleum	9.0	10.6	9.2	9.2
Gas	0.0	0.0	0.0	0.0
Total Territories	**9.1**	**10.8**	**9.4**	**9.4**
All Sectors				
Coal	479.6	473.7	476.5	495.7
Petroleum	581.1	559.7	569.8	572.7
Gas	274.4	285.1	292.4	298.9
Total	**1,335.1**	**1,318.5**	**1,338.6**	**1,367.3**

Source: Based on Energy consumption estimates from EIA, (1994b &1994h) and carbon coefficients from EIA (1994g) and IPCC (IPCC/OECD, 1994). For complete references see Annex A.

Similarly, the fossil fuels used in the manufacture of materials like plastics also store carbon, releasing this carbon only if the product is incinerated.

Figure I-2
Carbon Dioxide Emissions from Fossil Fuel Combustion by End-Use Sector: 1990
(MMT Carbon Equivalent)



Note: U.S. Territories comprise less than 1% of emissions.

Transportation Sector

The transportation sector is also a major source of CO_2, accounting for about 31 percent of U.S. emissions. Virtually all of the energy consumed in this sector comes from petroleum-based products. Nearly two-thirds of the emissions are the result of gasoline consumption in automobiles and other vehicles, with other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, accounting for the remainder.

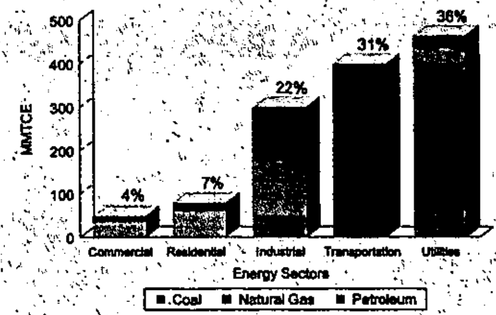
Residential and Commercial Sectors

The residential and commercial sectors account for about 19 and 16 percent, respectively, of CO_2 emissions from fuel consumption. Both sectors are heavily reliant on electricity for meeting energy needs, with about two-thirds of their emissions attributable to electricity consumption. End-use applications include lighting, heating, cooling, and operating appliances. The remaining emissions are largely due to the consumption of natural gas and oil, primarily for meeting heating and cooking needs.

Electric Utilities

As noted above, the U.S. relies on electricity to meet a significant portion of its energy requirements. In fact, as the largest consumers of U.S. energy (about 36 percent of total energy), electric utilities are collectively the largest producers of U.S. CO_2 emissions (see Figure I-3). This sector generates electricity for such uses as lighting, heating, electric motors, and air conditioning. Some of this electricity is generated with the lowest CO_2-emitting energy technologies, particularly nonfossil options, such as nuclear energy, hydropower, or geothermal energy. However, electric utilities rely on coal for 55 percent of their total energy requirements and account for about 85 percent of all coal consumed in the United States.

Figure I-3
Carbon Dioxide Emissions from Fossil Fuel Combustion by Sector and Fuel Type: 1990
(MMT Carbon Equivalent)



Note: U.S. Territories comprise less than 1% of emissions.

Methodology Used to Estimate Emissions

The methodology used by the U.S. 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 (see *Greenhouse Gas Inventory Reference Manual*; IPCC, 1994; Vol. 3). A detailed description of the U.S. methodology is presented in Annex A, and is characterized by the following five steps:

1. *Determine fuel consumption by fuel type and sector.* Fuel consumption data were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), which is responsible for the collection of all U.S. energy data. By aggregating consumption data by sector (*e.g.*, commercial, industrial, etc.), primary fuel types (*e.g.*, coal, oil, gas), and secondary fuel categories (*e.g.*, gasoline, distillate fuel, etc.), EIA estimates total U.S. energy consumption for a particular year.[3] A discussion of the data sources and comparison of different methodological approaches can be found in Box I-1.

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[3] 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 about 9 MMTCE of emissions in 1990.

Box I-1. About Energy Data and Estimating Carbon Emissions

When fuels are burned, the carbon contained within them combines with atmospheric oxygen to form carbon dioxide. In theory, if the carbon content of the fuel and the combusted quantity is known, the resulting volume of carbon dioxide can be estimated with a high degree of certainty. Therefore, energy-related carbon dioxide emissions can be estimated with a fairly high degree of precision using available energy data.

1. Data Availability

In the U.S., the organization responsible for reporting and maintaining annual energy statistics is the Energy Information Administration (EIA), an agency of the U.S. Department of Energy (U.S. DOE). EIA reports consumption statistics for the 50 U.S. states (e.g. the State Energy Data Report) and U.S. territories as well as international statistics. EIA is also responsible for reporting U.S. data to the IEA and U.N.

2. Data format

For consistency of reporting, the IPCC has recommended that national inventories report energy data (and emissions from energy) 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 U.S. by EIA are more of the "bottom up" nature, i.e., they are collected through EIA surveys at the point of delivery or use and aggregated to determine national totals. In other words, the EIA data reflect the reported consumption quantities of fuel categories and types.

For reporting to IEA, EIA converts the data for the 50 states into IEA fuel categories and units, calculates "apparent consumption," and adjusts for production, imports, exports, and stock changes in U.S. territories and islands. The "converted" data are then submitted to the IEA, along with the conversion factors used and other relevant information.

Both of the above approaches have advantages and disadvantages. For example, while the "top down" approach more accurately captures fuel flow (and therefore the carbon flow) in most countries, the "bottom up" allows for more detailed information by end-use sectors and fuel types.

3. Estimating Carbon Emissions

Theoretically, both approaches should yield similar carbon emissions results. But, in reality, in most countries' estimates will vary depending on the approach used to estimate consumption totals, the definition and interpretation of data sources, the carbon coefficients used, and the assumptions regarding both the quantity of carbon stored in products and combustion efficiency. Both approaches are believed to produce highly accurate results in the U.S.

Carbon emissions estimates from the "bottom up" approach are presented in this chapter and total 1,335 MMTCE. The "top down" approach results in carbon emissions of 1,320 MMTCE. A comparison of these two approaches is provided in Annex A.

2. *Determine the total carbon content of all fuels.* Total carbon is 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 were converted to CO_2. For 1990 the potential emissions were estimated to be 1,427 MMTCE. The carbon emission coefficients used by the U.S. are presented in Table I-2.

3. *Estimate the amount of carbon stored in products.* Non-fuel uses of fossil fuels can result in storage of some or all of the carbon contained in the energy for some period of time, depending on the end-use. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon for extended periods of time, while other products, such as lubricants or plastics, lose or emit some carbon when they are used and/or are burned as waste after utilization. The amount of carbon sequestered or stored in non-energy uses of fossil fuels was based on the best available data on the end uses and ultimate fate of the various energy products. These non-energy uses occur in the industrial and transportation sectors, and for 1990 were estimated to be about 66 MMTCE.

Table I-2. Key Assumptions for Estimating Carbon Dioxide Emissions

Fuel Type	Carbon Coefficients (kg C/10^6 Btu)	Stored C (%)	Combustion Efficiency (%)
Petroleum			
Gasoline	19.41	--	99.0
LPG	17.16	80[*]	99.0
Jet Fuel	19.74	--	99.0
Distillate Fuel	19.95	--	99.0
Residual Fuel	21.49	--	99.0
Asphalt and Road Oil	20.62	100[*]	99.0
Lubricants	20.24	50	99.0
Petrochemical Feed	19.37	80	99.0
Aviation Gas	18.87	--	99.0
Kerosene	19.72	--	99.0
Petroleum Coke	27.85	--	99.0
Special Naphtha	19.86	--	99.0
Waxes and Misc.	19.81	100	99.0
Petroleum Other	a	--	99.0
Coal			
Residential/Commercial	26.05	--	99.0
Industrial			
Coking	25.46	75	99.0
Other	25.47	75	99.0
Utility	25.57	--	99.0
Natural Gas			
Flare	14.92	--	
Natural Gas	14.47	100[*]	99.5

Sources: Carbon coefficients from EIA (1994g). Stored carbon from Marland & Pippen (1990) and Rypinski (1994). Combustion efficiency for coal from Bechtel (1993) and for oil and gas from IPCC (IPCC/OECD, 1994; Vol. 2.).

[*] Only the portion used as a feedstock is included in the carbon stored calculation.

[a] See Table A-1A in Annex A.

4. *Adjust for carbon that does not oxidize during combustion.* Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels will not be emitted to the atmosphere. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process range from approximately 1 percent for oil and coal to 0.5 percent for gas (see Table I-2 for the assumptions used by the U.S.).

5. *Subtract emissions from bunker fuels.* According to the IPCC guidelines, emissions from international transport activities, or bunker fuels, should not be included in national totals. This recommendation is due to international disagreement as to which countries are responsible for these emissions. These emissions were about 22.6 MMTCE in 1990.

Uncertainty in the Carbon Dioxide Emission Estimates

Uncertainties exist for all of the emission estimates provided in this report. For estimates of CO_2 from energy consumption, in principle 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 energy type, carbon content of fossil fuels consumed, and consumption of products with long-term carbon storage would yield an accurate estimate of CO_2 emissions.

There are uncertainties, however, over the levels of detail, data sources, carbon content of fuels and products, and combustion efficiency. For example, given the same energy type (*e.g.*, coal), the amount of carbon contained in the fuel per unit of useful energy can vary. Non-energy uses of the fuel (such as in the production of napthas, lubricants, etc.) can create situations where the carbon is not emitted to the atmosphere (*e.g.*, plastics, asphalt) or is emitted at a much delayed rate. The proportions of fuels used in these non-fuel production processes and their carbon content can also vary. Additionally, inefficiencies in the combustion process, which can result in ash or soot remaining unoxidized for long periods, can vary. These factors all contribute to the uncertainty in the CO_2 estimates. For the U.S., however, these uncertainties are believed to be relatively small.[4]

2. Other Greenhouse Gas Emissions from Stationary Fossil Fuel Combustion

Stationary combustion encompasses all fuel combustion activities except transportation (i.e., mobile combustion). Other than CO_2 gases from stationary combustion include the greenhouse gases methane and nitrous oxide and the photochemically important gases such as oxides of nitrogen, carbon monoxide, and non-methane volatile organic compounds, which are all products of incomplete combustion. The amount of emissions varies depending upon fuel, technology type, and pollution control policies. Emissions also vary with size and vintage of the combustion technology as well as maintenance and operational practices.

Stationary combustion is a significant source of oxides of nitrogen and carbon monoxide emissions. 1990 emissions of NO_x from stationary combustion represented 50 percent of national NO_x emissions, while CO emissions from stationary combustion contributed 7 percent to the national CO total. NMVOCs emissions from stationary combustion are a minor source, accounting for about 4 percent of the national total. Emissions of these criteria pollutants have declined from much higher levels in the past due to a combination of technological advances and more stringent emissions requirements. From 1990 - 1992, emissions of NO_x remained relatively constant, while emissions of CO and NMVOCs showed a slight decline (see Table I-3). Stationary combustion is believed to be a small source of methane and nitrous oxide. Methane emissions from stationary combustion in 1990 accounted for about 1.5 percent of total U.S. methane emissions, while nitrous oxide emissions from stationary combustion accounted for about 8.5 percent of all N_2O emissions.

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[4] U.S. CO_2 emission estimates from fossil fuel consumption are considered accurate within one or two percent. See, for example, Marland and Pippin, 1990 or EIA, 1993d.

Table I-3. U.S. Greenhouse Gas Emissions from Stationary Combustion: 1990-1992

(Thousand Metric Tonnes)

Year	NO_x	NMVOCs	CO	CH_4	N_2O
1990	10,695	685	6,128	424	35
1991	10,730	678	6,004	414	35
1992	10,635	639	5,603	386	35

Sources: 1. Criteria pollutant emission estimates are from U.S. EPA (1993b).

2. Methane emissions are based on NMVOC emissions from U.S. EPA (1993b) and emission factors from U.S. EPA (1993a).

3. N_2O emissions are based on IPCC/OECD emission factors for uncontrolled stationary combustion, wood fuel combustion, and U.S. fossil fuel and wood fuel energy consumption data. (IPCC/OECD, 1994; Vol. 2)

N_2O and NO_x emissions from stationary source combustion are closely related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. CO emissions from stationary combustion are generally a function of the efficiency of combustion and emission controls. CO emissions are highest when there is less oxygen in the air-fuel mixtures than necessary for complete combustion. This is likely to occur during combustion stopping and starting, or switching of fuels (for example, the switching of coal grades at a coal-burning utility plant). Methane and NMVOC emissions from stationary combustion are believed to be a function of the methane content of the fuel and post-combustion controls.

Methane emission estimates from stationary sources are highly uncertain, primarily due to major uncertainties in emissions from wood combustion (i.e., fireplaces and wood stoves). The largest source of N_2O emissions comes from utility coal combustion, accounting for about 37 percent of total N_2O emissions from stationary combustion in 1990. It is important to note, however, that both of these gases are currently not regulated in the U.S., and therefore, their emission processes are not as well understood as emission processes for some criteria pollutants. The estimates of methane and nitrous oxide emissions presented here are based on broad indicators of emissions (i.e., aggregate emissions ratios of CH_4 emitted to total NMVOCs and rate per amount of fuel used, respectively), rather than specific emission processes (i.e., rate by combustion technology and type of emission control).

Greenhouse gas emissions from energy-related stationary combustion activities have been grouped into four sectors:

- Industrial
- Commercial/Institutional
- Residential
- Electric Utilities

The major fuel source categories included in this section are: coal, fuel oil, natural gas, wood, other fuels (which encompasses bagasse, LPG, coke, and coke oven gas), and internal combustion (which includes emissions from internal combustion engines that are not used in transportation). A summary of the emissions from stationary combustion sources in 1990 is provided in Table I-4.

Emissions estimates for NO_x, CO, and NMVOCs in this section were taken directly from the U.S. EPA's *National Air Pollutant Emissions Trends: 1900 - 1992* (U.S. EPA, 1993b). U.S. EPA (1993b) estimates emissions of NO_x, NMVOCs, and CO by sector and fuel source using a "bottom-up" estimating procedure, *i.e.*, the emissions were calculated either for individual sources (*e.g.*, industrial boilers) or for many sources combined, using basic activity data (such as fuel consumption or deliveries, etc.) as indicators of emissions. The national activity data used to calculate the individual source categories were obtained from many different sources. Depending on the source category, these basic activity data may include fuel consumption or deliveries of fuel, tons of refuse

Table I-4. U.S. Greenhouse Emissions from Stationary Combustion by Sector and Fuel Source: 1990 (Thousand Metric Tonnes)

Source Category	NO_x	NMVOCs	CO	CH_4[a]	N_2O
Electric Utilities					
Coal	6,083	24	211	13	13
Fuel Oil	190	5	18	+	1
Natural Gas	507	2	46	NA	+
Wood	NA	NA	NA	NA	+
Other Fuels[b]	NA	NA	NA	NA	NA
Internal Combustion	45	1	10	+	NA
Total Utilities	6,825	32	285	13	14
Industrial					
Coal	556	6	78	3	4
Fuel Oil	271	15	42	1	5
Natural Gas	1,745	190	284	NA	1
Wood	NA	NA	NA	NA	7
Other Fuels[b]	117	33	156	3	NA
Internal Combustion	517	14	89	1	NA
Total Industrial	3,206	258	649	9	16
Commercial-Institutional					
Coal	35	1	14	1	+
Fuel Oil	90	4	15	+	1
Natural Gas	149	6	45	NA	+
Wood	NA	NA	NA	NA	+
Other Fuels[b]	10	4	47	+	NA
Internal Combustion	NA	NA	NA	NA	NA
Total Commercial	284	15	121	1	1
Residential					
Coal[e]	NA	NA	NA	NA	+
Fuel Oil[e]	NA	NA	NA	NA	1
Natural Gas[e]	NA	NA	NA	NA	+
Wood	60	367	4,930	367	3
Other Fuels[b]	319	14	143	1	NA
Internal Combustion	NA	NA	NA	NA	NA
Total Residential	379	381	5,073	369	4
Stationary Combustion Total	**10,695**	**685**	**6,128**	**424**[c]	**35**[d]

Source: NO_x, NMVOCs, and CO data are from U.S. EPA (1993b). CH_4 emissions were calculated from EPA (1993b) data using CH_4 to NMVOCs ratios from U.S. EPA (1993a) (see text). N_2O emissions were calculated from EIA data and IPCC emission factors. (EIA, 1994b, 1994h, 1994; IPCC/OECD, 1994; Vol. 1)

Notes:

1. Technically, of this group only CH_4 and N_2O are greenhouse gases. See Box 1.
2. Components may not sum to totals due to independent rounding.

"+" Denotes negligible; "NA" denotes not available.

a. Calculated using the midpoint of CH_4 to NMVOC ratios from U.S. EPA (1993a).

b. Other fuels include: LPG, waste oil, coke oven gas, coke, and wood (except in the residential sector, where wood has been dissaggregated) (U.S. EPA, 1993b).

c. This figure includes total CH_4 emissions from natural gas stationary sources as reported in U.S. EPA (1993a). This estimate (16-63 thousand metric tonnes, with a mean estimate of 32) was not disaggregated by sector in the EPA report. Therefore, 32 thousand metric tonnes has been added to the total at the bottom of the CH_4 column. See Table I-5 for data used in methane emission estimates.

d. Includes emission estimates from wood fuel combustion.

e. Coal, fuel oil, and natural gas emissions of NO_x, NMVOCs, CO, and CH_4 are included in "Other Fuels" (U.S. EPA, 1993b).

burned, raw material processed, etc. Activity data are used in conjunction with emission factors, which relate the quantity of emissions to the activity. The basic "bottom-up" calculation procedure for most source categories presented in EPA (1993b) is represented by the following equation:

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

where E = emissions
p = pollutant
s = source category
A = activity level
EF = emissions factor
C = percent control efficiency

Emission factors are generally available from the U.S. EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA, 1985), often referred to as AP-42 emission factors. The U.S. currently derives the overall control efficiency of a source category from its Aerometric Information Retrieval System -- AIRS database (U.S. EPA, 1992). The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by the IPCC (IPCC/OECD, 1994; Vol. 1).

Methane emissions from stationary combustion of coal, fuel oil, and wood were calculated using reported NMVOC emissions for each activity from U.S. EPA (1993b), and published emission ratios of CH_4 to NMVOCs (U.S. EPA, 1993a) for these activities. The emission ratios used are provided in Table I-5.

Table I-5. Ratio of CH_4 to NMVOCs Released During Combustion

Activity (Source Category)	**Ratio of CH_4 to NMVOCs** (Low - High)
Coal Combustion	0.05 to 1.00
Fuel Oil Combustion	0.05 to 0.10
Wood Combustion (Industrial Use)	0.2
Wood Combustion (Residential Use)	2
Other	0.1

Source: U.S. EPA (1993a); except for "Other", where the upper end of the fuel oil category was used as an approximation.

Notes: Emissions from wood-fired equipment are based on U.S. EPA (1985). For industrial wood combustion, the mean methane to NMVOC ratio is based on wood combustion in boilers. For residential wood combustion, the mean ratio is based on available emission factors for residential wood stoves.

Estimates of methane emissions from natural gas consumption came from U.S. EPA (1993a). The total emission estimate of 16 to 63 thousand metric tonnes of methane (0.1 to 0.4 MMTCE) is compiled by sector (utility, industrial, commercial, and residential) and technology type (boiler and non-boiler). The U.S. EPA (1993a) reported 300 thousand to 1.4 million metric tonnes (1.8 to 8.4 MMTCE) as the range of methane emissions from all stationary sources.

The estimates of methane emissions from stationary sources, other than gas-fired sources, are subject to considerable uncertainty due to the lack of accurate data regarding the technology type and the pollution control equipment in each of the other source categories (*e.g.*, coal, fuel oil, and especially wood).[5] As a result, estimates are based on broad estimates of the percentage of methane emissions relative to NMVOC emissions -- a methodology that results in very imprecise estimates. The estimates for gas-fired stationary combustion are more precise due to the greater level of disaggregation by sector and technology.

Nitrous oxide emissions were estimated using IPCC-recommended emission factors and U.S. fossil fuel and wood fuel consumption data. Estimates were obtained by multiplying the appropriate emission factors (by sectors and fuel types) by the appropriate U.S. energy data. The emission factors used were: 4.3 g N_2O/GJ[6] of energy input for wood in all sectors; 0.1 g N_2O/GJ for gas use and 0.6 g N_2O/GJ for oil use in all sectors; and for coal use, 0.8 g N_2O/GJ for the utility sector and 1.4 g N_2O/GJ for the industrial, commercial, and residential sectors.

Estimating emissions other than carbon dioxide from stationary combustion can be time consuming and complex. Moreover, the amount of gases emitted from these activities are not thought to be major contributors to climate change. The uncertainties associated with the emission estimates of these gases, especially methane and nitrous oxide estimates, are also much higher than the uncertainty associated with estimates of CO_2 from fossil fuel combustion. Uncertainties in the methane estimates are due primarily to the fact that

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[5] Methane emissions from gas-fired sources were extensively researched and documented in U.S. EPA (1993a).

[6] GJ = Gigajoule = one billion joules. One joule = 0.9478 Btu.

they are based on simple ratios of methane to emitted NMVOCs and are derived from a limited number of emissions tests. Uncertainties in the nitrous oxide estimates are due to the fact that emissions were estimated based on a limited set of emission factors. For the other gases, the uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, and the emission factors used.

3. Other Greenhouse Gas Emissions from Mobile Combustion

Mobile sources emit the greenhouse gases methane and nitrous oxide, and photochemically important gases, including carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds. Emissions of these trace gases are produced by the incomplete combustion of the fossil fuels used to power vehicles.

Fossil fueled motor vehicles comprise the single largest source of CO emissions in the U.S. For the period 1990-1992, CO emissions from mobile sources contributed about 80 percent of all U.S. CO emissions (see Table I-6). Motor vehicles also emit about 45 percent of total U.S. anthropogenic NO_x and NMVOC emissions. Mobile emissions are also a small but significant source of methane and nitrous oxide in the U.S. Road transport accounts for the majority of mobile source emissions. For the period 1990-1992, emissions of the criteria pollutants as a whole show a declining trend, while methane and nitrous oxide emissions have increased slightly.

As in combustion in stationary sources, N_2O and NO_x emissions are closely related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. CO emissions from mobile combustion are a function of the efficiency of combustion and post-combustion emission controls. CO emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. This occurs especially in idle, low speed and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the methane content of motor fuel, the amount of hydrocarbons passing unburnt through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

Emissions from mobile sources are estimated by major transport activity, (*i.e.*, road, air, rail, and ships), where several major fuel types, including gasoline, diesel fuel, jet fuel, aviation fuel, natural gas, liquified petroleum gas (LPG), and residual fuel oil are considered. Road transport accounts for the majority of mobile source fuel consumption, and hence, the majority of mobile source emissions. Table I-7 summarizes emissions from mobile sources by transport activity, vehicle type, and fuel type for 1990.[7]

Estimating emissions from mobile combustion, as with stationary combustion, can be time consuming and complex. Because of many factors, including type of fuel, type of technology, extent of emission control equipment, age of equipment, and operating and maintenance practices, emission estimates for mobile combustion vary significantly. However, compared to stationary sources, more detailed data are available on activity levels and emission factors by vehicle type. A brief description of the methodology used for each gas is provided below.

NO_x, NMVOCs, and CO

Emissions estimates for NO_x, NMVOCs, and CO (U.S. criteria pollutants) in this section were taken directly from EPA (1993b), except for emissions from

Table I-6. U.S. Greenhouse Gas Emissions from Mobile Combustion: 1990-1992

(Thousand Metric Tonnes)

Year	NO_x	NMVOCs	CO	CH_4	N_2O
1990	9,668	8,252	67,520	221	92
1991	9,514	8,047	66,269	242	103
1992	9,367	7,461	63,460	247	105

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[7] Annex B contains a description of the methodology and data sources used for these gases. Estimates of carbon dioxide emissions from mobile combustion are provided earlier in the section titled "Carbon Dioxide Emissions from Fossil Fuel Consumption." These CO_2 estimates are not provided at the level of detail indicated in Table I-7 for gases other than CO_2 because fuel consumption data for each of these categories, which would be needed to complete calculations, are not readily available.

ventilation and degasification systems at underground mines and surface mines as well as post mining operations. The analysis of the 1990 emissions is based on actual data from methane ventilation systems where available; where data were not available, various estimation procedures were employed.

The emission estimates for underground mines included:

- measured methane emissions in the ventilated air from gassy underground mines;
- estimated ventilation emissions from mines for which measurements were not available; and
- estimated emissions from degasification systems.

Emissions from surface mines were estimated using reported methane contents for the surface coals mined in each U.S. coal basin. Post-mining emissions from both underground mines and surface mines were estimated to be between 25 to 40 percent of the in-situ methane content of the coal mined in each basin. A more detailed discussion of emissions from each stage of the coal extraction process can be found in U.S. EPA (1993a).

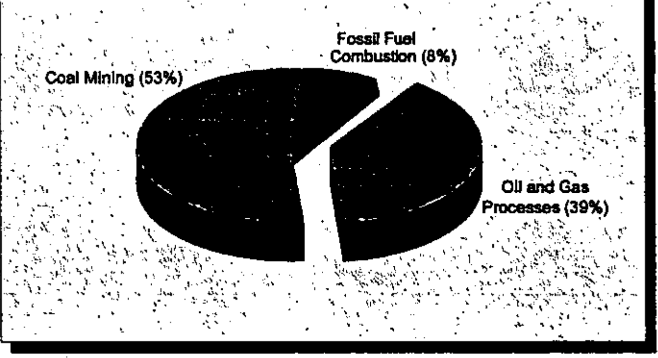
The key uncertainties in these estimates arise from emissions for which measurements are not available. This is the case for emissions from mine degasification systems at underground mines, from surface mining, and in some cases from ventilation systems. In addition, there is some uncertainty as to the exact number of mines that have degasification systems in place.

Due to a combination of instrument error and sampling and aggregation errors, measured estimates of emissions from ventilation systems may have an uncertainty range of ±20 percent. For degasification systems, it was assumed that, based on previous experience with degasification systems, mines recover 40 to 65 percent of their total emissions. To the extent that the degasification strategy varies by mine or coal basin, emissions could be over- or underestimated within this range. Estimates for surface mining are considerably less certain as there are no direct emission measurements, and these may range from 1 to 3 (and possibly as much as five) times the amount of methane contained in the coal.

2. Emissions from Natural Gas Production, Processing, Transport, and Distribution

The only significant emissions from natural gas production, processing, transport and distribution are methane. Methane emissions from the U.S. natural gas systems account for about 11 percent of total U.S methane emissions. 1990 emissions from the U.S. natural gas system were estimated to be between 13.1 and 25.6 MMTCE, with a central estimate of about 17.8 MMTCE.

Methane Emissions from Energy Activities by Source: 1990



Emissions from the U.S. natural gas systems, one of the most efficient natural gas systems in the world, are estimated to range from about 0.8 to 1.5 percent of the marketed gas. Like emissions from oil and gas production and distribution activities, these emissions are generally process related: fugitive emissions occur in all the stages of extraction, processing, and distribution. Fugitive emissions across all production stages are estimated to account for about 38 percent of 1990 U.S. natural gas systems emissions. Together with emissions from gas-fired engines and engine exhausts, these emissions account for about 75 percent of total estimated emissions, with the remaining 25 percent accounted for by system upsets and maintenance activities.

According to EPA (1993a), 1990 emissions from the U.S. natural gas system are estimated to be between 2,180 and 4,260 thousand metric tonnes of CH_4 (13.1 to 25.6 MMTCE), with a central estimate of about 3,000 thousand metric tonnes (17.8 MMTCE). This is less than 1 percent of the 1990 total marketed natural gas in the U.S. in the same year (see Table I-8).

Table I-8. Methane Emissions from U.S. Natural Gas Systems

Source of Emissions (stages)	1990 Emissions (10^3 MT) Low	High	Average % of 1990 Marketed Production
Field Production	690	1,820	0.29
Processing	40	270	0.02
Storage and Injection/Withdrawal	10	60	0.01
Transmission	590	2,060	0.28
Distribution	170	750	0.09
Engine Exhaust	270	640	0.11
Total[1]	**2,180**	**4,260**	**0.80**

Source: U.S. EPA (1993a).

Note: 1. The uncertainty in the total is estimated assuming that some of the uncertainty for each source is independent. Consequently, the range for the total is narrower than the sum of the ranges for the individual sources.

Methane emissions from natural gas systems were estimated using the following general approach:

- one or more "model facilities" were defined for each stage of the natural gas system, that is, each stage from production through storage, to define the representative facility or facilities in each stage of the production and distribution process;
- an emission type, based on detailed data and known emission processes, was estimated for each manufacturing facility;
- emission factors for each model facility were determined based on an appropriate measure of the facility's activity, such as throughput in cubic feet per year or miles of pipeline;
- average emission factors were determined for each stage by averaging the emission factors estimated for each of the model facilities in that stage; and,
- national emissions were estimated by multiplying the average emission factor for each stage by the total applicable size of the national system (such as cubic feet of throughput or miles of pipeline).

The major source of uncertainty in these estimates arises from extrapolating measurement data from a small number of "model" facilities and applying these to the industry as a whole. Subjective uncertainty ranges for the emission factors derived from these measurements were assigned based on the amount of information available. In some cases these ranges span an order of magnitude. The industry activity levels are typically subject to less uncertainty, and for this analysis are assumed to be ±25 percent. The uncertainty surrounding national estimates does not reflect uncertainty about the simple summation of sector uncertainties, because in many cases the uncertainties are independent and uncorrelated. Taking this into account, the overall uncertainty is about -25 percent and +45 percent of the mean estimate of about 2.97 million metric tonnes (17.8 MMTCE) for 1990.

3. Emissions from Oil and Gas Production, and Crude Oil Transportation, Refining, and Storage

Greenhouse gases are emitted from crude oil and natural gas production, and crude oil refining, transportation, and storage. These emissions are primarily methane, although smaller quantities of carbon dioxide, non-methane volatile organic compounds, and carbon monoxide can be emitted.

Natural gas venting and flaring occurs at oil wells where there are no markets to sell gas or the market value of the gas is well below the additional development and transportation costs of the gas, when gas handling facilities are under construction, or when the volume of gas that is produced is very low. Other emissions from oil production, transportation, refining, and storage are generally released by the processes themselves. These can be system leaks, disruptions, or routine maintenance releases. For 1990 methane emissions from these activities ranged from 0.6 to 3.72 MMTCE, with a point estimate of 1.6 MMTCE, accounting for about one percent of total U.S. methane emissions.

CO_2 Emissions from Oil Production and Processing Activities

CO_2 emissions from oil production and processing come from the natural gas that is flared at the production site, which releases CO_2 as a by-product of the combustion process. Barns and Edmonds (1990) note that of the total reported U.S. venting and flaring, approximately 20 percent is actually vented, with the remaining 80 percent flared. According to the *Natural Gas Annual 1992* (EIA 1993d), published by the U.S. Department of Energy's Energy Information Administration, the total amount of natural gas vented or flared is 4,261 million cubic meters for 1990, 4,813 million cubic meters for 1991, and 4,746 million cubic meters for 1992.

The amount of CO_2 resulting from the flared gas was estimated to be 6.56 million metric tonnes (1.79 MMTCE) for 1990, 7.4 million metric tonnes (2.02 MMTCE) for 1991, and 7.3 million metric tonnes (1.99 MMTCE) for 1992. These estimates were prepared using a conversion factor of 525 g C per m^3 as determined by Marland and Rotty (1984), and an assumed flaring efficiency of 100 percent. The assumed uncertainty range is ± 25 percent. The 20 percent vented as methane is accounted for in the section below.

Methane Emissions from Oil Production and Processing Activities

Methane emissions from oil production and processing were estimated in EPA (1993a) by determining representative emissions from major activities. These include

- fugitive emissions in the production field,
- routine maintenance emissions in the production field,
- crude oil storage facility emissions, and
- emissions from crude oil storage facilities, refineries, marine vessel operations, and venting and flaring.

These total emissions, based on model facilities, are estimated to be between 100,000 and 620,000 metric tonnes of CH_4 (0.6 to 3.72 MMTCE) per year.

The uncertainty surrounding the estimates for production-related activities are higher than for other sectors of the oil and natural gas system due to a general lack of emissions data. This is particularly true of venting and flaring data, the largest component of emissions, which in many cases is based on "balance" estimates of unaccounted-for-gas. The overall uncertainty range is estimated to be 1/4 to 4 times the estimated value.

NO_x, NMVOCs, and CO Emissions from Oil and Gas Production Activities

Criteria pollutant emissions from oil and gas production, storage, and transportation contribute only a relatively small portion to the overall U.S. emissions of these gases. Emissions of these gases were relatively stable for the 1990 - 1992 period (see Table I-9).

Due to the diverse nature of the various types of emissions and the fact that some emissions occur periodically or unexpectedly, precise measurements are not practical in many cases. As a result, the uncertainties associated with the emission estimates in this section vary, ranging anywhere from 25 to 50 percent.

Table I-9. NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities: 1990 -1992

(Thousand Metric Tonnes)

Year	NO_x	NMVOCs	CO
1990	92	668	393
1991	93	676	397
1992	85	648	365

Source: U.S. EPA (1993b).

The U.S. EPA (1993b) provided emission estimates for NO_x, NMVOCs, and CO from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations. 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. Emission estimates were determined using industry-published production data and applying average emission factors.

Table I-10. CO_2 Emissions from Wood Consumption by Sector: 1990 - 1992
(Million Metric Tonnes)

Sector	1990	1991	1992
Electric Utility	1.0	0.8	0.9
Industrial	124.8	122.1	127.3
Residential	46.4	49.0	51.6
Commercial	2.4	2.4	2.4
Total	**174.6**	**174.3**	**182.2**

Source: Consumption estimates (in trillion Btu) are from EIA (1994i).

Notes: Components may not sum to totals because of rounding.

1. Consumption estimates in trillion Btu were converted to short tons based on an average energy content of 14 million Btu per short ton of dry wood (1994i).
2. Estimates carry an error range of ± 25 percent.
3. According to EIA, commercial wood energy use is typically not reported because there are no accurate data sources to provide reliable estimates (EIA, 1994i). However, EIA's *1986 Nonresidential Building Energy Consumption Survey* estimates that commercial sector use is about 20 to 40 trillion Btu. An average of 30 trillion Btu is used here.

C. EMISSIONS FROM BIOMASS AND BIOMASS-BASED FUEL CONSUMPTION

1. *Emissions from Wood*

The combustion of biomass fuels (such as wood, charcoal, and wood waste) and biomass-based fuels (such as ethanol from corn or woody crops) produce carbon dioxide. However, the carbon dioxide emitted from biomass consumption in the long run does not increase total atmospheric carbon dioxide if this consumption is done on a sustainable basis (i.e., annual emissions of CO_2 due to consumption of biomass fuel, as well as CO_2 emissions associated with harvest, transport, and processing of the biomass, are completely offset by the annual uptake of CO_2 from regrowing biomass). As a result, carbon dioxide emissions from biomass have been estimated separately from fossil fuel-based emissions and are not included in the U.S. totals.

For 1990, CO_2 emissions from woody biomass were about 48 MMTCE. The U.S. industrial sector accounted for the largest share (73 percent) of CO_2 emissions from biomass consumption, while the residential sector accounted for 25 percent of the emissions from biomass use. The electric utility sector accounted for the smallest portion of emissions from biomass, just slightly over one half of one percent. This sectoral distribution was largely unchanged for 1991 and 1992 (Table I-10).

Emissions estimates were calculated based on the methodology recommended by the IPCC. Emissions were estimated by first converting U.S. consumption data (in trillions of Btus) reported in *Estimates of U.S. Biomass Energy Consumption 1992* (EIA, 1994i) to tonnes of dry matter using EIA assumptions (for 1990, U.S. biofuel consumption totals 2,359 trillion Btus). Next, the carbon content of the dry fuel was estimated based on IPCC default values of 45 to 50 percent carbon in dry biomass. The estimated amounts of carbon released from combustion were also estimated using IPCC-provided default values of 87 percent combustion efficiency. This is probably an underestimate of the efficiency of wood combustion processes in the U.S. The IPCC assumption has been used, however, since better data are not yet available.

2. *Emissions from Ethanol*

Biomass-based fuel use in the U.S. consists mainly of ethanol use in the transportation sector. Ethanol is mostly produced from corn grown in the

U.S. Midwest, and used primarily in the Midwest and South. Ethanol can be used directly, or mixed with gasoline as a supplement or an octane enhancer. The most common form is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are used to fuel public transport vehicles such as buses, or centrally-fueled fleet vehicles. Ethanol and ethanol blends are believed to burn "cleaner" than gasoline (lower in NO_x *and other hydrocarbons), and are being tested in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion releases carbon dioxide.*

Carbon dioxide emissions from ethanol use in the U.S. are generally declining, due to a combination of low gasoline prices and limited ethanol supply. In 1990, total U.S. CO_2 *emissions were 1.2 MMTCE, mostly from the South and Midwest (see table I-11). These emissions are not included in the U.S. total since the corn from which the ethanol is derived is produced on a sustainable basis.*

Table I-11. U.S. CO_2 Emissions from Ethanol by Region: 1990

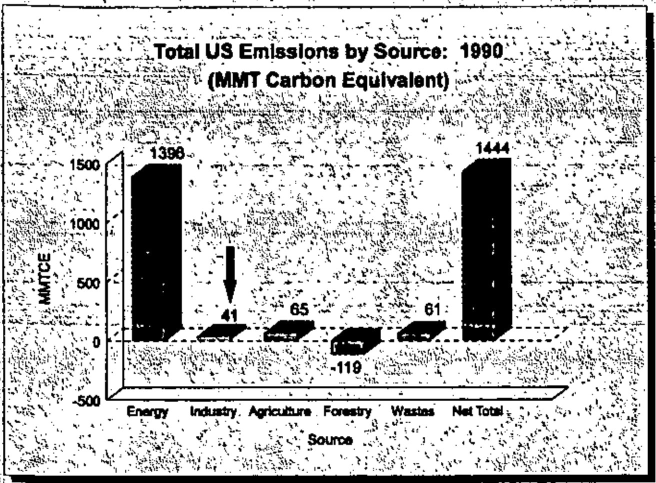
(Million Metric Tonnes)

Region	1990
Northeast	0.1
South	1.6
Midwest	2.4
West	0.4
Total	**4.4**

Source: EIA (1994i).

Emissions from ethanol were estimated using EIA (1994i). In 1990, the U.S. consumed an estimated 750 million gallons (or 63 trillion Btus) of ethanol, mostly in the transportation sector (EIA 1994i). Using an ethanol carbon coefficient of 19 milligrams C/Btu (OTA, 1991), 1990 emissions of CO_2 from the use of ethanol were calculated to be 4.4 million metric tonnes (1.2 MMTCE).

PART II. INDUSTRIAL PROCESSES



Emissions are often produced as a by-product of various non-energy related activities. That is, these emissions are produced directly from the process itself and are not a result of energy consumed during the process. For example, in the industrial sector raw materials are chemically transformed from one state to another. This transformation often results in the release of greenhouse gases such as carbon dioxide. The production processes addressed in this section include: adipic acid production, carbon dioxide manufacture, cement production, lime production, limestone use (*e.g.*, for iron and steel making, flue gas desulfurization, and glass manufacturing), nitric acid production, soda ash production and use, and aluminum production. Total carbon dioxide emissions from industrial processes were approximately 55 million metric tonnes in 1990 (15 MMTCE), accounting for 1.1 percent of total U.S. CO_2 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were about 96 thousand metric tonnes (7.1 MMTCE) in 1990, or 23.4 percent of total U.S. N_2O emissions. Emissions of HFCs and PFCs were about 19.2 MMTCE. Table II-1 contains a summary of non-energy related greenhouse gas emissions from industrial processes in the U.S.

Greenhouse gases are emitted from a number of industrial processes not covered in this section. For example, ammonia production is believed to be an industrial source of methane, nitrous oxide, and NMVOC emissions. However, emissions for these sources have not been estimated at this time due to a lack of information on the emission processes, the manufacturing data, or both. As more information becomes available, emission estimates for these processes will be calculated and included in future greenhouse gas emission inventories.

The emission estimates presented here generally follow the draft IPCC-recommended guidelines, although the only processes for which the IPCC provides a specific methodology for estimating emissions are cement, adipic acid, and nitric acid production. The IPCC has not provided specific details (*e.g.*, default emission factors) to calculate emissions from the other sources, but recommends a basic approach that can be followed for each source category, *i.e.*, multiplying production data for each process by an emission factor per unit of production. The methods used to estimate emissions in this section generally follow this basic approach. Most of the emission factors used below were derived using calculations that assume precise, efficient chemical reactions. As a result, uncertainties in the emission coefficients can be attributed to impurities contained in the raw materials or to inefficiencies in the chemical reactions associated with each production process. Additional sources of uncertainty specific to an individual source category are discussed in the appropriate section.

A. NON-FERROUS METALS

1. Aluminum Production

The production of aluminum results in emissions of several greenhouse gases, including carbon dioxide (CO_2) and two perfluorocarbons (PFCs), CF_4 and C_2F_6. Carbon dioxide is emitted as carbon contained in the anode and cathode of the electrolytic production cell is oxidized during the reduction of alumina to aluminum. Emissions of CO_2 from aluminum production in the U.S. were 2 MMTCE in 1990, or about 0.15 percent of total U.S. CO_2 emissions.

The aluminum production industry is thought to be the largest source of CF_4 and C_2F_6. Emissions of these two perfluorocarbons also occur during the reduction of alumina in the primary smelting process. As with emissions of carbon dioxide, the carbon is

Table II-1. U.S. Greenhouse Gas Emissions from Industrial Processes: 1990

Source	Emissions	
	Full Molecular Weight (10^3 metric tonnes)	MMTCE
CARBON DIOXIDE (CO_2)		
Cement Production	32,700	8.9
Lime Production	11,900	3.2
Limestone Use	5,100	1.4
Soda Ash Production and Use	4,100	1.1
Carbon Dioxide Manufacture	1,200	0.3
TOTAL	55,000	15.0
NITROUS OXIDE (N_2O)		
Adipic Acid Production	56	4.1
Nitric Acid Production	40	2.9
TOTAL	96	7.1
HFCs and PFCs		
HFC-23	5.5	15.05
HFC-134a	0.5	0.16
HFC-152a	0.3	0.01
PFCs (CF_4 and C_2F_6)	3.0	4.0
TOTAL		19.2

Note: Totals may not add to the sum of the individual source categories due to independent rounding.

present in the anode and cathode material; the fluorine is present in the molten cryolite in which the reduction of alumina occurs. Total U.S. emissions in 1990 ranged from roughly 1,200 to 3,700 metric tons of CF_4 ***(1.7 to 5.2 MMTCE). Emissions of*** C_2F_6 ***are estimated to be an order of magnitude lower, ranging from 120 to 370 metric tons (0.17 to 0.52 MMTCE).***

Carbon dioxide is emitted during the aluminum production process when alumina (aluminum oxide) 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. During reduction, some of this carbon is oxidized and released to the atmosphere as carbon dioxide.

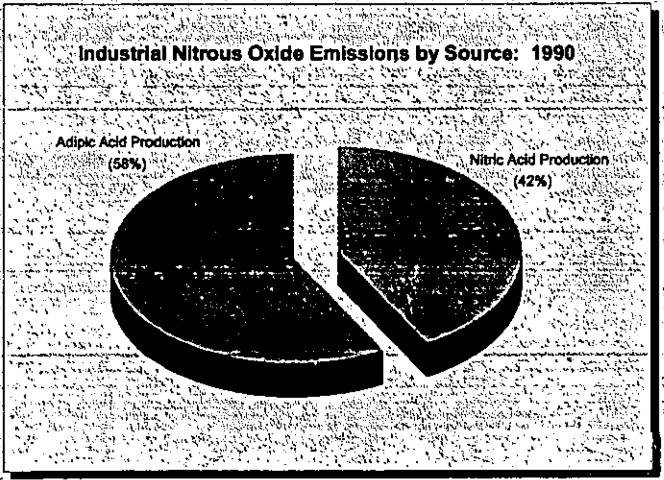
Approximately 1.5 to 2.2 tons of carbon dioxide are emitted for each ton of aluminum produced (Abrahamson, 1992). U.S. primary aluminum production in 1990 was 4,048 thousand metric tonnes (Bureau of Mines, 1993a). Using the midpoint of the emission factor range, CO_2 emissions from aluminum production are estimated to have been 7.5 million metric tonnes of CO_2 (2 MMTCE), or 0.15 percent of total U.S. CO_2 emissions in 1990. Aluminum production in 1991 and

1992 was 4,121 thousand metric tonnes and 4,042 thousand metric tonnes, respectively, generating 7.6 million metric tonnes of CO_2 (2.1 MMTCE) in 1991 and 7.5 million metric tonnes of CO_2 (2 MMTCE) in 1992. The CO_2 emissions from this source are already accounted for in the non-fuel use portion of CO_2 emissions from fossil fuel consumption, which was estimated in Part 1A of the inventory (*i.e.*, the carbon contained in the anode is considered a non-fuel use of petroleum coke). Thus, to avoid double-counting, CO_2 emissions from aluminum production are not included in the industrial process emission totals.

Aluminum production is also thought to be the largest source of two PFCs, CF_4 and C_2F_6. Emissions of these two potent greenhouse gases occur during the reduction of alumina in the primary smelting process. Emission estimates and a description of the estimation methodology are provided in the section on HFCs and PFCs.

B. INORGANIC CHEMICALS

1. Nitric Acid Production



The production of nitric acid (HNO_3) produces nitrous oxide (N_2O) as a by-product via the oxidation of ammonia. Nitric acid is a raw material used primarily to make synthetic commercial fertilizer. It is also a major component in the production of adipic acid (a feedstock for nylon) and explosives. In 1990, this inorganic chemical ranked thirteenth in total production of all chemicals in the United States.

Nitric acid plants are in operation in all regions of the U.S., with a total annual operating capacity of 10.3 million metric tons (SRI, 1993). Nitrous oxide emissions from this source were about 3 MMTCE in 1990, accounting for nearly 10 percent of total U.S. N_2O emissions. Nitric acid grew slightly from 1991 to 1993, resulting in N_2O emissions of 2.9 MMTCE in 1991, 3.0 MMTCE in 1992, and 3.1 MMTCE in 1993.

Nitric acid is an inorganic compound used primarily as a feedstock for nitrate fertilizer production. It is also a raw material used in the production of adipic acid and explosives. Relatively small quantities of nitric acid are employed for stainless steel pickling, metal etching, rocket propellants, and nuclear-fuel processing. Virtually all of the nitric acid produced in the U.S. is manufactured by the catalytic oxidation of ammonia (U.S. EPA, 1985). During this reaction, nitrous oxide is formed as a by-product and is released from reactor vents into the atmosphere. While the waste gas stream may be cleaned of other pollutants such as nitrogen dioxide, there are currently no control measures aimed at eliminating nitrous oxide.

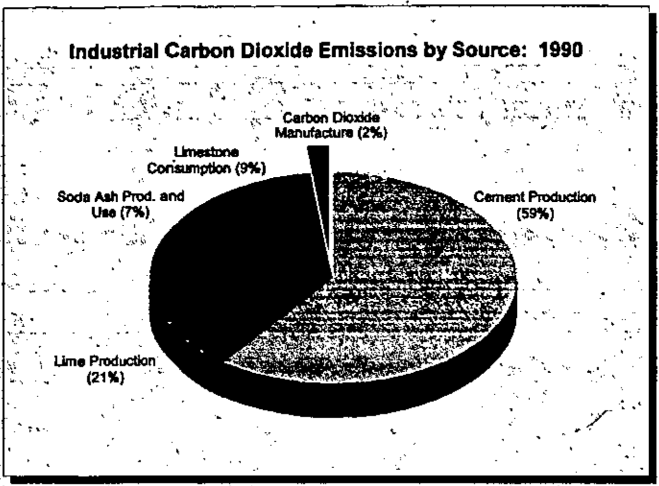
Nitric acid production in the U.S. was approximately 7.26 million metric tonnes in 1990 (C&EN, 1992). Off-gas measurements at one nitric acid production facility showed N_2O emission rates to be approximately 2-9 g N_2O per kg of nitric acid produced (Reimer *et al.*, 1992). Using the midpoint of the range of emission factors, nitrous oxide emissions from nitric acid production were about 40 thousand metric tonnes (3 MMTCE). Nitric acid production was 7.19 million metric tonnes in 1991, 7.30 million metric tonnes in 1992, and 7.74 million metric tonnes in 1993 (C&EN, 1993, 1994). This results in annual nitrous oxide emissions of 39.5, 40.2, and 42.6 thousand metric tonnes, respectively.

These emission estimates are highly uncertain because of insufficient information on manufacturing processes and emission controls. Although no abatement techniques are specifically directed at removing nitrous oxide, existing control measures for other pollutants will have some effect on the nitrous oxide contained in the gas stream. While the emission coefficients used here do account for these other abatement systems, there may be some variation between different production facilities depending on the existing level of pollution control at a given plant.

2. Carbon Dioxide Manufacture

Carbon dioxide is used in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil products, and a host of industrial and miscellaneous applica-

tions. For the most part, carbon dioxide used in these applications will eventually be released into the atmosphere.



Carbon dioxide emissions from this source are estimated to be about 0.33 MMTCE in 1990, or less than 0.1 percent of total U.S. CO_2 emissions. Carbon dioxide demand is expected to expand five percent annually through 1995, with the greatest opportunities in chemical manufacturing, enhanced oil recovery, and various industrial applications (Freedonia Group, 1991). As a result, carbon dioxide emissions are estimated to have been 0.34 MMTCE in 1991, 0.36 MMTCE in 1992, and 0.38 MMTCE in 1993.

Carbon dioxide is used for a variety of industrial and miscellaneous applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery. Carbon dioxide used for enhanced oil recovery is injected into the ground to increase reservoir pressure, and is therefore considered sequestered[1]. For the most part, however, carbon dioxide used in these applications will eventually enter the atmosphere.

With the exception of a few natural wells, carbon dioxide is produced as a by-product from the production of other chemicals (*e.g.*, ammonia), or obtained by separation from crude oil or natural gas. Depending on the raw materials that are used, the by-product carbon dioxide generated during these production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either during combustion or from non-fuel use). For example, ammonia is manufactured using natural gas and naphtha as feedstocks. Carbon dioxide emissions from this process are included in the portion of carbon for non-fuel use that is not sequestered (see Part I).

Carbon dioxide emissions were calculated by estimating the fraction of manufactured carbon dioxide that is not accounted for in these other emission sources. Carbon dioxide consumption for uses other than enhanced oil recovery was estimated to be 4.4 million short tons in 1990 (Freedonia Group, 1991). Carbon dioxide wells, natural gas wells, and fermentation account for approximately 30 percent of total production capacity in the U.S. Assuming that the remaining carbon dioxide is accounted for in emission estimates from other source categories, CO_2 emissions from this source are estimated to be about 1.2 million metric tonnes (0.33 MMTCE) in 1990. Because carbon dioxide demand is expected to expand five percent annually through 1995 (Freedonia Group, 1991), carbon dioxide emissions were estimated to have risen to 1.26 million metric tonnes (0.34 MMTCE) in 1991, 1.32 million metric tonnes (0.36 MMTCE) in 1992, and 1.4 million metric tonnes (0.38 MMTCE) in 1993. These estimates are highly uncertain due to the limited information on CO_2 production and use in the U.S.

C. ORGANIC CHEMICALS

1. Adipic Acid Production

Adipic acid production has been identified as a significant anthropogenic source of atmospheric nitrous oxide (N_2O). Adipic acid is a major component used in nylon production, as well as production of some low-temperature lubricants. It is also used to provide foods with a "tangy" flavor. The U.S. accounts for approximately one-third of the total annual global production of adipic acid (Thiemens & Trogler, 1991). Based on 1990 U.S. adipic acid production of 735 thousand metric tonnes (C&EN, 1992), nitrous oxide emissions from this source are estimated to be 4.1 MMTCE, or 13.7 percent of total

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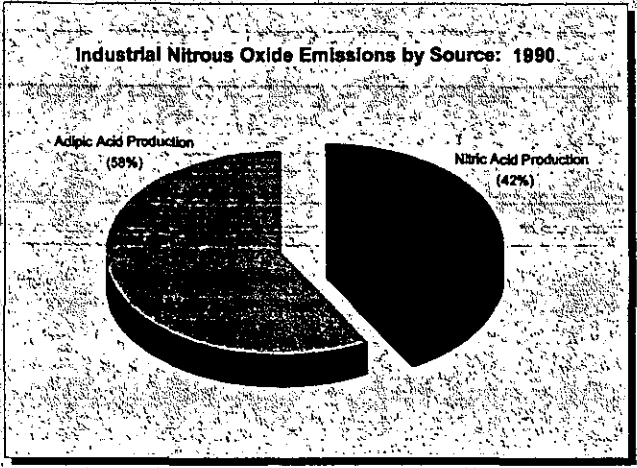
[1] It is unclear to what extent the CO_2 used for enhanced oil recovery will be re-released. For example, the carbon dioxide used for EOR is likely to show up at the wellhead after a few years of injection (Hangebrauk et al., 1992). This CO_2, however, is typically recovered and reinjected into the well. More research is required to determine the amount of carbon dioxide that may potentially escape. For the purposes of this analysis, it is assumed that all of the CO_2 remains sequestered.

U.S. N_2O emissions. Adipic acid production in the U.S. rose to 771 thousand metric tonnes in 1991 and fell to 708 thousand metric tonnes in 1992 and 1993. Annual N_2O emissions for those years were 4.3, 4.0, and 4.0 MMTCE, respectively.



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. Ninety percent of all adipic acid produced in the United States is used in the production of nylon 6,6.

Adipic acid is produced through a two-stage process. The second stage involves the oxidation of ketone-alcohol with nitric acid. Nitrous oxide is generated as a by-product of this reaction and enters the waste gas stream. In the U.S., this waste gas is treated to remove NO_x and other regulated pollutants (and, in some cases, N_2O as well) and is then released into the atmosphere. There are currently four plants in the U.S. that produce adipic acid. In 1990, two of these plants had emission control measures that destroyed about 98 percent of the nitrous oxide before it was released into the atmosphere (Radian, 1992). By 1996, all adipic acid production plants will have nitrous oxide emission controls in place as a result of a voluntary agreement among producers.

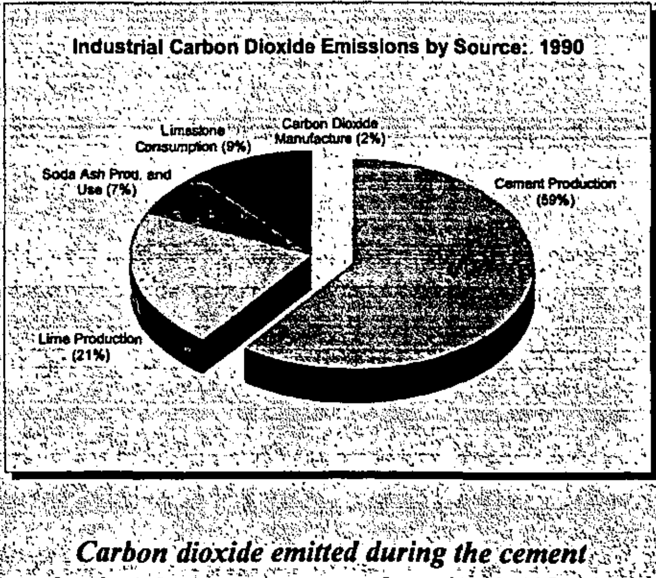
Since emissions of N_2O in the U.S. are not regulated, very little emissions data exist. However, based on the overall reaction stoichiometry for adipic acid, it is estimated that approximately 0.3 kg of nitrous oxide is generated for every kilogram of adipic acid produced (Radian, 1992). Based on 1990 U.S. adipic acid production of 735 thousand metric tonnes (C&EN, 1992) and existing levels of pollution control, nitrous oxide emissions from this source are estimated to be 56.2 thousand metric tonnes N_2O (4.1 MMTCE).

Adipic acid production in the U.S. was 771 thousand metric tonnes in 1991 and 708 thousand metric tonnes in 1992 and 1993 (C&EN, 1993, 1994). Using the methodology described above, nitrous oxide emissions from this source were estimated to be 59 thousand metric tonnes (4.3 MMTCE) in 1991 and 54 thousand metric tonnes (4.0 MMTCE) in 1992 and 1993.

Because N_2O emissions are controlled in some adipic acid production facilities, the amount of N_2O that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate accurate emission estimates, it is necessary to have production data on a plant-specific basis. In most cases, however, these data are confidential. As a result, plant-specific production figures were estimated by disaggregating total adipic acid production using existing plant capacities (SRI, 1990). This creates a significant degree of uncertainty in the adipic acid production data used to derive the emission estimates. The most accurate N_2O emissions estimates would be derived from actual production figures, if these data were reported by each plant.

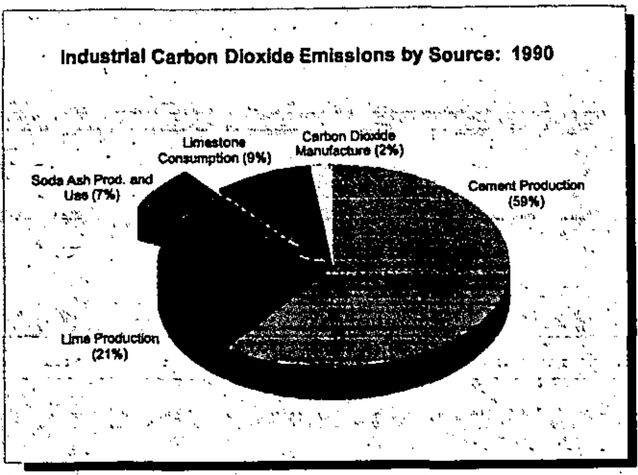
D. NON-METALLIC MINERAL PRODUCTS

1. Cement Production



Carbon dioxide emitted during the cement production process represents the most significant non-energy source of industrial carbon dioxide

4. Soda Ash Manufacture and Consumption



Commercial soda ash (sodium carbonate) is used in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. Internationally, two types of soda ash are produced — natural and synthetic. The U.S. produces only natural soda ash. During the production process, natural sources of sodium carbonate are heated and transformed into a crude soda ash that requires further refining. Carbon dioxide is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, carbon dioxide is released when soda ash is consumed.

Of the two states that produce natural soda ash, only Wyoming has net emissions of carbon dioxide. Because a different production process is used in California, those soda ash producers never actually release the carbon dioxide into the atmosphere. Instead, the CO_2 is recovered and used in other stages of production. U.S. carbon dioxide emissions from soda ash production are estimated to be approximately 0.39 MMTCE in 1990. Carbon dioxide emissions from soda ash production were 0.39 MMTCE in 1991, 0.40 MMTCE in 1992, and 0.38 MMTCE in 1993.

Soda ash consumption in the U.S. generated about 0.74 MMTCE of carbon dioxide in 1990. Annual soda ash consumption in the U.S. decreased slightly in 1991 and 1992, but recovered in 1993. Carbon dioxide emissions from soda ash consumption were 0.71 MMTCE in 1990 and 1992, and 0.74 MMTCE in 1993. Together, soda ash production and use accounted for almost 0.1 percent of total U.S. CO_2 emissions in 1990.

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and is strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes. It is used primarily as an alkali, either in glass manufacturing or simply as a material which reacts with and neutralizes acids or acidic substances. About 75 percent of world production is synthetic ash made from sodium chloride; the remaining 25 percent is produced from natural sodium carbonate-bearing deposits. The U.S. produces only natural soda ash.

During the production process, trona (the principal ore from which natural soda ash is made) 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 a by-product of the calcination process. CO_2 emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3H(CO_3)_2 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, it takes approximately 10.27 metric tonnes of trona to generate 1 metric tonne of CO_2. According to the U.S. Bureau of Mines, 14.7 million metric tonnes of trona were mined in 1990 for soda ash production (Bureau of Mines, 1993c). This results in CO_2 emissions of approximately 1.4 million metric tonnes (0.39 MMTCE). Trona production from 1991 to 1993 was 14.7, 14.9, and 14.5 million metric tonnes, respectively. Using the methodology described above, carbon dioxide emissions from soda ash production in these years were 1.43 million metric tonnes (0.39 MMTCE) in 1991, 1.45 million metric tonnes (0.40 MMTCE) in 1992, and 1.41 million metric tonnes (0.38 MMTCE) in 1993.

An alternative method of natural soda ash production uses sodium carbonate-bearing brines. To extract the sodium carbonate, the complex brines are first treated with carbon dioxide in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which will precipitate under these conditions. 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 never actually released.

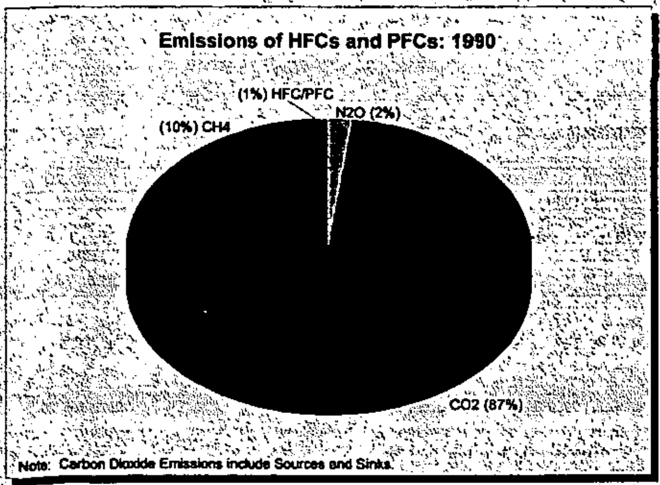
Glass manufacture represented about 49 percent of domestic soda ash consumption, with smaller amounts used for chemical manufacture, soap and detergents, flue gas desulfurization, and other miscellaneous uses. In each of these applications, a mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 tonnes of carbon (or 0.415 tonnes of carbon dioxide) is released for every tonne of soda ash consumed.

In 1990, U.S. consumption of soda ash was reported as 6.5 million metric tonnes (Bureau of Mines, 1993c), which generates about 2.7 million metric tonnes (0.74 MMTCE) of carbon dioxide. Annual soda consumption in the U.S. was 6.3 million metric tonnes in 1991 and 1992, and 6.5 thousand metric tonnes in 1993. As a result, carbon dioxide emissions from soda ash consumption were estimated to be 2.6 million metric tonnes (0.71 MMTCE) in 1991 and 1992, and 2.7 million metric tonnes (0.74 MMTCE) in 1993.

E. OTHER EMISSIONS

1. Emissions of HFCs and PFCs

Partially halogenated compounds (HFCs) and perfluorinated compounds (PFCs) are used primarily as alternatives to the ozone depleting substances (ODSs) being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. ODSs, which include chlorofluorocarbons (CFCs) and partially halogenated fluorocarbons (HCFCs,) are used in a variety of industrial applications, including refrigeration, solvent cleaning, foam production, sterilization, and fire extinguishing. Although the ODS replacements (i.e., HFCs and PFCs) are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases (for example, HFC-134a is 1,200 times more heat absorbent than an equivalent amount of CO_2 by weight in the atmosphere).



Note: Carbon Dioxide Emissions include Sources and Sinks

In 1990, HFCs and PFCs were not used widely as commercial chemicals. However, these gases were emitted as by-products from other industrial production processes. For example, HFC-23 was emitted as a by-product of HCFC-22 production, and CF_4 and C_2F_6 (two PFCs) were released during aluminum smelting. Emissions of these gases totaled approximately 19 MMTCE in 1990. The manufacture and emissions of HFCs and PFCs are expected to rise as their use as ODS replacements increases.

Partially halogenated compounds (HFCs) and perfluorinated compounds (PFCs) were introduced as alternatives to the ozone depleting substances (ODSs) being phased out under the *Montreal Protocol* and *Clean Air Act Amendments* of 1990 (see discussion on ODSs below). ODSs, which include chlorofluorocarbons (CFCs), partially halogenated fluorocarbons (HCFCs), and related compounds, are used in several major end use sectors, including refrigeration, air conditioning, solvent cleaning, foam production, sterilization, fire extinguishing, paints, coatings, and other chemical intermediates, and miscellaneous uses (*e.g.*, aerosols, propellants, and other products). Because HFCs and PFCs are not harmful to the stratospheric ozone layer, they are not controlled by the *Montreal Protocol*. However, HFCs and PFCS are powerful greenhouse gases and are, therefore, covered under the FCCC (for example, HFC-134a has an estimated direct GWP of 1,200, which makes HFC-134a 1,200 times more heat absorbent than an equivalent amount by weight of CO_2 in the atmosphere). As a result, emission estimates for these gases have been included in the U.S. inventory and are provided in Table II-5.

Because the use of CFC and HCFC substitutes was minimal in 1990, emissions of HFCs and PFCs were largely the result of by-product emissions from other production processes, and not the result of their use as CFC alternatives. For example, HFC-23 is a by-product emitted during HCFC-22 production, and PFCs (CF_4 and C_2F_6) are emitted during aluminum smelting. Emissions of HFCs and PFCs should continue to rise, however, as their use as ODS replacements increases.

Partially halogenated compounds (HFCs)

Emission estimates were developed using a computer model that estimates ODS emissions based on:

- a vintaging framework that generates results using information on the stock of equipment in each end use, chemical use per piece of equipment, equipment lifetimes, and emission rates from each piece of equipment, and
- substitution scenarios that describe when chemicals will replace ODSs as they are phased out under the *Copenhagen Amendments* to the *Montreal Protocol*. The scenarios are based on estimated market penetration and the number of years it may take to fully implement a substitute.

Table II-5. Emissions of HFCs and PFCs: 1990
(Million Metric Tonnes)

Compound	Molecular Basis	GWP	Carbon-Equivalent[a]
HFCs			
HFC-23	0.00552	10,000	15.05
HFC-134a	0.0005	1,200	0.16
HFC-152a	0.0003	150	0.01
PFCs			
Total PFCs	0.003	5400	3.98

[a] The GWP for HFC-23 was obtained from U.S. EPA's Office of Air and Radiation and is based on unpublished data from DuPont Chemical Company and others. The GWPs for the other compounds are from IPCC (1992).

Source: U.S. EPA, 1994b

Because HFCs were not used widely as commercial chemicals in 1990, emissions of these compounds were relatively small. Emissions of HFC-134a were estimated to be approximately 500 metric tonnes (0.16 MMTCE) in 1990. Emissions of HFC-152a (a component of the refrigerant blend R-500) were estimated to be approximately 300 metric tonnes (0.01 MMTCE). HFCs continue to be evaluated and introduced on the market as refrigerants, solvents, fire extinguishing agents, sterilizers, and foam blowing agents.

HFC-23 is currently emitted as a by-product of HCFC-22 production. Even after HCFC-22 is phased out under the *Montreal Protocol*, production of HCFC-22 as a polymer precursor will continue. By-product emissions of HFC-23 are assumed to be 4 percent of HCFC-22 production. HCFC-22 production was estimated to be about 138 thousand metric tonnes in 1990, resulting in 5.5 thousand metric tonnes of HFC-23 (15.05 MMTCE).

Perfluorocarbons (PFCs)

The aluminum production industry is thought to be the largest source of two PFCs -- CF_4 and C_2F_6. Emissions of these two potent greenhouse gases occur during the reduction of alumina in the primary smelting process.[4] Aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) in the Hall-Heroult reduction process, whereby alumina is dissolved in molten cryolite (Na_3AlF_6), which acts as the electrolyte and is the reaction medium. PFCs are formed during disruptions of the production process known as anode effects (AE), which are characterized by a sharp rise in voltage across the production vessel. The PFCs can be produced through two mechanisms: direct reaction of fluorine with the carbon anode; and electrochemical formation. In both cases the fluorine originates from dissociation of the molten cryolite.

Because CF_4 and C_2F_6 are inert, and therefore pose no health or local environmental problems, there has been little study of the processes by which emissions occur and the important factors controlling the magnitude of emissions. In general, however, the magnitude of emissions for a given level of production depends on the frequency and duration of the anode effects during that production period. The more frequent and long-lasting the anode effects, the greater the emissions.

The methodology used to estimate emissions of PFCs from aluminum production first calculates a per unit production emissions factor as a function of several important operating variables, including average anode effect frequency and duration. Total annual emissions are then calculated based on reported annual production levels. The five components of the per unit production emissions factor are:

- the amount of CF_4 and C_2F_6 emitted during every minute of an anode effect, per kAmp of current;
- the average duration of anode effects, expressed in anode effect minutes per effect;

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[4] Perfluorocarbons are not emitted during the smelting of recycled aluminum.

- the average frequency of anode effects, expressed in anode effects per day;
- the current efficiency for aluminum smelting (no units); and,
- the current required to produce a metric ton of aluminum, assuming 100 percent efficiency.

Using currently available data for the U.S., this methodology yields a range in the emissions factor of 0.3 to 0.9 kg CF_4 per metric ton of aluminum produced EPA, 1993c). The emissions factor for C_2F_6 is estimated to be an order of magnitude lower, and therefore ranges from 0.03 to 0.09 kg C_2F_6 per metric ton of aluminum produced. Based on 1990 aluminum production of 4.048 million metric tons, total U.S. emissions of PFCs in 1990 were estimated to be 1,200 to 3,700 metric tons of CF_4 (1.7 to 5.2 MMTCE) and 120 to 370 metric tons of C_2F_6 (0.17 to 0.52 MMTCE). U.S. aluminum production in 1991 and 1992 varied less than 2 percent from the 1990 level, resulting in minor fluctuations in emissions estimates of CF_4 and C_2F_6 (relative to the current uncertainty in these emissions estimates).

Because there has been relatively little study of emissions from this source, considerable uncertainty remains in several of the values used in the estimates presented here. In particular, the value for emissions per AE minute per kAmp is based on a single measurement study which may not be representative of the industry as a whole (U.S. EPA, 1993c). For example, this emissions factor may vary by smelter technology type, among other factors. The average duration of anode effects, according to preliminary results of ongoing research, may in fact be considerably shorter than the current values used. The average frequency of anode effects and the current efficiency are well documented, although they may change over time as operating efficiencies improve. Because recent studies indicate that the values for the important variables used in developing the emission coefficient may actually be lower than previously thought, the estimates presented here are likely to be conservatively high.

Emissions of CFCs and Related Compounds

Chlorofluorocarbons (CFCs) and other halogenated fluorocarbons, which were emitted into the atmosphere for the first time this century, are a family of man-made compounds used in a variety of industrial applications, including foam blowing, refrigeration, and solvent cleaning. These compounds, which contain chlorine and bromine, have been shown to deplete stratospheric ozone, and thus are typically referred to as ozone-depleting substances, or ODSs. In addition, they are important greenhouse gases because they block infrared radiation that would otherwise escape into space (EIA, 1993d). Unlike other greenhouse gases, however, these compounds do not occur naturally in the atmosphere. CFCs and other halogenated fluorocarbons include the following substances: chlorofluorocarbons, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and partially halogenated fluorocarbons (HCFCs).

Many governments, recognizing the harmful effects of these compounds on the atmosphere, signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* in 1987 to limit the production and consumption of a number of CFCs and other halogenated compounds[5]. The U.S. furthered its commitment to phase-out these substances by signing and ratifying the *Copenhagen Amendments* to the Montreal Protocol in 1992. Under these amendments, the U.S. committed to eliminating the production of all halons by January 1, 1994 and all CFCs by January 1, 1996.

Under the *Clean Air Act* (CAA), which developed the U.S. phaseout schedule for the *Montreal Protocol*, ODSs were categorized based on their ozone depletion potential. Compounds are classified as "Class I" or "Class II" substances, and must adhere to a distinct set of phase-out requirements.

- **Class I** ODSs include fully halogenated CFCs, halons, tetrachlorocarbon (commonly known as carbon tetrachloride), and 1,1,1 trichloroethane (a.k.a. methyl chloroform). Fully halogenated compounds have no hydrogen atoms in their makeup and are so called because they contain chlorine, fluorine, or bromine atoms (elements belonging to the halogen family). Of the elements in the halogen family, chlorine and bromine are thought to be ozone-depleting agents, while fluorine is believed to be a potent greenhouse gas. Halon compounds contain bromine atoms instead of chlorine atoms, while methyl

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[5] There are currently 133 countries that have signed the *Montreal Protocol*.

chloroform is actually a partially halogenated compound (the only one to be included in this Class). These compounds are the primary ODSs in use today.

- **Class II** ODSs include partially halogenated chlorine compounds (known as HCFCs), which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially-halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere, and therefore pose only about one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs. Although HCFCs pose less of a threat to the earth's stratospheric ozone layer, they are still powerful greenhouse gases, with GWPs several orders of magnitude larger than CO_2 (for example, HCFC-22 has an estimated direct GWP of 1600, which makes HCFC-22 1600 times more heat absorbent than an equivalent amount by weight of CO_2 in the atmosphere).

The production and use of Class I and Class II substances in the U.S. are being phased out in accordance with the *Montreal Protocol* and the 1990 *Clean Air Act*. Under these measures, the production of Class I substances in the U.S. will cease by January 1996, while the production of Class II substances will be gradually phased out by January 2015. Another group of partially-halogenated compounds that do not contain chlorine, known as HFCs, are being developed as long-term replacements for Class I and Class II substances.

Although the IPCC emission inventory guidelines do not include reporting emissions of CFCs and related compounds, the U.S. believes that no inventory is complete without the inclusion of these emissions; therefore, emission estimates for several Class I and Class II ozone-depleting substances are provided in Table II-6. It should be noted that the use of these compounds is declining as the U.S. fulfills its obligations under the *Montreal Protocol*. Also, the effects of these compounds on radiative forcing are not provided here. Although CFCs and related compounds have very large direct GWPs, their indirect effects are believed to be negative, possibly equal in magnitude to their direct effects. Given the uncertainties surrounding the net effect of these gases, they are reported here on a full molecular basis only.

Table II-6. U.S. Emissions of ODSs and Related Compounds for 1990
(Million Metric Tonnes; Molecular Basis)

Compound	Emissions
Class I	
CFC-11	0.06
CFC-12	0.1
CFC-113	0.05
CFC-114	0.005
CFC-115	0.003
Carbon Tetrachloride	0.03
Methyl Chloroform	0.3
Halon-1211	0.001
Halon-1301	0.001
Class II	
HCFC-22	0.08
HCFC-141b	0.002
HCFC-124	0.03

Emissions of ODSs were estimated by the U.S. EPA using the Atmospheric and Health Effects Framework (AHEF) model. The EPA model starts with global production forecasts for each compound and estimates U.S. consumption based on forecasted regional shares. These data are further subdivided by end-use.

With the exception of solvents, emissions from ODSs and related compounds are not instantaneous, occurring gradually over time, *i.e.*, emissions in a given year are the result of both ODS and related compound use in that year and their use in previous years. Each end-use has a certain release profile, which gives the percentage of the compound that is released to the atmosphere each year until all releases have occurred.

The emission estimates provided here account for ODS use in both the current year and in previous years. Uncertainties exist over the levels of production, data sources, and emissions profiles that are used by the model to estimate yearly emissions for each compound.

Methyl chloroform, CFC-12, and HCFC-22 were three of the most prevalent ODS emissions in 1990, 1991, and 1992. In 1990, an estimated 316 thousand metric tonnes of methyl chloroform were emitted into the atmosphere, along with an estimated 112 thousand metric tonnes of CFC-12, and 82 thousand metric tonnes of HCFC-22. In contrast, emissions of HCF-134a, a replacement compound, were 0.5, 0.9, and 1.2 thousand metric tonnes from 1990 through 1992. However, while the use of methyl chloroform, CFC-12, and HCFC-22 is declining, the use of HFC-134a, a CFC substitute, is showing a marked increase.

2. NO_x, NMVOCs, and CO

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of criteria air pollutants. Total U.S. emissions of NO_x, NMVOCs, and CO from non-energy industrial processes in 1990 are reported by detailed source category in Table II-7. Emissions for 1991 and 1992 are summarized in Table II-8. The emission

Table II-7. U.S. Emissions of NO_x, CO and NMVOCs from Industrial Processes: 1990
(Thousand metric tonnes)

Source Category	NO_x	CO	NMVOC
CHEMICAL AND ALLIED PRODUCT MANUFACTURING			
Organic Chemical Manufacturing	38	259	621
Inorganic Chemical Manufacturing	17	86	34
Polymer & Resin Manufacturing	21	17	284
Agricultural Chemical Manufacturing	251	15	23
Paint, Varnish, Lacquer, Enamel Manufacturing	--	--	10
Pharmaceutical Manufacturing	--	0	230
Other Chemical Manufacturing	34	1339	405
METALS PROCESSING			
Nonferrous Metals Processing	24	622	18
Ferrous Metals Processing	48	1265	47
Metals Processing NEC	1	0	0
OTHER INDUSTRIAL PROCESSES			
Agriculture, Food, & Kindred Products	5	0	230
Textiles, Leather, & Apparel Products	0	0	9
Wood, Pulp & Paper, and Publishing Products	70	596	40
Rubber and Miscellaneous Plastic Products	0	0	42
Mineral Products	196	39	13
Machinery Products	2	0	3
Electronic Equipment	--	11	0
Transportation Equipment	0	0	0
Miscellaneous Industrial Processes	6	5	96
STORAGE AND TRANSPORT			
Bulk Terminal & Plants	--	0	597
Service Stations	--	--	645
Organic Chemical Storage & Transport	2	87	141
Inorganic Chemical Storage & Transport	0	0	0
Bulk Materials Storage	1	5	0
TOTAL[a]	**715**	**4,346**	**3,488**

[a] Totals may not add due to independent rounding.

Source: U.S EPA, 1993b

estimates in this section were taken directly from the U.S. EPA's *National Air Pollutant Emissions Trends, 1900 - 1992* (U.S. EPA, 1993b). This EPA report provided emission estimates of these gases by sector, using a "top down" estimating procedure: the 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.

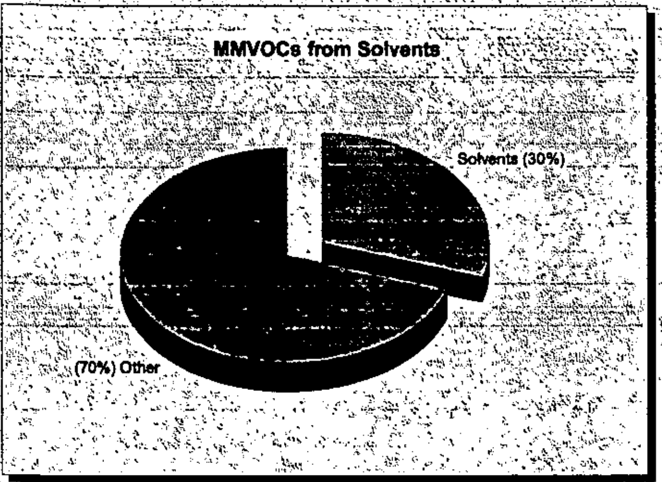
Activity data are used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the U.S. EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA, 1985). The EPA currently derives the overall emission control efficiency of a source category from a variety of sources, including published reports, the 1985 NAPAP (National Acid Precipitation and Assessment Program) emissions inventory, or other EPA data bases.

Table II-8. U.S. Emissions of NO_x, CO, and NMVOC from Industrial Processes: 1991-1992
(Thousand metric tonnes)

Source	NO_x		CO		NMVOC	
	1991	1992	1991	1992	1991	1992
Chemical & Allied Product Manufacturing	363	364	1,729	1,699	1,613	1,595
Metals Processing	72	71	1,807	1,794	63	64
Other Industrial Processes	270	273	645	655	431	431
Storage and Transport	3	3	93	91	1,387	1,295
TOTAL[a]	708	710	4,275	4,239	3,494	3,385

a Totals may not add due to independent rounding.
Source: U.S EPA, 1993b

PART III. EMISSIONS FROM SOLVENT USE



The use of solvents and other chemical products can result in emissions of various greenhouse and photochemically important trace gases. Nonmethane VOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based solvents, along with small amounts of carbon monoxide (CO) and oxides of nitrogen (NO_x).

Emissions from solvent use in the U.S. consist mainly of VOCs, along with trace amounts of CO and NO_x. VOC emissions from solvent use showed a slight decline from 1990 to 1991, while emissions of CO and NO_x remained relatively stable for the period 1990 - 1992 (Table III-1). Surface coatings accounted for the majority of emissions from solvent use (over 40 percent), while "non industrial" uses accounted for about 30 percent of the emissions during the same period. Emissions from dry cleaning accounted for slightly over three percent of the yearly emissions from solvents use. VOC emissions from solvent use accounted for about 30 percent of 1990 overall VOC emissions.

Although a comparatively minor source category in the U.S., emissions from solvent use have been reported separately by the U.S. to be consistent with the 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 U.S. 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 solvents use include:

- Degreasing
- Graphic arts
- Surface coating
- Other industrial uses of solvents (*i.e.*, electronics, etc.)
- Dry cleaning
- Non-industrial uses (*i.e.*, uses of paint thinner, etc.)

Table III-1. Emissions of VOC, NO_x, and CO from Solvent Use: 1990 - 1992

(Thousand Metric Tonnes)

Gas	1990	1991	1992
VOCs	5,740	5,499	5,498
NO_x	2	2	3
CO	2	2	2

Source: EPA (1993a).

Table III-2 contains detailed 1990 emission estimates from solvents by the major source categories.

Estimates of emissions from solvents came from U.S. EPA (1993a), which estimated emissions based on a "bottom up" process. This process involves aggregating solvent use data based on information relating to solvent uses from different sectors such as degreasing, graphic arts, etc. Emission factors for each consumption category are then applied to the data to estimate emissions. For example, emissions from surface coatings are mostly due to solvent evaporation as the coatings solidify. By applying the appropriate solvent emission factors to the type or types of solvents used for surface coatings, an estimate of emissions can be obtained.

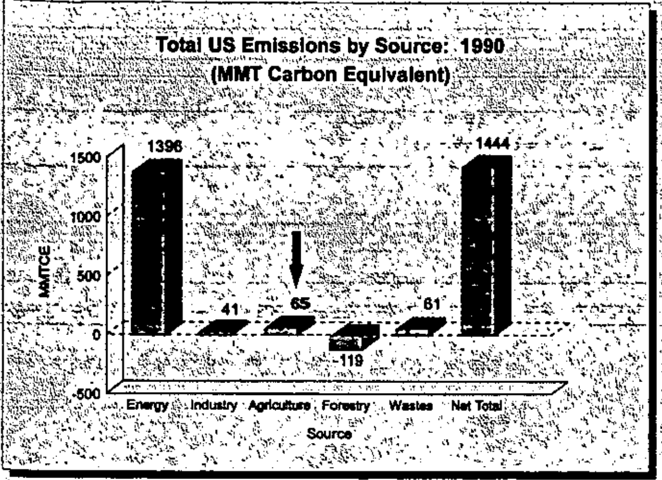
Table III-2. U.S. Emissions of VOCs, NO_x, and CO by Category: 1990

(Thousand Metric Tonnes)

Source	VOCs	NO_x	CO
Degreasing	682	+	1
Graphic Arts	621	+	+
Surface Coating	2,375	2	1
Other Industrial	149	+	+
Dry Cleaning	190	NA	NA
Non-Industrial	1,723	NA	NA
Total	**5,740**	**2**	**2**

Source: EPA (1993a).
Note: "+" Denotes less than 453.5 metric tonnes (500 short tons).

PART IV. EMISSIONS FROM AGRICULTURE

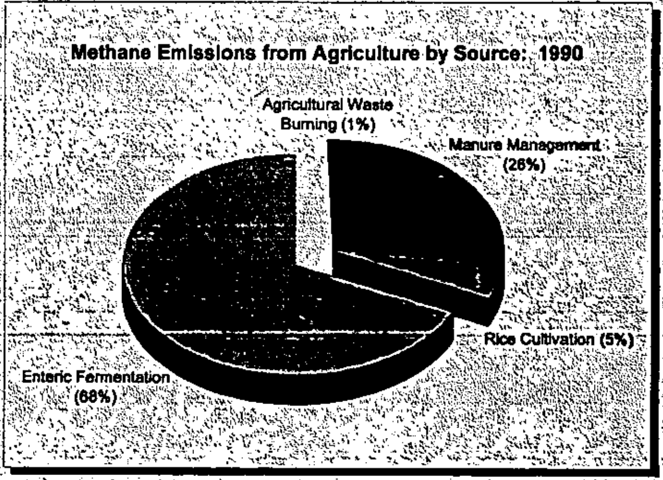


Agricultural activities contribute directly to emissions of greenhouse gases through a variety of different processes. This part of the U.S. inventory presents emission estimates for five types of agricultural activities: management of domestic livestock, management of domestic livestock and poultry manure, cultivation of rice, fertilizer use, and field burning of agricultural crop wastes. Several other agricultural activities, such as irrigation and tillage practices, may contribute to greenhouse gas emissions, but emissions from these sources are uncertain and are believed to be insignificant.[1] Agriculture-related land-use change activities, such as conversion of grassland to cultivated land, are discussed in part V of this inventory.

In 1990, agricultural activities were responsible for emissions of 65 MMTCE, or approximately 5 percent of total U.S. emissions. Methane (CH_4) is the most significant gas emitted by agricultural activities, accounting for 52 MMTCE. Domestic livestock, manure management, rice cultivation, and field burning of agricultural crop wastes are all sources of methane. In 1990, domestic livestock and manure management together were responsible for 94 percent of methane emissions from agricultural activities, and about 30 percent of total methane emissions from all anthropogenic activities in the U.S. Of all domestic animal types, beef and dairy cattle are by far the largest emitters of methane. Management of cattle and their manure account for about 75 percent of U.S. methane emissions from all agricultural activities. Rice cultivation and agricultural waste burning are minor sources of methane, having released about 5 and 1 percent of U.S. methane emissions from agriculture, respectively.

In addition to methane, agricultural activities are a source nitrous oxide (N_2O), carbon monoxide (CO), and nitrogen oxides (NO_x). Fertilizer use is a major contributor to nitrous oxide emissions, responsible for about 44 percent of total U.S. emissions. Agricultural crop waste burning is a source of nitrous oxide, carbon monoxide, and nitrogen oxides, in addition to methane. However, as with methane, agricultural crop waste burning accounts for less than 1 percent of total U.S. emissions of each gas.

A. METHANE EMISSIONS FROM ENTERIC FERMENTATION IN DOMESTIC LIVESTOCK



Methane is a natural by-product of animal digestion. During digestion, methane is produced through a process referred to as enteric fermentation in which microbes that reside in animal digestive systems break down feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest methane emissions among all animal types because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which a significant amount of methane-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems. The amount of methane produced and excreted by an individual animal depends upon its digestive system (i.e., whether or not it possesses a rumen), and the amount and type of feed it consumes.

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[1] Irrigation associated with rice cultivation is included in this inventory.

Enteric fermentation in domestic livestock is a major source of methane in the U.S. Emissions in 1990 are estimated to have been approximately 28 to 42 MMTCE. This represents about 22 percent of total U.S. methane emissions, and about 68 percent of methane emissions from the agriculture sector.

Of all domestic livestock, cattle are by far the largest source of methane. In 1990, cattle accounted for 95 percent of total emissions from enteric fermentation in domestic livestock; of total cattle emissions, beef cattle accounted for 73 percent, and dairy cattle the rest. The North Central and South Central states each account for roughly 35 percent of emissions from beef cattle, primarily due to the large beef cattle populations managed in those states. The North Central, West, and North Atlantic states each account for roughly 43, 20, and 18 percent of emissions from dairy cattle. These regional contributions are also largely a reflection of the large dairy cattle populations in those states.

Emissions from enteric fermentation in domestic livestock increased by about 0.8 percent per year between 1990 and 1992, and by about 1 percent in 1993. This increase is primarily due to increasing beef cattle populations. Methane emissions from enteric fermentation in the U.S. ranged from 28 to 42 MMTCE in 1991, 28 to 43 MMTCE in 1992, and 29 to 43 MMTCE in 1993.

Methane is produced during the normal digestive processes of animals. During digestion, feed consumed by the animal is fermented by microbes resident in the digestive system. This microbial fermentation process, referred to as enteric fermentation, produces methane as a by-product, which is exhaled or eructated by the animal. The amount of methane produced and excreted by an individual animal is dependent primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among animal types, the ruminant animals (*i.e.*, cattle, buffalo, sheep, goats, and camels) are the major emitters of methane because of their unique digestive system. Ruminants possess a rumen, or large "forestomach," in which microbial fermentation breaks down consumed feed into soluble products that can be utilized by the animal. The microbial fermentation that occurs in the rumen enables ruminants to digest coarse plant material that non-ruminant animals cannot digest. Ruminant animals have the highest methane emissions among all animal types because a significant amount of methane-producing fermentation occurs within the rumen.

Non-ruminant domestic animals, such as pigs, horses, mules, rabbits, and guinea pigs, also produce methane through enteric fermentation, although this microbial fermentation occurs in the large intestine. The non-ruminants have much lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems.

In addition to the type of digestive system that an animal possesses, its feed intake also affects the amount of methane produced and excreted. In general, the higher the feed intake, the higher the methane emissions. Feed intake is positively related to animal size, growth rate, and production (*i.e.*, 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.

This section presents estimates of methane emissions resulting from enteric fermentation in domestic livestock. The emission estimates were obtained or derived from U.S. EPA (1993a). Only animals managed by humans for production of animal products, including meat, milk, hides and fiber, and draft power are included.[2] Although methane emissions from non-ruminants are significantly less than those for ruminants, both animal types are included in order to produce a complete inventory.

U.S. EPA (1993a) contains estimates of methane emissions from domestic livestock in the U.S. for the year 1990. To derive these estimates, U.S. EPA developed emission factors for representative animal types and then multiplied the emission factors by applicable animal populations. The resultant emissions by animal type were then summed over all animal

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[2] Wild animals also produce methane emissions. The principal wild animals that contribute to U.S. emissions are wild ruminant animals such as antelope, caribou, deer, elk, and moose. Termites have also been identified as a potentially important source of methane emissions and are generally examined separately from other wild animals. These sources are not included the U.S. inventory because they are not considered anthropogenic.

types to estimate total annual methane emissions. The emission estimates for 1990 presented here were taken directly from U.S. EPA (1993a); emission estimates for 1991, 1992, and 1993 were derived using the emission factors in U.S. EPA (1993a) and 1991, 1992, and 1993 animal population statistics from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and the USDA Economic Research Service.

The principal uncertainty in estimates of methane emissions from livestock digestion results from the large diversity of animal management practices found in the U.S., all of which cannot be precisely characterized and evaluated. Also, the methodological assumptions used to derive emission factors are only as accurate as the experimental data upon which they are based. Nevertheless, significant scientific literature exists that describes the quantity of methane produced by individual ruminant animals, particularly cattle. Also, cattle production systems in the U.S are well characterized compared to other livestock management systems in the U.S.

For these reasons, it is possible to estimate methane emissions from cattle in the U.S. using fairly detailed analyses of feeding practices and production characteristics. Also, due to their large population, large size, and particular digestive characteristics, cattle account for the majority of methane emissions from livestock in the U.S. Therefore, estimates of emissions from cattle presented below are based on a detailed analysis that accounts for regional differences in sizes, ages, feeding systems, and management systems among cattle subgroups.

Methane emissions from other animals account for a very small fraction of total methane emissions from livestock in the U.S. 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 much smaller than for cattle. Therefore, emissions from each of these other animal types are derived using a more simple analysis that is based on average emission factors representative of entire populations of each animal type.

1. Methane Emissions from Cattle

In order to derive emission factors representative of the diverse types of cattle found in the U.S., U.S. EPA (1993a) applied a mechanistic model of rumen digestion and animal production (Baldwin et al., 1987) to 32 different diets and 9 different cattle types.[3] The cattle types (listed in Table IV-1) were defined to represent the different sizes, ages, feeding systems, and management systems that are typically found in the U.S. Representative diets were defined for each category of animal, reflecting the diverse feeds and forages consumed by different types of cattle in different regions of the U.S. Using the mechanistic model, an emission factor was derived for each combination of animal type and representative diet. Based upon the extent to which each diet is used in each of five regions of the U.S., regional average emission factors for each of the 9 cattle types were derived.[4] These emission factors were then multiplied by the applicable animal populations in each region, and the results were summed over all cattle types and all regions to produce the total emissions estimate for U.S. cattle.

The methodology employed in U.S. EPA (1993a) is a detailed version of the draft Tier 2 methodology recommended by the IPCC (IPCC/OECD, 1994). This greater level of detail used in the analysis is possible because of in-depth scientific understanding of cattle digestion processes typical of the U.S., as well as the availability of extensive data on U.S. cattle production systems.

National weighted-average emission factors, and national populations, for each of the nine animal types analyzed by U.S. EPA (1993a) are presented in Table IV-1. The regional data from which these numbers were derived, as well as a more detailed discussion of the methodology used to derive the emission factors, are presented in Annex C. Total methane emissions from the U.S. cattle herd in 1990 are estimated to be 5.54 million metric tonnes CH_4 (33.2 MMTCE). Methane emissions from beef cattle account for about 73 percent of this total, and dairy cattle the rest.

Regional variability in methane emissions from

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[3] The basic model of Baldwin et al. (1987) was revised somewhat to allow for evaluations of a greater range of animal types and diets. See U.S. EPA (1993a) for more detail.

[4] Feed intake of bulls does not vary significantly by region, so only a national emissions factor was derived for this cattle type.

cattle is largely a reflection of the uneven distribution of cattle populations across the U.S. (see Table IV-2). The North Central and South Central states each account for roughly 35 percent of emissions from beef cattle, primarily due to the large beef cattle populations managed in those states. The North Central, West, and North Atlantic states, which support large dairy herds, each account for roughly 43, 20, and 18 percent of emissions from dairy cattle. The North Central states account for approximately 40 percent of total methane emissions from all cattle.

There are a variety of factors that make the 1990 emissions estimate uncertain. First, animal population and production statistics, particularly for range fed cattle, are uncertain. Second, the diets analyzed using the rumen digestion model are broad representations of the types of feed consumed within each region, so the full diversity of feeding strategies is not represented. And last, the rumen digestion model is itself uncertain since it was validated using uncertain experimental data. Together, these sources of uncertainty result in an overall uncertainty of about ± 20 percent in the emission estimate (U.S. EPA, 1993a). Applying this uncertainty range to the national emission estimate results in low and high estimates of 4.40 and 6.65 million metric tonnes CH_4 (26 to 40 MMTCE).

Table IV-1. Methane Emissions from U.S. Cattle in 1990, By Animal Type

Animal Type	Emission Factor (kg/head/yr)	Population (10^3 head)	Emissions (10^6 metric tonnes)
Dairy Cattle			
Replacements 0-12 months[a]	19.6	4,205	0.082
Replacements 12-24 months[a]	58.8	4,205	0.247
Mature Cows	114.6	10,130	1.161
Subtotal	80.4	18,540	1.490
Beef Cattle			
Replacements 0-12 months[a]	22.3	5,535	0.124
Replacements 12-24 months[a]	65.0	5,535	0.360
Mature Cows	66.7	33,478	2.234
Weanling System Steers/Heifers[b]	23.1	5,260	0.122
Yearling System Steers/Heifers[c]	47.3	21,040	0.994
Bulls	100.0	2,200	0.220
Subtotal	47.5	85,398	4.054
Total Cattle		**103,938**	**5.544**

[a] A portion of the offspring are retained to replace mature cows that die or are removed from the herd (culled) each year. Those that are retained are called "replacements."

[b] In "weanling systems," calves are moved directly from weaning to confined feeding programs. This system represents a very fast movement of cattle through to marketing. Weanling system cattle are marketed at about 420 days of age (14 months).

[c] "Yearling systems" represent a relatively slow movement of cattle through to marketing. These systems include a wintering over, followed by a summer of grazing on pasture. Yearling system cattle are marketed at 565 days of age (18.8 months).

Source: U.S. EPA, 1993a.

Table IV-2. Methane Emissions from U.S. Cattle in 1990, By Region

Region	Dairy Cattle Emissions (10⁶ metric tonnes)	Beef Cattle Emissions (10⁶ metric tonnes)	Total Regional Emissions (10⁶ metric tonnes)
North Atlantic	0.267	0.031	0.298
South Atlantic	0.111	0.315	0.426
North Central	0.644	1.442	2.086
South Central	0.166	1.402	1.568
West	0.303	0.865	1.168
National Total	**1.490**	**4.054**	**5.544**

Source: U.S. EPA, 1993a.

Emission estimates for 1991, 1992, and 1993 were derived using the nationally weighted-average emission factors for each cattle type from U.S. EPA (1993a) and national populations from the USDA (1994a, 1994b, 1994d). The following factors should be considered when assessing these emission estimates:

- Because all estimates were done nationally (rather than regionally), regional shifts in animal populations were not considered. There continues to be a shift in dairy cows away from the North Central U.S. and toward the West. This shift, which would affect emissions since emission factors vary regionally, is not reflected in these estimates.
- Emission factors for mature dairy cattle were increased to reflect higher feed intakes in 1991, 1992, and 1993, relative to 1990. The higher feed intakes were implemented to increase milk production per cow.
- The mix of Weanling and Yearling slaughters was kept constant. Although we believe that there has been a shift toward more Weanling slaughters, this change has not been quantified.

Total methane emissions from the U.S. cattle herd in 1991, 1992, and 1993 are estimated to be 5.59 million metric tonnes CH_4 (33.5 MMTCE), 5.63 million metric tonnes CH_4 (33.8 MMTCE), and 5.70 million metric tonnes CH_4 (34.2 MMTCE), respectively (see Table IV-3). Assuming an uncertainty range of ± 20 percent, emission estimates for 1991, 1992, and 1993 are between 4.5 and 6.7 million metric tonnes CH_4 (27 and 40 MMTCE), between 4.5 and 6.8 million metric tonnes CH_4 (27 and 41 MMTCE), and between 4.6 and 6.8 million metric tonnes CH_4 (27 and 41 MMTCE), respectively. The growth in emissions, 0.7 percent per year between 1990 and 1992 and 1.2 percent per year between 1992 and 1993, is due primarily to increasing beef cattle populations. The higher emissions per head for dairy cattle in 1991-1993, relative to 1990, was largely offset by smaller populations, resulting in relatively flat dairy emissions for the four-year period.

Table IV-3. Methane Emissions from U.S. Cattle: 1991-1993 (10⁶ metric tonnes)

Cattle Type	1991	1992	1993
Dairy	1.51	1.50	1.50
Beef	4.08	4.13	4.20
Total Cattle	**5.59**	**5.63**	**5.70**

Sources: Emission factors from U.S. EPA (1993a). Cattle populations from USDA (1994a, 1994b, 1994d).

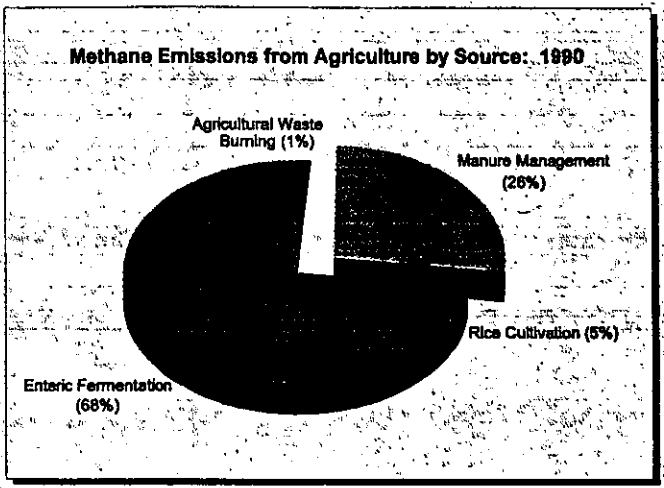
2. Methane Emissions from Other Domestic Animals

Methane emissions from other domestic animals (i.e., sheep, goats, pigs, and horses) were estimated by U.S. EPA (1993a) using emission factors from Crutzen et al. (1986) and population data from FAO (1991) and USDA (1994b, 1994e).[5] These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology and emission factors employed in U.S. EPA (1993a) are the same as those recommended by the IPCC (IPCC/OECD, 1994).

In 1990, total methane emissions from other animals are estimated to be 275 thousand metric tonnes CH_4 (1.7 MMTCE) (Table IV-4). The uncertainty in this estimate is probably greater than that for the cattle emissions estimate because a less detailed analysis was performed. However, since cattle account for over 95 percent of the emissions from all domestic livestock, the uncertainty in the cattle estimates drive the overall uncertainty for all livestock. Therefore, the same uncertainty range that was applied to cattle (20 percent) has been applied to other animals (U.S. EPA, 1993a). This results in low and high estimates of 200 and 350 thousand metric tonnes CH_4 (1.2 to 2.1MMTCE).

Enteric fermentation emissions from other animals changed little from 1990 to 1993. This is a reflection of very slight fluctuations in other animal populations and the small magnitude of the emission source. The emission factors, populations, and total emission estimates for each of the inventory years are presented in Table IV-4.

B. METHANE EMISSIONS FROM MANURE MANAGEMENT



When animal manure decomposes in an anaerobic environment, decomposition of the organic material in the manure produces methane. The way in which manure is managed is the most important factor affecting the amount of methane produced, since certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems, e.g., lagoons, ponds, tanks, or pits, tend to produce a significant quantity of methane. When manure is handled as a solid or when it is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Higher temperatures and moist climatic conditions also promote methane production.

Table IV-4. Methane Emissions from Other Animals

Animal	Emission Factor (kg/head/yr)	Population (10^3 head)				Emissions (10^6 metric tonnes)			
		1990	1991	1992	1993	1990	1991	1992	1993
Sheep	8	11,364	11,000	10,750	10,013	0.09	0.09	0.09	0.08
Goats	5	1,900	1,900	1,900	1,900	0.01	0.01	0.01	0.01
Pigs	1.5	53,852	54,477	57,684	58,116	0.08	0.08	0.09	0.09
Horses	1.8	5,215	5,215	5,215	5,215	0.09	0.09	0.09	0.09
Total	--	--	--	--		**0.27**	**0.27**	**0.28**	**0.27**

Sources: Emission factors from Crutzen et al. (1986). Populations from FAO (1991) and USDA (1994b, 1994e).

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[5] Population data for goats and horses were not realdily available for 1991 and 1992. These emissions are small and were assumed to be constant.

In 1990, emissions from manure management are estimated to have been approximately 10 to 22 MMTCE. This represents about 8 percent of total U.S. methane emissions, and about 26 percent of methane emissions from the agriculture sector. Liquid-based manure systems account for over 80 percent of the total emissions from manure management. Of the animal manure types included in the analysis, swine manure is the highest emitter, responsible for about 49 percent of total emissions. Dairy cattle manure accounts for about 32 percent of the U.S. total.

Emissions from manure management decreased by 6.4 percent in 1991. This decrease is the result of numerous factors, including changes in total animal populations, manure production rates, distribution of waste systems, and distribution of animal types. Methane emissions increased by 2 percent in 1992 and 3.5 percent in 1993. These increases reflect changes in animal populations, including higher beef and swine populations and a redistribution of dairy cattle towards lagoon management systems (which are characterized by higher methane emission rates).

Animal manure is primarily composed of organic material and water. When animal waste decomposes in an anaerobic environment (*i.e.*, in the absence of oxygen), the organic material in the waste is broken down by methanogenic bacteria that are present in the waste. Methane, carbon dioxide, and stabilized organic material are produced as end products.

The principal factors that affect the amount of methane produced during decomposition are the way in which the manure is managed and the climatic environment in which the manure decomposes. Methane production will only occur under anaerobic conditions. Therefore, when manure is stored or treated in systems that promote an oxygen-free environment (*e.g.*, as a liquid in lagoons, ponds, tanks, or pits), the manure tends to produce a significant quantity of methane. When manure is handled as a solid (*e.g.*, in stacks or pits) or when it is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Air temperature and moisture also affect the amount of methane produced since they influence the growth of the bacteria responsible for methane formation. Methane production generally increases with rising temperature. Also, for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor methane production.

The composition of the manure also affects the amount of methane produced. Manure composition depends on the composition and digestibility of the animal diet. The greater the energy content and digestibility of the feed, the greater the amount of methane that potentially could be produced by the resulting manure. For example, feedlot cattle fed a high energy grain diet produce a highly biodegradable manure with a high methane-producing capacity. Range cattle feeding on a low energy forage diet produce a less biodegradable manure with only half the methane-producing capacity of feedlot cattle manure. However, as described above, in either case the amount of methane that is actually produced and emitted to the atmosphere depends largely on the way that the manure is managed.

Like those from enteric fermentation, estimates of methane emissions from manure management were obtained or derived from U.S. EPA (1993a). The 1990 emission estimates were taken directly from U.S. EPA (1993a); emission estimates for 1991, 1992, and 1993 were derived using the emission factors in U.S. EPA (1993a) and animal population statistics from the USDA. As with enteric fermentation emissions, only animals managed by humans for production of animal products, including meat, milk, hides and fiber, and draft power, are included.

The methodology employed in U.S. EPA (1993a) to derive 1990 methane emission estimates for manure management in the U.S. is based on the approach developed by Safley *et al.* (1992a), and is consistent with the draft Tier 2 methodology recommended by the IPCC (IPCC/OECD, 1994). This methodology consists of the following steps:

(1) Estimate annual methane emissions for each animal type *i* and manure system *j* in each state *k*:

Annual methane emissions for each animal type *i* and manure management system *j* in each state *k* = number of animals of type *i* in state *k* × typical animal mass of animal *i* × average annual volatile solids[6] production per unit of animal mass for animal *i* × the methane producing capacity[7] of the manure of animal *i* × the methane conversion factor[8] of the manure system *j* in the state *k* × the percent of animal *i*'s manure managed in manure system *j* in state *k*

(2) Estimate total annual methane emissions for animal *i* by summing annual emissions over all applicable manure management systems *j* and states *k*.

(3) Estimate total annual methane emissions from all animals by summing over all animal types *i*.

The data used to derive the estimate of emissions from animal manure (*i.e.*, animal populations, sizes, and volatile solids production; maximum methane producing capacities; methane conversion factors; and manure system usages) are presented in Annex C. These data were obtained from the U.S. Census of Agriculture, the U.S. Department of Agriculture, livestock manure management experts throughout the U.S., and the scientific literature. Specific sources for the data are also noted in Annex C. Some of the animal populations used by U.S. EPA in these calculations are estimates as of 1987, since this was the last year for which detailed data could be obtained. Therefore, the 1990 emissions estimate is based on changes in animal production and population between 1987 and 1990 for several animal types.

Based on these data, total 1990 methane emissions from manure management are estimated to be 2.3 million metric tonnes CH_4 (14 MMTCE). Liquid-based manure systems account for over 80 percent of the total emissions (Table IV-5). Of the animal manure types included in the analysis, swine manure is the highest emitter, responsible for about 50 percent of total emissions. Dairy cattle manure accounts for about 30 percent of the U.S. total.

Uncertainties in these point estimates result from assumptions concerning several factors used in the calculations. In particular, the methane conversion factors (MCFs) are based on dry manure, and therefore they may be underestimates for dry, open air systems (*i.e.*, pasture, range, drylots, solid storage, and paddocks) in regions of the U.S. with significant rainfall. Also, the methane-producing potential of liquid/slurry and pit storage manure systems may be greater than assumed in this analysis. To account for these uncertainties, U.S. EPA developed low and high emission estimates by varying the MCFs for different manure management systems. (A discussion of the derivation of the low and high estimates is provided in Annex C.) The resultant range in emissions is 1.7 to 3.6 million metric tonnes CH_4 (10 to 22 MMTCE) (see Table IV-5).

Emission estimates for 1991, 1992, and 1993 were derived using the methodology described above and state populations from the National Agricultural Statistics Service of the USDA. However, several changes were made to the 1990 assumptions before they were used to estimate 1991-1993 methane emissions, including:

- a change in the distribution of waste systems utilized for a limited number of states (based on interviews with persons familiar with manure management practices in their respective states), and

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[6] Volatile solids (VS) are defined as the organic fraction of the total solids in manure that will oxidize and be driven off as a gas at a temperature of 600°C. Total solids are defined as the material that remains after evaportion of water at a temperature between 103° and 105°C.

[7] The methane producing capacity of the manure for a particular animal type is the maximum amount of methane that can be produced per kilogram of volatile solids, and varies by animal type and diet.

[8] The methane conversion factor is the extent to which the maximum methane producing potential is realized for a given manure management system and climate.

- an increase in the Volatile Solids (VS) production figure for dairy cows from 10.0 to 10.9 kg/day/1000 kg animal mass to reflect increasing feed intake of dairy cows.

Emissions from manure management decreased to 2.13 million metric tonnes (12.8 MMTCE) in 1991. This decrease is the result of numerous factors (including changes in total animal populations, distribution of waste systems, and distribution of animal types) and cannot be attributed to a single animal type or management technique. For example, while the population and feed intake of dairy cattle increased, the distribution of waste systems utilized in some states shifted away from the higher methane-generating practices. Although these changes should have opposite effects on methane emissions, the net effect was a decrease in total dairy emissions.

Methane emissions increased to 2.18 million metric tonnes (13.1 MMTCE) in 1992 and 2.25 million metric tonnes (13.5 MMTCE) in 1993. This increase is

Table IV-5. Range of Methane Emission Estimates from Manure Management: 1990

	Low (10^6 metric tonnes)	**Point Estimate (10^6 metric tonnes)**	**High (10^6 metric tonnes)**
MANURE MANAGEMENT SYSTEM			
Solid Systems			
Pasture/Range	0.09	0.12	0.59
Drylot	0.02	0.03	0.15
Solid Storage	<0.01	<0.01	0.02
Other Solid Systems[a]	0.15	0.26	0.54
Total Solid Systems[d]	0.26	0.41	1.30
Liquid Systems			
Liquid/Slurry Storage	0.19	0.21	0.42
Pit Storage	0.21	0.23	0.46
Anaerobic Lagoon	1.04	1.42	1.42
Total Liquid Systems[d]	1.44	1.87	2.30
Total[d]	**1.70**	**2.28**	**3.60**
ANIMAL TYPE			
Beef	0.13	0.17	0.67
Dairy	0.56	0.73	1.04
Swine	0.85	1.12	1.43
Poultry[b]	0.14	0.23	0.38
Other[c]	0.02	0.02	0.09
Total[d]	**1.70**	**2.28**	**3.60**

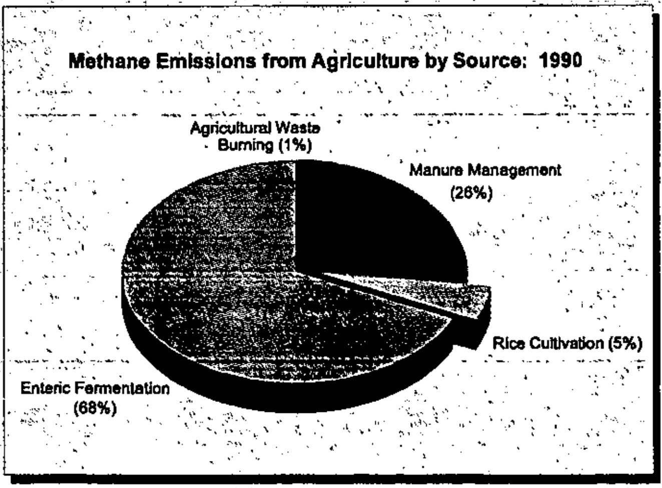
a Other solid systems include litter, deep pit stacking, and paddocks.
b Includes broilers, layers, turkeys, and ducks.
c Includes sheep, goats, horses, mules, and donkeys.
d Totals may not add due to rounding.

Table IV-6. Methane Emissions from Manure Management: 1991 - 1993

	1991		1992		1993	
	Population (10^3 head)	Emissions (10^6 metric tonnes)	Population (10^3 head)	Emissions (10^6 metric tonnes)	Population (10^3 head)	Emissions (10^6 metric tonnes)
Dairy	14,376	0.71	14,104	0.70	14,062	0.71
Beef	89,746	0.18	90,857	0.19	91,929	0.19
Swine	54,477	1.00	57,684	1.05	57,798	1.11
Other		0.24		0.24		0.24
		2.13		**2.18**		**2.25**

due primarily to changes in animal populations, most notably in New Mexico and California, both of which rely on liquid-based management systems. These results are summarized in Table IV-6.

C. METHANE EMISSIONS FROM RICE CULTIVATION



Most of the world's rice, and all of the rice in the U.S., is grown on flooded fields. When fields are flooded, anaerobic conditions in the soils develop, and methane is produced through anaerobic decomposition of soil organic matter. Methane is released primarily through the rice plants, which act as conduits from the soil to the atmosphere.

Rice cultivation is a very small source of methane in the U.S. In 1990, methane emissions from this source are estimated to have been approximately 0.65 to 4.5 MMTCE. This represents less than 1 percent of total U.S. methane emissions from all sources, and about 4 percent of U.S. methane emissions from agricultural sources. Seven states grow rice: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Emissions from Arkansas account for about 35 percent of the total, primarily because it has the largest rice area harvested. Louisiana, which has a longer growing season, has the second highest level of emissions, accounting for about 25 percent of the national total.

Emission estimates increased by about 5 percent between 1990 and 1991, stayed flat between 1991 and 1992, and increased by 2 percent between 1992 and 1993. This is a reflection of the relatively large areas harvested for most states in 1992. However, the areas harvested fluctuated inconsistently from year to year, so the four years of emission estimates do not suggest a meaningful trend.

Most of the world's rice is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soils and floodwater, and anaerobic conditions in the soils develop. Methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. However, not all of the methane that is produced is released into the atmosphere. As much as 60 to 90 percent of the produced methane is oxidized by aerobic methanotrophic bacteria in the soils (Holzapfel-Pschorn et al., 1985; Sass et al., 1990). Some of the methane is also leached away as dissolved methane in floodwater that percolates from the field. The remaining non-oxidized methane is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Some methane also escapes from the soil via diffusion and bubbling through the floodwaters.

The water management system under which rice is grown is one of the most important factors affecting methane emissions. Upland rice fields are not flooded, and therefore are not believed to produce methane. In deepwater rice fields (*i.e.*, fields with flooding depths greater than 1 meter), the lower stems and roots of the rice plants are dead, thereby effectively blocking the primary CH_4 transport pathway to the atmosphere. Therefore, while deepwater rice growing areas are believed to emit methane, the quantities released are likely to be significantly less than areas with more shallow, typical flooding depths. Also, 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, methane emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil methane to oxidize but also inhibits further methane production in the soils.

Other factors that influence methane emissions from flooded rice fields include soil temperature, soil type, fertilization practices, cultivar selection, and other cultivation practices (*e.g.*, tillage, seeding, and weeding practices). Many studies have found, for example, that methane emissions increase as soil temperature increases. Several studies have indicated that some types of nitrogen fertilizer inhibit methane generation, while organic fertilizers enhance methane emissions. However, while it is generally acknowledged that these factors influence methane emissions, the extent of the influence of these factors individually or in combination has not been well quantified.

Methane emissions from rice cultivation in the U.S. were derived using the draft methodology recommended by the IPCC (IPCC/OECD, 1994). This method utilizes a daily emission factor, which is multiplied by the harvested area flooded and the number of days of flooding during the growing season. Agricultural statisticians in each of the seven states in the U.S. that produce rice were contacted to determine water management practices and flooding season lengths in each state. All rice growing areas in the U.S. are continually flooded; none are either upland or deepwater. Because flooding season lengths varied considerably among states, the IPCC/OECD (1994) method was applied to each of the seven states separately, and results were summed over all states.

Daily methane emission factors were taken from results of field studies performed in California (Cicerone et al., 1983); Texas (Sass et al., 1990, 1991a, 1991b, 1992); and Louisiana (Lindau et al., 1991; Lindau and Bollich, 1993). A range based on the endpoints of the emission rates measured in these studies -- 0.1065 to 0.5639 g/m^2/day -- was applied to the areas and season lengths in each state.[9] Since these measurements were taken in rice growing areas of the U.S., they are representative of rice soil temperatures, and water and fertilizer management practices typical of the U.S.

The climatic conditions of southwest Louisiana, Texas, and Florida allow for a second or "ratoon" rice crop in those areas. This second crop rice is produced from regrowth on the stubble after the first crop has been harvested. The emission estimates presented here account for this additional harvested area.

Rice fields for the second crop typically remain flooded for a shorter period of time than for the first crop. Recent studies indicate, however, that the methane emission rate of the second crop may be significantly higher than that of the first crop. The rice straw produced during the first harvest has been shown to dramatically increase methane emissions during the ratoon cropping season (Lindau & Bollich, 1993). It is not clear to what extent the shorter season length and higher emission rates offset each other. As scientific understanding improves, these emission estimates can be adjusted to better reflect these variables.

To avoid unrepresentative results based upon fluctuations in economic or climatic conditions, a three-year average (centered on 1990) for the area harvested in each state (USDA, 1991; USDA, 1993) was used to estimate 1990 emissions. Also, since the

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[9] Two measurements from these studies were excluded when determining the emission coefficient range. A low seasonal average flux of 0.0595 g/m^2/day in Sass et al. (1990) was excluded because this site experienced a mid-season accidental drainage of floodwater, after which methane emissions declined substantially and did not recover for about two weeks. Also, the high seasonal average flux of 2.041 g/m^2/day in Lindau and Bollich (1993) was excluded since this emission rate is anomalously high, compared to other flux measurements in the U.S., as well as in Europe and Asia (see IPCC/OECD,1994).

number of days that the rice fields remain permanently flooded varies considerably with planting system and cultivar type, a range for the flooding season length was adopted for each state. The harvested areas and flooding season lengths for each state are presented in Table IV-7. Arkansas and Louisiana have the largest harvested areas, approximately 40 and 20 percent of the U.S. total, respectively. California, Louisiana, and Florida have the longest flooding season lengths, 138, 105, and 105 days, respectively.

Total methane emissions for the U.S. in 1990 are estimated to have been 109-749 thousand metric tonnes of CH_4 (0.65 to 4.5 MMTCE) in 1990 (Table IV-8). Emissions from Arkansas account for over 35 percent of this total, primarily because it has the largest rice area harvested. Louisiana, because of its relatively large rice area and long growing season, has the second highest level of emissions, accounting for about 25 percent of the national total.

Using the same methodology described above, methane emissions from rice cultivation were estimated to be 114-784 thousand metric tonnes (0.68-4.7 MMTCE) in 1991, 114-783 thousand metric tonnes (0.68-4.7 MMTCE) in 1992, and 116-799 thousand metric tonnes (0.70-4.8 MMTCE) in 1993 (see Table IV-8). To be consistent with the draft IPCC/OECD guidelines, three-year averages of areas harvested were used for each emission estimate (the 1993 emission estimate, however, was based on a two-year average). The small increase in total emissions in 1991 and 1992 compared to 1990 (about 5 percent) is a reflection of the relatively large areas harvested for most states in 1992. However, the areas harvested fluctuated inconsistently from year to year, so the three years of emission estimates do not suggest a meaningful trend.

Table IV-7. Area Harvested and Flooding Season Length for Rice-Producing States

State	**Area Harvested (ha)**					**Flooding Season Length (days)**	
	1989	1990	1991	1992	1993	low	high
Arkansas	461,352	485,633	509,915	558,478	497,774	75	100
California	165,925	159,854	141,643	159,450	176,851	123	153
Florida[a]							
primary	5,585	4,978	8,580	8,944	8,903	90	120
ratoon	2,792	2,489	4,290	4,472	4,452		
Louisiana[a]							
primary	196,277	220,558	206,394	250,911	214,488	90	120
ratoon	58,883	66,168	62,940	55,484	46,484		
Mississippi	95,103	101,174	89,033	111,291	99,150	75	82
Missouri	31,971	32,376	37,232	45,326	37,637	80	100
Texas[a]							
primary	136,787	142,857	138,810	142,048	120,599	60	80
ratoon	54,715	57,143	56,700	56,819	48,240		
Total	**1,209,389**	**1,273,248**	**1,255,536**	**1,393,221**	**1,254,577**		

[a] These states have a second, or "ratoon", cropping cycle which may have a shorter flooding season than the one listed in the table.

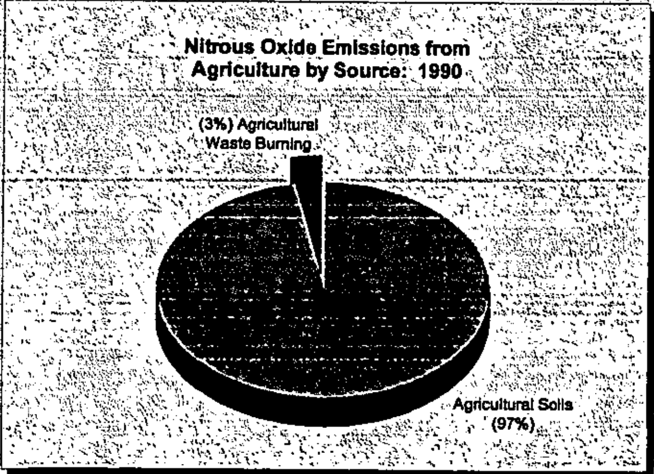
Table IV-8. CH_4 Emissions from Rice Cultivation in the U.S.

State	Annual Emissions (10^3 metric tonnes)[a]							
	1990		1991		1992		1993[b]	
	low	hi	low	hi	low	hi	low	hi
Arkansas	38.8	273.8	41.4	292.1	41.7	294.4	42.2	297.8
California	20.4	134.4	20.1	132.6	20.9	137.5	22.0	145.1
Florida	0.9	6.5	1.1	7.6	1.3	8.9	1.3	9.0
Louisiana	25.9	183.0	27.6	194.5	26.7	188.7	27.2	192.0
Mississippi	7.6	44.0	8.0	46.5	8.0	46.2	8.4	48.7
Missouri	2.9	19.1	3.3	21.6	3.4	22.6	3.5	23.4
Texas	12.5	88.3	12.7	89.4	12.0	84.7	11.8	82.9
Total	**109.0**	**749.1**	**114.1**	**784.3**	**114.0**	**782.9**	**116.4**	**798.9**

a Emission Factor: 0.1065 - 0.5639 (g CH_4/m^2/day)

b Emission estimates for 1993 are based on two-year averages for harvested area (*i.e.*, 1992 and 1993).

D. EMISSIONS FROM AGRICULTURAL SOIL MANAGEMENT



Various agricultural soil management practices contribute to greenhouse gas emissions. The use of synthetic and organic fertilizers adds nitrogen to soils, thereby increasing natural emissions of nitrous oxide. Other agricultural soil management practices such as irrigation, tillage practices, or the fallowing of land can also affect trace gas fluxes to and from the soil since soils are both a source and a sink for carbon dioxide and carbon monoxide, a sink for methane, and a source of nitrous oxide. However, there is much uncertainty about the direction and magnitude of the effects of these other practices, so only the emissions from fertilizer use are included in the inventory at this time.

Fertilizer use is the most significant source of nitrous oxide in the U.S. Nitrous oxide emissions in 1990 due to consumption of synthetic fertilizers (both multi-nutrient and nitrogen) and organic fertilizers were about 13.5 MMTCE. This represents approximately 44 percent of total U.S. nitrous oxide emissions, and about 97 percent of nitrous oxide emissions from all agricultural sources. Approximately 55 percent of the fertilizer was consumed in the Midwest.

Due to an increase in fertilizer consumption between 1990 and 1993, emissions increased by about 3.6 percent over the period.

Nitrous oxide is produced naturally in soils through the microbial processes of denitrification and nitrification.[10] A number of anthropogenic activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities include application of fertilizers, acid deposition, and cultivation of nitrogen-fixing crops. This section discusses emissions of N_2O due to the use of fertilizers. Synthetic nitrogen fertilizers, synthetic multi-nutrient fertilizers, and organic fertilizers are included in the emission estimates. Emissions due to atmospheric deposition and nitrogen-fixing crops are not included for two reasons: these emission sources are highly uncertain, and activity data are not readily available.

Research has shown that a number of factors affect nitrification and denitrification rates in soils, including: water content, which regulates oxygen supply; temperature, an important factor in microbial activity; nitrogen concentration, in particular nitrate and ammonium concentration; available organic carbon for microbial activity; and soil pH. These conditions vary greatly by soil type, crop type, management regime, and fertilizer application. Moreover, the interaction of these conditions and their combined effect on the processes leading to nitrous oxide emissions are not fully understood.

Scientific knowledge regarding nitrous oxide production and emissions from fertilized soils is limited. Significant uncertainties exist regarding the agricultural practices, soil properties, climatic conditions, and biogenic processes that determine how much fertilizer nitrogen various crops absorb, how much remains in soils after fertilizer application, and in what ways the remaining nitrogen either evolves into nitrous oxide or into gaseous nitrogen and other nitrogen compounds.

A major difficulty in estimating the magnitude of emissions from this source has been the relative lack of emissions measurement data across a suitably wide variety of controlled conditions, making it difficult to develop statistically valid estimates of emission factors. Previous attempts have been made to develop emission factors for different fertilizer and crop types for the purposes of developing national emissions inventories. However, the accuracy of these emission factors has been questioned. For example, while some studies indicate that N_2O emission rates are higher for ammonium-based fertilizers than for nitrate, other studies show no particular trend in N_2O emissions related to fertilizer types (see Eichner (1990) and Bouwman (1990) for reviews of the literature). Therefore, it is possible that fertilizer type is not the most important factor in determining emissions. One study suggests that N_2O emissions from the nitrification of fertilizers may be more closely related to soil properties than to the type of fertilizer applied (Byrnes *et al.*, 1990). Until a sufficient number of studies are conducted to develop statistically valid emission factors, the IPCC recommends that countries assume that 1 percent of the nitrogen applied as fertilizer is released into the atmosphere (IPCC/OECD, 1994).

Nitrous oxide emissions from fertilizer use in 1990 were estimated using this draft IPCC methodology, although with a slightly higher emission coefficient. The emission coefficient used (1.17 percent) was based on research done by the U.S. Department of Agriculture (CAST, 1992). The amount of fertilizer consumed (synthetic nitrogen, multiple-nutrient, and organic fertilizer, measured in mass units of nitrogen) was multiplied by this emission coefficient. Fertilizer data for the U.S. were obtained from the Tennessee Valley Authority's National Fertilizer and Environmental Research Center (TVA, 1993).[11] Because agricultural activities fluctuate from year to year due to economic, climatic, and other variables, the IPCC recommends that an average of three years of fertilizer consumption (centered on 1990) should be used. Total 1990 N_2O emissions from fertilizer use are estimated to be 183 thousand metric tonnes N_2O (13.5 MMTCE) (see Table IV-9):

$$\begin{aligned} N_2O \text{ Emissions} &= \text{Fertilizer Consumption (tonnes N)} \times 0.0117 \times 44/28 \\ &= 9{,}966 \text{ thousand metric tonnes N} \times 0.0117 \times 44/28 \\ &= 183 \text{ thousand metric tonnes } N_2O \end{aligned}$$

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[10] Denitrification is the process by which nitrates or nitrites are reduced by bacteria and which results in the escape of nitrogen into the air. Nitrification is the process by which bacteria and other microorganisms oxidize ammonium salts to nitrities, and further oxidize nitrites to nitrates.

[11] Fertilizer consumption data may be underestimates since they do not include organic fertilizers that do not enter the commerical market.

Table IV-9. Fertilizer Consumption and N_2O Emissions in the U.S.

	1989	1990	1991	1992	1993
Annual Fertilizer Consumption[1] (10^3 tonnes N)	9,609.5	10,048.1	10,239.4	10,384.1	10,303.7
3-year Average Fertilizer Consumption[2] (10^3 tonnes N)		9,965.7	10,223.9	10,309.1	10,343.9
N_2O Emissions (10^3 tonnes N_2O)[3]		183.2	188.0	189.5	190.2

[1] Includes synthetic multiple nutrient fertilizers, synthetic nitrogen fertilizers, and organic fertilizers.
[2] Since 1994 data are not available, the 1993-centered average is the average of 1992 and 1993 consumption.
[3] Based on an emission coefficient of 1.17 percent.
Source: Fertilizer consumption data from TVA, 1993

Approximately 55 percent of the synthetic nitrogen, multiple-nutrient, and organic fertilizer consumed in 1990 (measured on a mass of nitrogen basis) was consumed in the Midwest (TVA, 1993).

The methodology described above was also used to estimate N_2O emissions from fertilizer use in 1991, 1992, and 1993(see Table IV-9).[12] Fertilizer consumption increased 4 percent from 1989 to 1990, and then leveled off to an average annual rate of increase of 2 percent between 1990 and 1992. Consumption then declined by about 1 percent between 1992 and 1993. Based on the consumption statistics, nitrous oxide emissions in 1991, 1992, and 1993 are estimated to be approximately 188 thousand metric tonnes (13.8 MMTCE), 190 thousand metric tonnes (14.0 MMTCE), and 190 thousand metric tonnes (14.0 MMTCE), respectively.

These estimates are highly uncertain due to the large degree of uncertainty associated with the emission factor. A survey of the current scientific literature on field N_2O flux provides a rather broad range for the emission coefficient -- greater than 0.001 and less than 0.1 (CAST, 1992). Also, the emission coefficient used (1.17 percent) is probably too low for organic fertilizers; and as mentioned earlier, organic fertilizer consumption may be underestimated since the statistics only include fertilizers that enter the commercial market. Uncertainty is also introduced due to the variable nitrogen content of organic fertilizers. Nitrogen content varies by type of organic fertilizer as well as within individual types, and average values are used to estimate total organic fertilizer N consumed. Further research is required to constrain these uncertainties and develop more accurate estimates of N_2O emissions from fertilizer.

E. EMISSIONS FROM FIELD BURNING OF AGRICULTURAL WASTES

In some parts of the U.S., agricultural crop wastes are burned in the field to clear remaining straw and stubble after harvest and to prepare the field for the next cropping cycle. When crop residues are burned, a number of greenhouse gases are released, including carbon dioxide, methane, carbon monoxide, nitrous oxide, and oxides of nitrogen. However, crop residue burning is not thought to be a net source of carbon dioxide because the carbon dioxide released during burning is reabsorbed by crop regrowth during the next growing season.

Field burning of crop residues is not a common method of agricultural waste disposal in the U.S., so emissions from this source are minor. Emissions in 1990 from this source are estimated to have been approximately 80 thousand metric tonnes of methane (0.5 MMTCE), 2,760 thousand metric tonnes of carbon monoxide, 5 thousand metric tonnes of nitrous oxide (0.4 MMTCE), and 115 thousand metric tonnes of nitrogen oxides. These estimates are highly uncertain because data on the amounts of residues burned each year are not available. The emission estimates represent approximately 0.3, 3.3, 1.2, and 0.5 percent of total U.S. emissions of methane, carbon monoxide, nitrous oxide, and nitrogen oxides, respectively. Cereal crops (e.g., wheat, corn, and sorghum) account for about 75 percent of the carbon gases released and 50 percent of the nitrogen gases released.

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[12] Fertilizer consumption data are not yet available for 1994, so only 1992 and 1993 consumption data were used to estimate 1993 emissions.

Emissions increased on average by about 10 percent between 1990 and 1991, decreased by about 3 percent between 1991 and 1992, and then increased by about 3 percent between 1992 and 1993. These fluctuations reflect average annual fluctuations in crop production.

Large quantities of agricultural crop wastes are produced from farming systems. There are a variety of ways to dispose of these wastes. For example, agricultural residues can be plowed back into the field, composted, landfilled, or burned in the field. Alternatively, they can be collected and used as a biomass fuel or sold in supplemental feed markets. This section addresses field burning of agricultural crop wastes. Field burning of crop wastes is not thought to be a net source of CO_2 because the carbon released to the atmosphere during burning is reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, CO, N_2O, and NO_x, which are released during combustion. In addition, field burning may result in enhanced emissions of N_2O and NO_x many days after burning (Anderson *et al.*, 1988; Levine *et al.*, 1988), although this process is highly uncertain and will not be accounted for in this section.

The methodology for estimating greenhouse gas emissions from field burning of agricultural wastes is based on the amount of carbon burned, emission ratios of CH_4 and CO to CO_2 measured in the smoke of biomass fires, and emission ratios of N_2O and NO_x to the nitrogen content of the fuel. The methodology is the same as the draft methodology of the IPCC (IPCC/OECD, 1994).

The first step in estimating emissions from agricultural waste burning is to estimate the amounts of carbon and nitrogen released during burning:

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[13]

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

To avoid unrepresentative results based upon fluctuations in economic or climatic conditions, a three-year average (centered on 1990) for crop production (USDA, 1991; USDA, 1993) was used to estimate 1990 emissions. Estimates of the amounts of crop residues burned *in situ*, or in the field, are not readily available. Therefore, the default value recommended by the IPCC for developed countries, 10 percent, was used. However, this default value, based on Crutzen and Andreae (1990), may be an overestimate for the U.S. because open burning is banned in many states.

Emissions of carbon as CH_4 and CO are calculated by multiplying the amount of carbon released by the appropriate emission ratio (*i.e.*, CH_4/C or CO/C). Similarly, N_2O and NO_x emissions are calculated by multiplying the amount of nitrogen released by the appropriate emission ratio (*i.e.*, N_2O/N or NO_x/N). The specific values used in this inventory and the results are presented in Tables IV-10 and IV-11. Field burning of agricultural wastes was estimated to release approximately 80 thousand metric tonnes CH_4 (0.5 MMTCE), 2,760 thousand metric tonnes CO, 5 thousand metric tonnes N_2O (0.4 MMTCE), and 115 thousand metric tonnes NO_x in 1990. Cereal crops account for about 75 percent of the carbon released and 50 percent of the nitrogen released.

Using the same methodology described above, trace gas emissions for 1991, 1992, and 1993 were estimated using production data from the USDA (1994c). The data and results are contained in Tables IV-10 and IV-11. Emissions increased by 7 to 12 percent from 1990 to 1991, decreased by about 3 percent between 1991 and 1992, and then increased by 2 to 4 percent from 1992 to 1993. These fluctuations reflect average changes in production: three-year production averages for most crops increased from 1990 to 1991, and then declined between 1991 and 1992.

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[13] 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 draft 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" is added to the calculations.

Table IV-10. Key Assumptions for Estimating Emissions from Crop Waste Burning

Crop	Production 3-yr. avg. (10³ tonnes)				Res/Crop Ratio	Res Burned (%)	Dry Matter (%)	Fraction Carbon	Fraction Nitrogen
	1990	1991	1992	1993[a]					
Cereals									
Wheat	61,273	65,104	62,071	66,147	1.3	10%	91.1%	0.4853	0.004
Barley	9,367	9,757	9,598	9,342	1.2	10%	90.4%	0.4567	0.006
Maize	194,192	210,755	197,293	200,996	1.0	10%	88.0%	0.4709	0.0081
Oats	4,715	4,334	3,602	3,636	1.3	10%	90.6%	0.4853	0.007
Rye	284	270	271	283	1.6	10%	90.0%	0.4853	0.007
Rice	7,077	7,457	7,457	7,615	1.4	10%	90.0%	0.4144	0.0067
Millet[b]	183	180	180	180	1.4	10%	88.5%	0.4853	0.007*
Sorghum	15,017	17,291	17,245	15,440	8.0	10%	90.0%	0.4853	0.0085*
Pulse									
Soya	52,945	55,342	54,277	54,383	2.1	10%	89.3%	0.45	0.023*
Beans	1,359	1,342	1,183	1,008	2.1	10%	88.7%	0.45	0.023*
Peas	204	172	185	169	1.5	10%	90.2%	0.45	0.023*
Lentils	56	62	79	81	2.1	10%	89.3%	0.45	0.023*
Tuber and Root									
Sugarbeet	24,448	25,661	25,323	25,192	0.3	10%	90.0%	0.4072	0.0228
Artichoke[c]	59	56	54	52	0.8	10%	90.0%	0.4226	0.011
Peanut	1,893	1,937	1,896	1,762	1.0	10%	90.1%	0.4226	0.011
Potatoes	17,995	18,826	19,087	19,159	0.4	10%	86.7%	0.4226	0.011
Other	534	544	532	543	0.4	10%	86.7%	0.4226	0.011
Sugarcane	26,555	26,838	27,560	27,618	0.8	10%	90.0%	0.4695	0.003

a Crop production for 1993 are two-year averages (i.e., 1992 and 1993).

b Because millet is such a small commodity relative to other crops, the USDA no longer tracks its production. These production estimates were taken from the FAO (1993).

c The USDA provided artichoke production for California only. Total artichoke production was estimated by assuming that California accounted for 90% of the entire market.

Sources: Data on annual crop production were taken from USDA (1991, 1993, 1994c). Residue/crop ratios, dry matter contents, and carbon contents were taken from Strehler and Stützle (1987) and University of California (1977). Nitrogen contents were also taken from Strehler and Stützle (1987) except where indicated by an asterisk (*). These data were taken from Barnard (1990). The percent of produced residue that is burned is based on Crutzen and Andreae (1990).

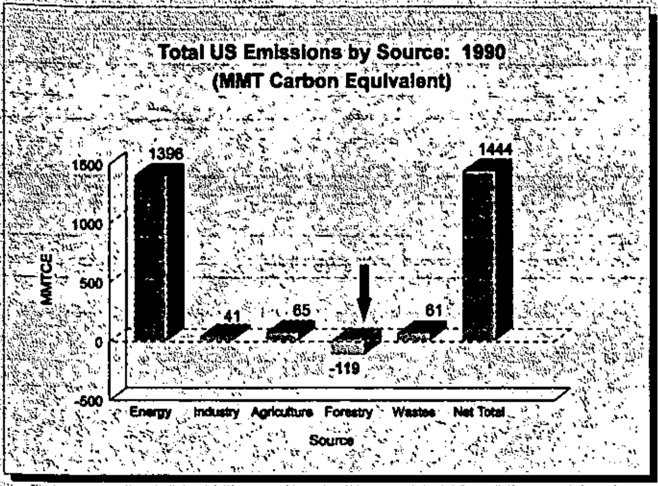
Table IV-11. Trace Gas Emissions from Field Burning of Agricultural Crop Wastes: 1990 - 1992

Gas	Crop Type	Carbon or Nitrogen Released				Emission	Conversion	Emissions (10^3 tonnes)[b]			
		1990	1991	1992	1993	Ratio	Factor	1990	1991	1992	1993
CH_4	Cereals	14,685	16,090	15,437	16,095	0.003	16/12	59	64	62	64
	Pulse	3,762	3,925	3,842	3,837	0.003	16/12	15	16	15	15
	Tuber & Root	503	525	524	518	0.003	16/12	2	2	2	2
	Sugarcane	735	742	762	764	0.003	16/12	3	3	3	3
	Total[a]	**19,684**	**21,282**	**20,565**	**21,214**	**0.003**	**16/12**	**79**	**85**	**82**	**85**
CO	Cereals	14,685	16,090	15,437	16,095	0.06	28/12	2,056	2,253	2,161	2,253
	Pulse	3,762	3,925	3,842	3,837	0.06	28/12	527	549	538	537
	Tuber & Root	503	525	524	518	0.06	28/12	70	73	73	73
	Sugarcane	735	742	762	764	0.06	28/12	103	104	107	107
	Total[a]	**19,684**	**21,282**	**20,565**	**21,214**	**0.06**	**28/12**	**2,756**	**2,979**	**2,879**	**2,970**
N_2O	Cereals	226	249	239	249	0.007	44/28	2	3	3	3
	Pulse	192	201	196	196	0.007	44/28	2	2	2	2
	Tuber & Root	20	21	20	20	0.007	44/28	0.2	0.2	0.2	0.2
	Sugarcane	5	5	5	5	0.007	44/28	0.05	0.05	0.05	0.05
	Total[a]	**443**	**475**	**461**	**470**	**0.007**	**44/28**	**5**	**5**	**5**	**5**
NO_x	Cereals	226	249	239	249	0.121	30/14	59	65	62	65
	Pulse	192	201	196	196	0.121	30/14	50	52	51	51
	Tuber & Root	20	21	20	20	0.121	30/14	5	5	5	5
	Sugarcane	5	5	5	5	0.121	30/14	1	1	1	1
	Total[a]	**443**	**475**	**461**	**470**	**0.121**	**30/14**	**115**	**123**	**119**	**122**

[a] Totals may not add due to rounding.

[b] Burning efficiency (the fraction of dry biomass exposed to burning that actually burns) was assumed to be 93 percent and combustion efficiency (the fraction of carbon in the fire that is oxidized completely to CO_2) was assumed to be 88 percent (U.S. EPA, 1994a).

PART V. EMISSIONS FROM LAND-USE CHANGE AND FOREST MANAGEMENT



The biosphere emits and absorbs a wide variety of carbon and nitrogen trace gases, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of nitrogen (NO_x), and nonmethane hydrocarbons (NMHC).[1] *When humans use and alter the biosphere through land-use change and forest management activities, such as clearing an area of forest to create cropland, restocking a logged forest, draining a wetland, or allowing a pasture to revert to a grassland, the natural balance of these trace gas emissions and uptake is altered and their atmospheric concentrations adjust. Globally, the most important human activity that affects the biosphere is deforestation, particularly the clearing of tropical forests for agricultural use. Deforestation is estimated to be responsible for about 20 percent of the current annual global emissions of CO_2 from anthropogenic activities (IPCC, 1992).*

In the U.S., however, forest management activities and the regeneration of previously cleared forest area are believed to be the primary activities responsible for current greenhouse gas fluxes from land-use change and forest management, as the amount of forest land changed by only about 0.1 percent per year between 1977 and 1992. The net CO_2 flux in 1990 due to these activities is estimated to have been an uptake (sequestration) of 119 MMTCE. This carbon uptake represents an offset of about 9 percent of the CO_2 emissions from energy-related activities. The Northeast, North Central, and South Central regions of the U.S. account for 98 percent of the uptake of carbon, largely due to high growth rates that are the result of intensified forest management practices and the regeneration of forest land previously cleared for cropland and pasture. Western states are responsible for a small net release of carbon, reflecting mature forests with a near balance between growth, mortality, and removals.

Relative to 1990, net flux rates for 1991 and 1992 are estimated to have declined slightly, to 118 and 117 MMTCE, respectively. This declining trend in sequestration is due to maturation of existing forests and associated slowing of carbon accumulation rates. A flux estimate has not yet been derived for the year 1993 since the last U.S. forest inventory was completed in 1992.

The U.S. land area is roughly 2,263 million acres, of which 33 percent, or 737 million acres, is forest land (Powell et al., 1993). The amount of forest land has remained fairly constant over recent decades, declining by approximately 5 million acres between 1977 and 1987 (USDA Forest Service, 1982; Waddell et al., 1989), and increasing by about 0.5 million acres between 1987 and 1992 (Powell et al., 1993). These changes represent fluctuations of well under 1 percent of the forest land area, or on average, about 0.1 percent per year. Other major land uses in the U.S. include range and pasture lands (36 percent), cropland (18 percent), urban uses (3 percent), and other lands (10 percent) (Daugherty, 1991).[2] Urban lands are the fastest growing land use.

Given that U.S. forest land area changed by only about 0.1 percent per year over the last 15 years, the major influences on the net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon

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[1] Nonmethane hydrocarbons (NMHCs) are a subset of nonmethane volatile organic compounds.

[2] Other lands include farmsteads, transportation uses, marshes, swamps, deserts, tundra, and miscellaneous other lands.

stored in the biomass[3] and soils of forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration will, over decades, result in increased storage in biomass and soils (*i.e.*, in general, forests contain more biomass and soil carbon than cropland).

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- trees (*i.e.*, living trees, standing dead trees, roots, stems, branches, and foliage);
- soil;
- the forest floor (*i.e.*, woody debris and tree litter); and,
- understory vegetation (*i.e.*, shrubs and bushes).

As a result of biological processes (*e.g.*, growth and mortality) and anthropogenic activities (*e.g.*, harvesting, thinning, and other removals), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage in living trees. As these trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes will release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the change in the total net amount of carbon stored in each of these pools (*i.e.*, in each ecosystem component) over time.

The net change in forest carbon, however, is not likely to be equivalent to the net flux between forests and the atmosphere. Because most of the timber that is harvested and removed from U.S. forests is used in wood products, removals may not always result in an immediate flux of carbon to the atmosphere. Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 through either combustion or decay,[4] although the exact rate of emission varies considerably between different product pools and may in fact result in effective long-term carbon storage. For example, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If timber is harvested for energy use, subsequent combustion results in an immediate release of carbon. Paper production may result in emissions over years or decades.

The U.S. forest carbon flux estimates for 1990, 1991, and 1992 presented in this inventory are based on a total accounting of biomass carbon stored in all forest ecosystems and the tracking of changes in the total biomass carbon stored on forest lands. The tracking of soil carbon, as well as carbon in product pools, have not been included at this time due to methodological uncertainties and inadequate data. The forest carbon in trees, understory vegetation, and the forest floor is tracked by utilizing dynamic forest resource survey data collected by the U.S. Forest Service (USFS). These resource data include estimates of timber volume by species, size class, and other categories, which are combined with information from the research literature to derive estimates of the total carbon stored in forest biomass.

The net flux is the difference in total carbon storage between two years for which forest survey data are available (and therefore for which carbon inventories can be derived) divided by the number of years between the surveys. If carbon storage decreases, then the difference is a net emission to the atmosphere; if carbon storage increases, then the difference is a net sequestration of carbon on land.

The inventory methodology applied here differs somewhat from that recommended by the IPCC (IPCC/OECD, 1994). Instead of directly inventorying carbon stocks and changes in stocks over time, the draft IPCC

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[3] Biomass is a shorthand term for organic material. The amount of biomass in a given land area includes all the living and dead organic material, both above and below the ground surface.

[4] Actually, if timber undergoes combustion, some small portion of the carbon - as much as 10 percent of the total carbon released - will be released as CO and CH_4 rather than CO_2. In addition, if timber products are placed in landfills, about 50 percent of the carbon that eventually decomposes is oxidized to CO_2 and about 50 percent is released as CH_4. However, eventually both CO and CH_4 oxidize to CO_2 in the atmosphere.

methodology uses average annual statistics on land-use change and management activities, and applies carbon density and flux data to these activity estimates to derive total flux estimates. The IPCC has adopted this type of methodology because the majority of the world's countries do not have the detailed forest inventory statistics available in the U.S. and used in preparing this inventory.

Theoretically, the two methods should result in similar flux estimates. However, the U.S. inventory methodology explicitly tracks changes in forest carbon through time using direct measurement of timber volume and forest ecology studies, while the IPCC methodology is an indirect approach using average annual activity data and theoretically or experimentally derived carbon data. Although there are large uncertainties associated with the inventory estimates, the methodology employed here is likely to have resulted in a more accurate flux estimate than if the basic IPCC methodology had been employed.

The estimates of the 1990, 1991, and 1992 forest carbon flux presented here were derived from Birdsey and Heath (1993) and Birdsey (1994). These estimates are based on national compilations of forest inventory statistics for 1977 (USFS, 1982), 1987 (Waddell *et al.*, 1989), and 1992 (Powell *et al.*, 1993). These statistics measure the changes in timber volume over time due to timber growth, harvest, and mortality. Although the estimates cover only timberland, which is a subset of the forest land base, they capture the most productive and intensively managed forest lands.[5] Birdsey and Heath (1993) and Birdsey (1994) calculated total stored biomass carbon in each of the ecosystem components in the years 1987 and 1992 using the timber inventory data and number of conversion factors from the research literature.[6] The 1990 flux was derived by subtracting the biomass carbon storage estimated for 1992 from that for 1987, and dividing by 5. Therefore, the 1990 flux is actually an average annual flux for the period 1987-1992. Flux estimates for 1991 and 1992 were derived using exponential interpolation between a flux for 1982 (from the 1977 and 1987 storage estimates) and the 1990 flux.

The 1990 carbon flux from U.S. forests is estimated to have been a net sequestration of carbon from the atmosphere to the biosphere of 119 MMTCE. This is equivalent to approximately 436 million metric tonnes CO_2. Carbon sequestration rates are estimated to have declined slightly in 1991 and 1992, to 118 and 117 MMTCE, respectively. Also, because 1992 is the last year for which a forest inventory has been compiled, a flux estimate for 1993 is not yet available.

There is considerable regional variation in the carbon flux estimates for 1990, reflecting different underlying trends in the forest resource base throughout the United States. A regional breakdown of carbon flux estimates from forest land is presented in Table V-1. This table also shows the contribution of each of the forest ecosystem components to the total flux.

All of the net uptake of carbon in U.S. forest land in 1990 occurred in the Eastern regions (see Table V-1 and Figure V-1.)[7] This is primarily due to forest regeneration on areas previously cleared for cropland and pasture and the use of intensified forest management practices. All of these Eastern regions have significant net carbon uptakes, except for the Southeast states where harvesting activity has increased recently. In Western states, *i.e.*, the Rocky Mountain and Pacific Coast regions, carbon flux is slightly negative since forest growth, mortality, and harvesting are in near balance.

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[5] Forest land in the U.S. includes all land that is at least 10 percent stocked with trees of any size. Timberlands are the most productive of these forest lands, growing at a rate of 20 cubic feet per acre per year or more. In 1992 there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell *et al.*, 1993). Forest land classified as Timberlands are unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by a statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land. While this inventory does not quantify the carbon flux on Productive Reserved or Other Forest Lands, this missing flux is assumed to be relatively minor because trees on these lands grow slowly and the standing stock of trees is not managed intensively.

[6] Birdsey and Heath (1993) and Birdsey (1994) also include soil carbon in their calculations, but this component of forest carbon has not been included in the U.S. inventory at this time because of significant associated uncertainties.

[7] The East includes the Northeast, North Central, Southeast, and South Central regions.

Table V-1: Regional Carbon Flux Estimates

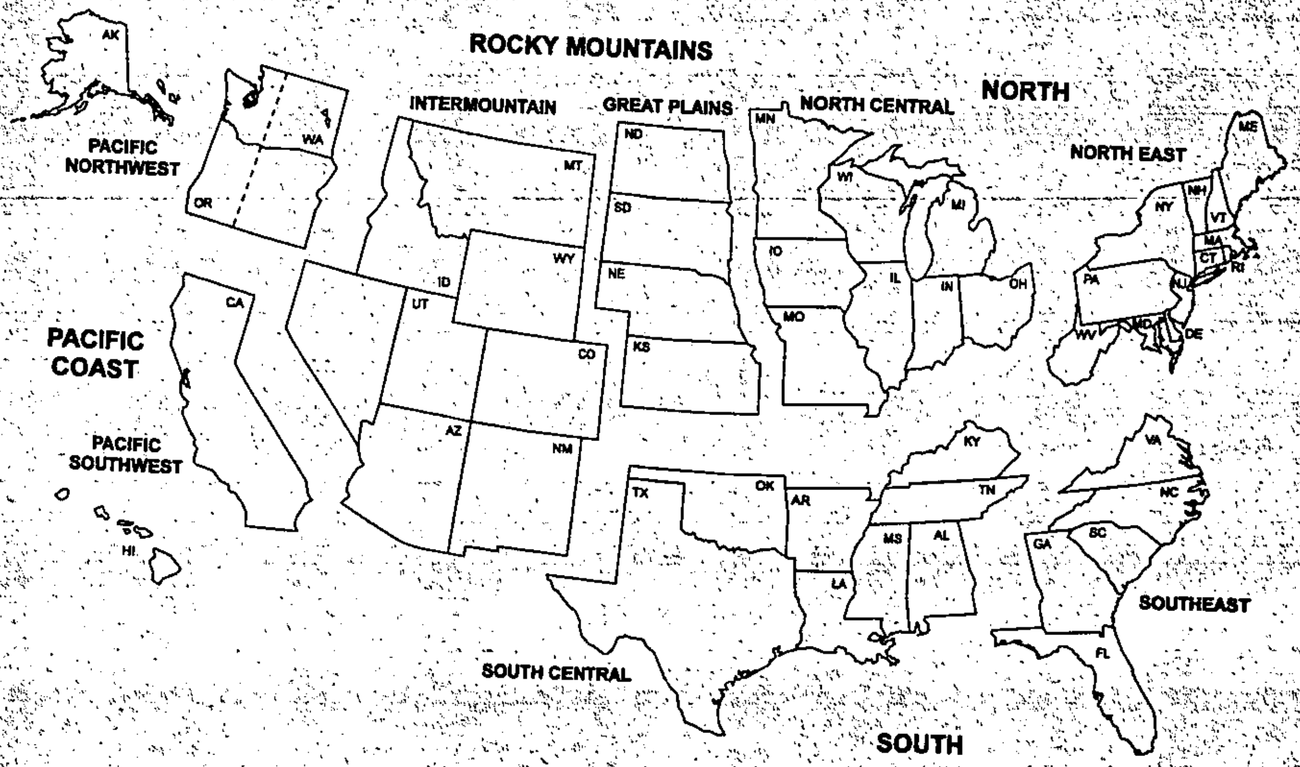
Region[a]	Carbon Flux by Ecosystem Component, 1990 (10^6 tonnes C)			Total Carbon Flux, 1990 (10^6 tonnes C)
	Forest Floor	Understory	Trees	
Northeast	10	1	37	48
North Central	7	<1	29	36
Southeast	<1	0	1	2
South Central	2	1	35	38
Rocky Mountains	2	>-1	-4	-2
Pacific Coast	-1	0	-2	-3
U.S. Total	**21**	**2**	**96**	**119**

Sources: Birdsey and Heath (1993), Birdsey (1994)

Note: A positive flux indicates uptake; a negative flux indicates emissions.

a. Regions are defined in Figure V-1.

Figure V-1. Regions and States for the U.S. Inventory



Source: Waddell *et al.* (1989)

The uptake of carbon due to forest regeneration is an ongoing result of land-use changes in previous decades. The rate of clearing forest land for crop cultivation and pasture slowed greatly in the late 19th century and by 1920 had all but ceased. The reduced need for cropland and pasture resulted from improved agricultural productivity and the reduced use of draft animals following the widespread use of tractors. As farming expanded in the Midwest and West, large areas of previously cultivated land in the Eastern states were brought out of crop production, primarily between 1920 and 1950, and allowed to revert to forest land. The regeneration of forest land greatly increases carbon storage in standing biomass, and the impacts of these land-use changes are still affecting carbon fluxes from Eastern forests. In addition to land-use changes in the early part of this century, carbon fluxes from Eastern forests are affected by a trend towards managed growth on private land since World War Two, resulting in a near doubling of forest biomass density in Eastern forests since the early 1950s.

The Southeast states are an exception to these Eastern forest trends, with increases in timber removals and decreases in growth rates resulting in a small net uptake of carbon compared to other Eastern regions. The Southeast accounted for 25 percent of timber removals in 1991, up from 20 percent in 1976, largely in response to the removal of forest land from commercial harvesting in the West. Moreover, the rate of timber growth in the Southeast has diminished, reflecting maturing forests, and timber mortality in the Southeast increased 3 percent between 1986 and 1991.

The Rocky Mountain and Pacific Coast states have relatively little impact on the U.S. net carbon flux. This reflects a near balance between growth, mortality, and removals, associated with mature forests with low growth, and a decline in timber removals from 1987 to 1992 of 5 percent and 10 percent, respectively, in these two regions.

Within regions where there has been an increase in carbon storage, and thus a net uptake of carbon, the majority of the carbon flux is accounted for by increased storage in the trees (see Table V-1). Additional carbon is stored in the understory vegetation and the forest floor. These trends reflect the growth of new and existing forests due to ongoing forest regeneration and intensified forest management. However, the declining uptake rates for the 1990-1993 period indicate that growth rates are slowing on average. This is a reflection of maturing forests in which carbon accumulation rates have begun to lessen.

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests. Four major uncertainties are discussed briefly below, as well as areas needing further research and analysis.

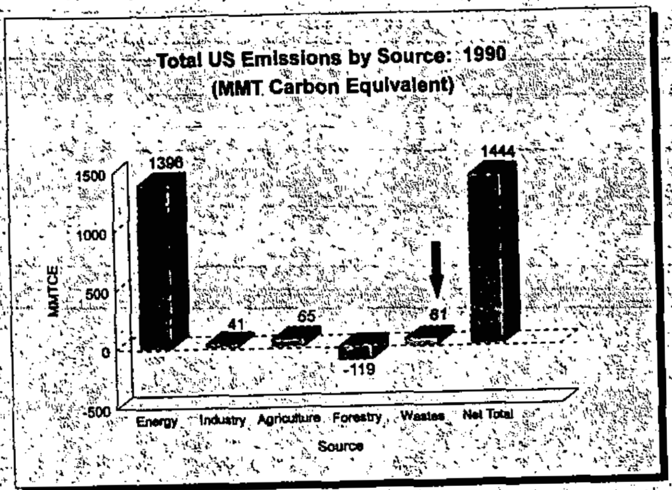
First, the impacts of forest management activities on soil carbon are quite uncertain, particularly after harvest. Research indicating a 20 percent loss of soil carbon after harvest (Moore *et al.*, 1981) has been used by Birdsey and Heath (1993) and Birdsey (1994), whereas results showing little or no net change in soil carbon following harvest (Johnson, 1992) and during regeneration have been used in other studies (*e.g.*, Turner *et al.*, 1993). Since forest soils contain over 50 percent of the total stored forest carbon in the U.S., this difference can have a large impact on flux estimates. However, because of uncertainties associated with soil carbon flux, this component is not included in the inventory at this time.

Second, Birdsey and Heath (1993) and Birdsey (1994) assume that harvested timber effectively results in immediate carbon emissions (*i.e.*, they do not model time-dependent emissions from the product pools). This assumption is consistent with the methodology recommended by the IPCC (IPCC/OECD, 1994) and will result in an accurate assessment of net emissions if the amount of material in product pools, and the distribution of this material among different pools, have not changed over the past 100 years or so. However, other studies that model the product pools in the U.S. estimate a net accumulation of carbon in product pools in 1990. This is because more timber carbon was transferred to wood products than was released to the atmosphere due to the decay or combustion of material stored in product pools (Turner *et al.*, 1993). Turner *et al.* estimate that the net accumulation of carbon in the product pools is 36 million metric tonnes C in 1990. This would indicate that less carbon was actually emitted to the atmosphere as a result of timber removals than the current inventory estimate accounts for, and that the total net flux would be a larger uptake of carbon in 1990-1992. However, estimates of the net annual accumulation of carbon in product pools are highly uncertain due to scientific uncertainties associated with decay rates as well as a lack of accurate historical carbon pool statistics. Therefore, this result is not included in the inventory estimate.

Third, the current inventory estimate does not include forest land in Alaska and Hawaii or reserved timberland. Inclusion of Alaska and Hawaii would significantly increase the storage estimates in both studies, but is not likely to significantly alter the flux estimates because forests in these states are believed to be in relative equilibrium, *i.e.*, neither accumulating or emitting significant quantities of carbon. Reserved timberlands are not managed or harvested, and therefore are not likely to contribute greatly to total flux estimates.

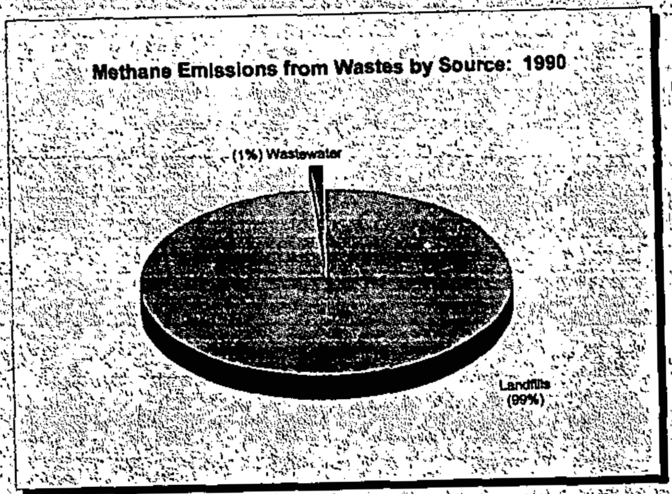
Finally, forest management activities may also result in fluxes of other greenhouse and radiatively important gases since dry soils are an important sink for CH_4, a source of N_2O, and both a source and a sink for CO, and vegetation is a source of several NMHCs. However, the effects of forestry activities on fluxes of these gases are highly uncertain, and, therefore, are not included in the inventory at this time. Similarly, there are several land-use changes that are not accounted for in the inventory due to uncertainties in their effects on trace gas fluxes as well as poorly quantified land-use change statistics. These land-use changes include loss and reclamation of freshwater wetland areas, conversion of grasslands to pasture and cropland, and conversion of managed lands to grasslands and other unmanaged, non-forest dryland types.

PART VI. EMISSIONS FROM WASTE



Anaerobic decomposition of organic materials in landfills by bacteria can result in emissions of methane, carbon dioxide, and other greenhouse and photochemically important gases. Currently, methane emissions from landfills are the largest single anthropogenic source of methane in the U.S., contributing about 37 percent of total U.S. methane emissions. Other anaerobic decomposition processes, such as wastewater streams with high organic material content from municipal and industrial processes, can also emit large quantities of methane. In addition, the combustion of waste, both in incinerators and by open burning, is also a source of many greenhouse and photochemically important gases. This section covers methane emissions from U.S. landfills, wastewater streams, and criteria pollutant emissions from waste incineration.

A. LANDFILLS



Organic landfill materials such as yard waste, household garbage, food waste, and paper can decompose and produce methane. This decomposition process is a natural mechanism through which microorganisms derive energy for growth. Methane production typically begins one or two years after waste placement in a landfill and may last from 10 to 60 years. Methane emissions from landfills are the largest single anthropogenic source of methane in the U.S. In 1990, methane emissions from U.S. landfills ranged between 49 and 71 MMTCE, or about 37 percent of total U.S. methane emissions. Emissions from U.S. municipal solid waste landfills, which received over 70 percent of the total solid waste generated in the U.S., account for about 90 to 95 percent of the total landfill emissions, while industrial landfills account for the remaining 5 to 10 percent. There are an estimated 6,000 landfills in the U.S., with 1,300 of the largest landfills accounting for about half of the emissions. Currently, about 10 percent of the methane is recovered for use as an energy source. Emissions of methane from landfills over the period 1990 - 1992 have been relatively constant (Table VI-1).

Organic waste first decomposes aerobically (in the presence of oxygen) and is then attacked by anaerobic bacteria which convert organic material to simpler forms like cellulose, amino acids, sugars, and fats. These simple substances are further broken down through fermentation into gases and short-chain organic compounds which form the substrates for methanogenic bacteria. Methane producing bacteria then convert these fermentation products into stabilized organic materials and a biogas consisting of approximately 50 percent carbon dioxide and 50 percent methane by volume. The percentage of carbon dioxide in the biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen, 1987).

Landfills in the U.S. are classified by size, ranging from class 1 to class 7. Class 1 landfills are the smallest in size and are also the most common type of landfills. However, class 1 landfills account for less than five percent of the total waste landfilled to date. On the other hand, there are 19 class 7 landfills in the

Table VI-1. U.S. Methane Emissions from Landfills: 1990 - 1992

(Thousand Tonnes of CH_4)

Source	Number	1990	1991	1992
Large Municipal Landfills	152	2,600-4,200	NA	NA
Medium Municipal Landfills	1,137	3,300-6,000	NA	NA
Small Municipal Landfills	4,744	900-1,500	NA	NA
Industrial Landfills	NA	600-900	NA	NA
Total[a,b]	**6,033[c]**	**8,100-11,800[d]**	**10,100**	**10,200**

Source: U.S. EPA (1993a)

Note:
a. The uncertainty in the total is estimated assuming that some of the uncertainty for each source is independent. Consequently, the uncertainty range for the total is more narrow than the sum of the ranges for the individual sources.
b. The total does not include an additional 1,500 thousand tonnes of methane recovered from landfills that was flared or used as an energy source.
c. Excluding industrial landfills. Also, this table does not include the 3000 class 1 landfills that, because of their very small size, are believed to produce negligible amounts of methane.
d. Equivalent to 48.6-70.8 MMTCE.

U.S. which account for over 25 percent of the total waste. Because of their different sizes and characteristics, landfills generate different rates of methane emissions. Table VI-2 contains a summary of the landfill class sizes and the associated emissions factors used to estimate landfill emissions.

Estimates of methane emissions from landfills are from U.S. EPA (1993a). The U.S. EPA employed a statistical model relating measured methane recovery rates from landfills with recovery systems to the physical characteristics of landfills to estimate U.S. emissions.[1]

Some landfills practice flaring of recovered landfill gas, which converts the methane portion of the gas to carbon dioxide. While landfill gas contains roughly equal amounts of methane and carbon dioxide, landfill carbon dioxide emissions are small compared to emissions from other sources discussed. Moreover, carbon dioxide from landfills is believed to come mainly from organic materials. Since these materials are assumed to absorb a similar amount of carbon during the growing cycle, the net contribution of landfills to the global carbon dioxide budget is assumed to be zero.[2] The same is not true for the methane that may be produced since the methane is typically only produced as a by-product of the landfilling process.

The total methane emissions from landfills reported above do not include an estimated 1,500 thousand metric tonnes (9 MMTCE) of methane annually recovered by landfills with recovery systems. Currently, this recovered methane is either flared or used as an energy source, resulting in carbon dioxide emissions. Assuming that the 9 MMTCE of recovered methane is flared or combusted for other purposes, potential carbon dioxide emissions of 4,125,000 metric

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[1] The *IPCC Draft Guidelines for National Inventories* (IPCC/OECD, 1994) presents a methodology conceptually similar to U.S. EPA (1993a) but simpler in execution.

[2] In some instances landfills may be a long-term sink for carbon if the organic material does not degrade. Further research is necessary to determine the extent to which landfills may be acting as longer term carbon sinks.

Table VI-2. Summary of U.S. Landfill Emission Rate Estimates

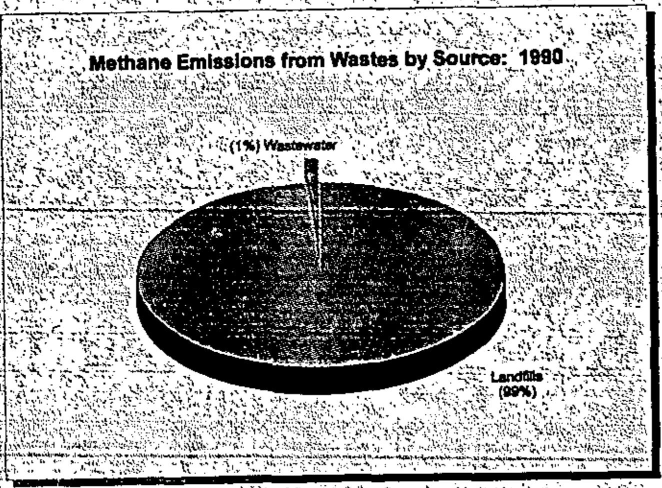
Landfill		Methane Emissions (m^3 per minute)		
Class/size	**# in Class**	**Low**	**Mean**	**High**
1	3,000	+	+	+
2	4,744	1.1	1.6	2.0
3	425	5.4	7.6	9.8
4	712	13.5	19.9	26.3
5	106	37.0	42.7	48.4
6	27	72.5	85.8	99.2
7	19	253.7	322.6	361.6

Source: U.S. EPA (1993a).
Note: "+" denotes negligible.

tonnes (1.125 MMTCE) were produced using the carbon dioxide to methane molecular ratio of 44/16. Although estimated here, this quantity of carbon dioxide emissions is not included in the U.S. emissions total because, as described earlier, these emissions were likely to have occurred naturally if the materials in the landfills had been allowed to decompose aerobically.

There are a number of reasons why the estimates of landfill emissions are uncertain. Currently, there are limited measurements of landfill emissions on which to base an analysis. Landfill gas recovery data are being used as a surrogate in existing analyses. In general, the statistical model used in the U.S. EPA (1993a) analysis may not accurately capture the relationship between emissions and various physical characteristics of U.S. landfills. To the degree that emission data and inputs for the model are not representative of landfills as a whole, error may be introduced. Additional factors that increase uncertainty are the accuracy of data on landfill size and waste characteristics, waste management practices, and the oxidation rate of methane as it passes through the soil cover of a landfill.

B. WASTEWATER



Wastewater can be treated using aerobic and/or anaerobic technologies, or if untreated, can degrade under either aerobic or anaerobic conditions. Methane is produced when organic material in treated and untreated wastewater degrades anaerobically, i.e., without the presence of oxygen. Based on available data, methane emissions from municipal wastewater in the U.S. are about 0.9 MMTCE, or about one half of one percent of total U.S. methane emissions. Estimates for 1991 and 1992 are assumed to be about the same as 1990 levels. At this time, data are not sufficient to estimate methane emissions from industrial wastewater streams in the U.S.

Highly organic wastewater streams such as waste streams from food processing or pulp and paper plants rapidly deplete available oxygen in the water stream as their organic matter decomposes. The organic content, otherwise known as "loading" of these wastewater streams, is expressed in terms of biochemical oxygen demand, or "BOD." BOD represents the amounts of oxygen taken up by the organic matter in the wastewater during decomposition. Under the same conditions, wastewater with higher BOD concentrations will produce more methane than wastewater with relatively lower BOD concentrations. Most industrial wastewater has a low BOD content, while food processing facilities such as fruit, sugar, meat processing plants, and breweries can produce untreated waste streams with high BOD content.

Although IPCC-recommended methodologies for estimating municipal and industrial wastewater methane emissions exist, the data required by these methodologies are not easily obtained, especially industrial wastewater data. Estimates of municipal wastewater methane for the U.S. provided in this section are taken from U.S. EPA (1994a). That report's methodologies, which are similar to the proposed IPCC methodologies, are based on BOD loading in the wastewater flow in the U.S.

The following equation was developed by the U.S. to estimate methane emissions from municipal wastewater:

$$\frac{kg\ CH_4}{yr} = (Population)\left(\frac{kg\ BOD_5}{capita/day}\right)\left(\frac{365\ days}{yr}\right)\left(\frac{0.22\ kg\ CH_4}{kg\ BOD_5}\right)\left(\begin{array}{c}Fraction\\ Anaerobically\\ Digested\end{array}\right)$$

Based on available data, U.S. EPA (1994a) estimated methane emissions from municipal wastewater in the U.S. to be about 150,000 metric tonnes (0.9 MMTCE), or about one half of one percent of total U.S. methane emissions. Because of the lack of data, more detailed estimates are not yet available for 1991 and 1992. For these years, methane emissions from municipal wastewater in the U.S. are assumed to be at about the same levels as 1990. Insufficient data are available to estimate emissions from industrial wastewater.

There is uncertainty in this estimate due to a lack of data characterizing wastewater management practices, the quantities of wastewater that are subject to anaerobic conditions, the extent to which methane is emitted under anaerobic conditions, and flaring or utilization practices.

C. WASTE COMBUSTION

Like other types of combustion, waste combustion, whether in incinerators or out in the open, can be a source of carbon dioxide, NO_x, CO and NMVOCs. Waste combustion is also a source of methane and nitrous oxide, but emissions pathways are still highly uncertain.

The criteria pollutants from waste incineration (such as emissions from municipal solid waste (MSW) incineration plants) constitute only a small fraction of total U.S. criteria pollutant emissions for 1990 - 1992. U.S. emissions of VOCs, CO, and NO_x from waste incineration remained relatively unchanged for the period 1990 - 1992 (Table VI-3). Open burning contributes the majority of criteria pollutant emissions from waste combustion: about 82 percent of VOCs, 61 percent of NO_x, and 50 percent of CO emissions. Detailed 1990 emissions are provided in Table VI-4.

Table VI-3. U.S. VOC, CO, and NO_x Emissions from Waste Incineration: 1990 - 1992

(Thousand Metric Tonnes)

Source	1990	1991	1992
VOCs	290	283	290
CO	1528	1,491	1528
NO_x	74	74	74

Source: U.S. EPA (1993b).

Criteria pollutants from waste combustion are inventoried annually by the U.S. EPA. Emissions of criteria pollutants from waste incineration were reported in *National Air Pollutant Emission Trends, 1900 - 1992,* (EPA, 1993b). The U.S. EPA estimated emissions from waste combustion by applying activity emission factors (such as MSW incineration or open burning) to collected or estimated local and regional activities to obtain local and regional emissions, which were then aggregated to obtain national emissions.

Presently, net carbon dioxide emissions from waste incineration are not included in this inventory because a large fraction of the carbon in combusted waste (for example, food waste) is quickly recycled, typically on an annual basis as crops re-grow or trees are replanted. Combusted wastes can also contain plastics or other fossil-fuel based products that contribute to net carbon dioxide emissions. At this time, however, carbon emissions from the incineration of fossil-based products are not estimated.

Table VI-4. U.S. VOCs, CO, and NO$_x$ Emissions from Waste Incineration by Source: 1990

(Thousand Metric Tonnes)

Source	VOCs	CO	NO$_x$
Municipal Waste Incineration	52	770	29
Open Burning	239	758	45
Total	**290**	**1,528**	**74**

Source: U.S. EPA (1993b).

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ANNEX A
ESTIMATING EMISSIONS OF CO_2 FROM FOSSIL ENERGY CONSUMPTION

The purpose of this annex is to provide detailed descriptions of two different methods for estimating emissions of CO_2 from fossil energy consumption and to discuss their differences. This annex is divided into three sections. The first section presents the methodology used to estimate emissions in the main body of this report. This methodology is a detailed, end-use oriented approach, often referred to as a "bottom-up" methodology, which relies on obtaining fossil energy consumption information at a very disaggregated level by specific use of the energy within the U.S. economy. This methodology is conceptually similar to the detailed technology-based approach discussed in the IPCC emission inventory guidelines (IPCC/OECD, 1994; Vol 3). The second section presents a methodology that relies on aggregated data monitoring the flow of fossil energy into and out of the U.S. economy at the national level. This approach is often referred to as a "top-down" methodology, and it is the default estimation methodology recommended by the IPCC (IPCC/OECD, 1994; Vol. 3). In the third section, the two methods are compared and the resulting differences briefly discussed.

I. Estimating Carbon Dioxide Emissions Using the Bottom-up Methodology

The bottom-up methodology is characterized by the seven basic steps described below. This discussion focuses on emission estimates for the year 1990, with the relevant data presented in Tables A-1 through A-6. Relevant data sources and notations are referenced in each table. Emission estimates for 1991, 1992, and 1993 were calculated using the same bottom-up methodology.

1. Determine energy consumption by energy type and sector.

The bottom-up methodology used by the U.S. for estimating CO_2 emissions from fossil energy consumption is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates (IPCC, 1994; Vol. 3). Basic consumption data by sector are presented in Rows A-E of Table A-1, with total U.S. fossil fuel consumption by energy type presented in Row F of Table A-1. Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy, which is responsible for the collection of all U.S. energy data. All the EIA data were collected through surveys at the point of delivery or use, so they reflect the reported consumption of fuel by sector and fuel type. Individual data elements came from a variety of sources within EIA. Most information is from published reports, although some data have been drawn from unpublished energy studies and databases maintained by EIA. Exact sources are indicated in footnotes provided in each table of this annex.

Sectoral and category totals are presented in the last column and last row of Table A-1. By aggregating consumption data by sector (*i.e.*, residential, commercial, industrial, transportation, and electric utilities), primary fuel type (*e.g.*, bituminous coal, natural gas, and petroleum), and secondary fuel category (*e.g.*, gasoline, distillate fuel, etc.), one can estimate total U.S. energy consumption for a particular year. The 1990 total energy consumption across all sectors and energy types is 71,836 trillion Btu, as indicated in the last entry of Row F in Table A-1.

There are differences between the consumption figures presented in Table A-1 and those recommended in the IPCC emission inventory methodology. First, all consumption data in the U.S. inventory are presented using higher heating values (HHV) rather than the lower heating values (LHV) reflected in the IPCC emission inventory methodology. This convention is followed because all data obtained from EIA were based on HHV. Second, the energy data in Table A-1 do not include energy use from U.S. territories. The IPCC methodology, however, recommends that countries report emissions according to the reporting format used by the International Energy Agency (IEA). Since the IEA data for the U.S. include energy use in U.S. territories, U.S. energy consumption data have been adjusted accordingly to ensure that emissions from these territories are included in the U.S. total (see Step 5 for further discussion). Third, the consumption figures in Table A-1 include bunker fuels. The IPCC recommends that countries estimate emissions from bunker fuels separately and exclude these emissions from national totals. This adjustment is described below in Step 6.

2. *Determine the total carbon content of all fuels.*

Total carbon was estimated by multiplying energy consumption by a carbon coefficient that reflected the amount of carbon per unit of energy for each fuel. The resulting quantities are potential emissions, or the maximum amount of carbon that could potentially be released to the atmosphere if all carbon in the fuels were converted to CO_2. Potential emissions by sector and fuel type are given in Rows H-L of Table A-1, with total potential emissions provided in Row M. The carbon coefficients used in the U.S. inventory are given in Row G of Table A-1 and Table A-1A. These carbon coefficients are estimates derived by EIA from detailed fuel information and are similar to the carbon coefficients contained in the IPCC's default methodology, with modifications reflecting fuel qualities specific to the U.S.

3. *Estimate the amount of carbon stored in products.*

Depending on end use, non-fuel uses of fossil energy can result in storage of some or all of the carbon contained in the energy product for some period of time. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon contained in the petroleum feedstock for extended periods of time. Other non-fuel products, such as lubricants or plastics, also store carbon, but can lose or emit some of this carbon when they are used and/or burned as waste after utilization.

The amount of carbon sequestered or stored in non-fuel uses of fossil fuel energy products was based on data concerning the end uses and ultimate fate of various energy products, with all non-fuel use attributed to the industrial and transportation sectors. This non-fuel consumption is presented in Rows A and B of Table A-2. Non-fuel consumption was then multiplied by a carbon coefficient (Row C of Table A-2) to obtain the carbon content of the fuel, or the maximum amount of carbon that could potentially be sequestered if all the carbon in the fuel were stored in non-fuel products. Values for the total amount of carbon that could be stored are given in Rows D and E of Table A-2. Carbon content was then multiplied by the fraction of carbon actually sequestered in products (Row F of Table A-2), resulting in the final estimate of carbon sequestration by sector and fuel type in Rows G-H of Table A-2. Total sequestered carbon is provided in Row I of Table A-2. Assumptions of the proportion of carbon sequestered were based on IPCC (1994; Vol. 3) and U.S. specific estimates by EIA. Subtracting carbon sequestered from potential emissions results in net potential carbon emissions (Row A of Table A-3).

4. *Adjust for carbon that does not oxidize during combustion.*

Since combustion processes are not 100 percent efficient, some of the carbon contained in fuels would not be emitted to the atmosphere. Rather, it remains stored as soot or other byproducts of inefficient combustion. The estimated fraction of carbon not oxidized in U.S. energy conversion processes due to inefficiencies during the combustion process ranges from one percent for oil and coal to 0.5 percent for gas. Except for coal these assumptions are consistent with the default values recommended by the IPCC. In the U.S. unoxidized carbon from coal combustion was estimated to be no more than one percent (Bechtel, 1993). Row B of Table A-3 presents fractions oxidized by fuel type. Row C of the same table gives the actual net emissions once oxidation has been considered (but prior to adding emissions from territories or subtracting emissions from bunker fuels).

5. *Account for fuel consumed in U.S. Territories*

EIA's energy use data for the U.S. includes only the 50 U.S. states and the District of Columbia. The data reported for the U.S. by international agencies, such as the International Energy Agency (IEA), includes consumption in the U.S. territories. To account for this difference, emission estimates for the U.S. territories were computed separately and added to domestic emissions from fossil fuel combustion for energy. Energy consumption data from U.S. territories are presented in Rows A-G of Table A-4. They are reported in thousands of barrels per day, except for coal, which is reported in thousands of short tons. To calculate territory emissions, it was necessary to convert consumption in barrels per day and short tons to units of annual energy consumption by multiplying the physical units with appropriate conversion factors from EIA (EIA, 1994b), which are presented in Row H. The resulting energy consumption by territory is given in Rows I-N of Table A-4, with total consumption in all territories provided in Row O.

The remaining calculations for territories followed the same procedure used for the consumption of fuels in the fifty States, *i.e.* estimation of carbon content and adjustment for the fraction of carbon not oxidized (see Rows P-Y of Table A-4). Once these calculations were completed, actual emissions from territories (Row Y) were added to actual emissions from the fifty States (see Row D of Table A-3).

6. *Subtract emissions from bunker fuels.*

According to the decision reached at INC-9, emissions from international transport activities, or bunker fuels, should not be included in national totals. There is international disagreement as to which countries are responsible for these emissions, and until this issue is resolved, countries are to report these emissions separately. EIA data include bunker fuels (primarily residual oil) as part of consumption by the transportation sector. To compensate for this, bunker fuel emissions were calculated separately and subtracted from total net emissions. The calculations for bunker fuel emissions followed the same procedures used for consumption of all fossil fuels in the United States (*i.e.*, estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized). These calculations are summarized in Table A-5. Total emissions from bunker fuels were then subtracted from actual net emissions from domestic fuel consumption (see Row E of Table A-3). Bunker fuel emissions were allocated to the transportation sector.

7. *Summarize emission estimates.*

Table A-6 summarizes actual CO_2 emissions in the U.S. by major consuming sector (*i.e.*, residential, commercial, industrial, transportation, and electric utilities) and major fuel type (*i.e.*, coal, natural gas, and oil). Adjustments for bunker fuels and carbon sequestered in products have already been made. Emissions are expressed in terms of million metric tons of carbon equivalent (MMTCE), except in the last column and row of Table A-6, which shows carbon dioxide emissions on a full molecular weight basis (Column E and Row H).

Table A-7 summarizes U.S. carbon dioxide emissions by end-use sector. To determine these estimates, emissions from the electric utility sector were distributed over the four end use sectors according to their share of electricity consumed. Column A presents electricity consumption by end-use sector, which was used to calculate the fraction of total electricity consumed by each of the four end-use sectors (Column B). This fraction was then multiplied by total emissions from the utility sector from Table A-6, Column D, resulting in the portion of utility emissions attributable to each end-use sector (Column D). These end use emissions from electricity consumption were then added to the non-utility emission estimates taken from Table A-6 (Column E), resulting in emissions from each of the four end-use sectors (Column F).

II. Estimating Carbon Dioxide Emissions Using the Top-Down Methodology

It is possible to estimate carbon emissions from fossil fuel consumption using alternative methodologies and/or different data sources than those described above. For example, the IPCC recommends a "top-down" (carbon balance) approach for estimating carbon dioxide emissions (see *Greenhouse Gas Inventory Workbook* (IPCC/OECD, 1994; Vol. 3)). This method estimates fossil fuel consumption by adjusting national aggregate production data for imports, exports, and stock changes rather than relying on end-user surveys. The operating principle is that once carbon is brought into a national economy, it is either saved in some way (*e.g.*, stored in products, kept in fuel stocks, or left unoxidized in ash) or released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required. The following discussion provides the detailed calculations for estimating CO_2 emissions for the U.S. using the IPCC-recommended "top-down" methodology.

1. *Collect and Assemble Data in Proper Format*

To ensure the comparability of national inventories, the IPCC has recommended that inventories report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected from several DOE/EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes.[1] These data are presented in the appropriate format in Table A-8.

The carbon content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of CO_2 emissions, fuel statistics should be provided on an energy basis (*e.g.*, Btu's or joules). Because detailed fuel statistics are typically provided in physical units (as in Table A-8), they must first be converted to units of energy before carbon emissions can be calculated. Fuel statistics were converted to their energy equivalents by using conversion factors provided by DOE/EIA (EIA, 1991d; EIA, 1993d). These factors are listed in Table A-9. The resulting fuel statistics (in trillion Btu) are provided in Rows A-E of Table A-10.

2. *Estimate Apparent Fuel Consumption*

The next step of the IPCC method is to estimate "apparent consumption" of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and adjusting for stock changes. In this way, carbon enters an economy through energy production and imports (and *decreases* in fuel stocks) and is transferred out of the country through exports (and *increases* in fuel stocks). Thus, apparent consumption of primary fuels (including crude oil, natural gas liquids, coking coal, steam coal, subbituminous coal, lignite, and natural gas) can be calculated as follows:

Production + Imports − Exports − Stock Change

Flows of secondary fuels (*e.g.*, gasoline, residual fuel, coke) should be added to primary apparent consumption. The *production* of secondary fuels, however, should be ignored in the calculations of apparent consumption since the carbon contained in these fuels is already accounted for in the supply of primary fuels from which they were derived (*e.g.*, the estimate for apparent consumption of crude oil already contains the carbon from which gasoline would be refined). Flows of secondary fuels should therefore be calculated as follows:

Imports − Exports − Stock Change

Note that this calculation can result in negative numbers for apparent consumption. This is a perfectly acceptable result since it merely indicates a net export or stock increase in the country of that fuel *when domestic production is not considered.*

The IPCC-recommended default methodology calls for estimating apparent fuel consumption *before* converting to a common energy unit. However, certain primary fuels in the U.S. (*e.g.*, natural gas and steam coal) have separate conversion factors for production, imports, exports, and stock changes. In these cases, it is not appropriate to multiply apparent consumption by a single conversion factor since each of its components have different heat contents. Therefore, U.S. fuel statistics were converted to their heat equivalents first, followed by the estimation of apparent consumption. The results are provided in Row F of Table A-10.

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[1] For the U.S., national aggregate energy statistics typically exclude data on the U.S. territories. As a result, national statistics were adjusted to include production, imports, exports, and stock changes within the U.S. territories.

3. *Estimate Carbon Emissions*

Once apparent consumption is estimated, the remaining calculations are virtually identical to those for the bottom-up approach (see Section I above). That is:

- Potential carbon emissions are estimated using fuel-specific carbon emission factors (see Table A-11).[2]
- The carbon sequestered in non-fuel uses of fossil fuels (*e.g.*, plastics or asphalt) is then estimated and subtracted from the total amount of carbon (see Table A-12).
- The carbon contained in bunker fuels is subtracted from the remaining amount of carbon to obtain net carbon emissions (Rows C and D in Table A-13).[3]
- Finally, to obtain actual carbon emissions, net carbon emissions are adjusted for any carbon that remains unoxidized as a result of incomplete combustion (*e.g.*, carbon contained in ash or soot; see Rows E and F in Table A-13).[4]

4. *Convert to CO_2 Emissions*

Because the IPCC reporting guidelines recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating CO_2 emissions from fossil fuel consumption is converting from units of carbon to units of CO_2. Actual carbon emissions were multiplied by the molecular to atomic weight ratio of CO_2 to carbon (44/12) to obtain total carbon dioxide emitted from fossil fuel combustion. The results are contained in Row G of Table A-13.

III. Comparison Between The Two Methods

These two alternative methods can both produce reliable estimates that are comparable within a few percent. The major difference between these methods lies in the energy data used to derive carbon emissions (*i.e.*, actual reported consumption for the bottom-up methodology vs.

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[2] Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coking coal, steam coal, coke, and natural gas liquids, the IPCC-recommended emission factors were used in the top-down calculations for these fuels.

[3] Bunker fuels refer to quantities of fuels used for international transportation. The IPCC methodology accounts for these fuels as part of the energy balance of the country in which they were *delivered* to end-users. Thus, CO_2 emissions from the combustion of those fuels are attributed to the country of delivery even though most of the actual emissions may occur outside its boundaries. This is done to ensure that all fuel is accounted for in the methodology. For informational purposes, the IPCC methodology originally recommended that emissions from bunker fuels be estimated separately, but not subtracted from the national total. However, at the 9th session of the INC, it was recommended that countries report bunker fuel emissions separately and exclude these emissions from the national total.

[4] For the portion of carbon that is unoxidized during coal combustion, the IPCC suggests a global average value of 2 percent. However, because combustion technologies in the U.S. are more efficient, the U.S. inventory uses 1 percent in its calculations.

apparent consumption derived for the top-down methodology). In theory, both approaches should yield the same results. In practice, however, slight discrepancies may occur. For the U.S. these differences are discussed below.

1. *Differences in Total Amount of Energy Consumed*

The following table summarizes the differences between the two methods in estimating total energy consumption in the U.S.

Energy Consumption in the U.S.: Bottom-Up Versus Top-Down Methodology
(Trillion Btu)

	Coal	**Gas**	**Oil**	**TOTAL**[b]
Bottom-Up[a]	18,943	19,348	34,001	72,291
Top-Down[a]	18,882	19,297	33,009	71,189
Difference	*+0.3%*	*+0.3%*	*+2.9%*	*+1.5%*

a. Includes U.S. territories. Totals may not equal sum of components due to independent rounding.
b. Totals presented may not equal the sum of the individual source categories due to independent rounding.

Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the bottom-up methodology provides an energy total that is about 1.5 percent higher than the top-down methodology. The greatest difference lies in the higher amount of oil consumption estimated using the bottom-up methodology. There are several potential sources for these discrepancies:

- Product Definitions: The fuel categories in the top-down approach are different than the bottom-up categories, particularly for petroleum. For example, the top-down approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly, but refined into other products. As a result, the U.S. does not focus on estimating the energy content of crude oil, but rather estimating the energy content of the various products from the crude oil refining process. The U.S. does not believe that estimating apparent consumption for crude oil, and the resulting energy content of the crude oil, is the most reliable method for the U.S. for estimating energy consumption. Other differences in product definition include using sector specific coal statistics in the bottom-up approach (*i.e.*, residential, commercial, industrial coking, industrial other, and transportation coal), while the top-down method uses coking coal and steam coal (steam coal consists of both anthracite and bituminous coal). Also, the LPG used in the bottom-up calculations is actually a combination of the NGL and LPG statistics used in the top-down methodology.

- Heat Equivalents: It can be difficult to obtain heat equivalents for certain fuel types, particularly for categories such as "crude oil" where the key statistics are derived from thousands of producers in the U.S. and abroad. Similarly, for the top-down methodology, the U.S. used a weighted average for steam coal based on the fraction of production that is anthracite and bituminous because the U.S. does not typically estimate the energy content of a "steam coal" category. However, this overstates the bituminous fraction of the steam coal because a portion of bituminous production is also part of coking coal.

- Possible inconsistencies in U.S. Energy Data: The U.S. has not focused its energy data collection efforts on obtaining the type of aggregated information used in the top-down methodology. Rather, the U.S. believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the U.S. to obtain reliable energy data.

- Balancing Item: The top-down method uses *apparent* consumption estimates while the bottom-up method uses *reported* consumption estimates. While these numbers should be equal, there always seems to be a slight difference that is often accounted for in energy statistics as a "balancing item."

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of CO_2. The following table summarizes the differences between the two methods in potential carbon emissions.

Potential Carbon Emissions in the U.S.: Bottom-Up Versus Top-Down Methodology[a]
(MMT Carbon)

	Coal	Gas	Oil	TOTAL
Bottom-Up[b]	485	280	671	1,436
Top-Down[b]	491	279	654	1,424
difference	*-1.2%*	*+0.3%*	*+2.5%*	*0.8%*

a. This comparison is based on potential carbon emissions rather than actual net emissions. The two methods are identical from this point forward since the carbon sequestered calculation and the amount oxidized are the same for both methods.

b. Includes U.S. territories.

As previously shown, the bottom-up methodology resulted in a 1.5 percent higher estimate of energy consumption in the U.S. than the top-down methodology, but the resulting estimate of carbon emissions was only 0.8 percent higher. Since natural gas figures were consistently higher in the bottom-up methodology and the oil figures showed only a small variation, the major source of the difference was due to coal estimates, where the bottom-up method yielded coal consumption that was slightly higher and emissions that were lower than in the top-down method. Potential reasons for these patterns may include:

- Product Definitions: Coal data is aggregated differently in each methodology, as noted above, with U.S. coal data typically collected in the format used the bottom-up methodology. This results in more accurate estimates than in the top-down methodology. Also, the top-down methodology relies on a "crude oil" category for determining petroleum-related emissions. Given the many sources of crude oil in the U.S., it is not an easy matter to track potential differences in carbon content between different sources of crude, particularly since information on the carbon content of crude oil is not regularly collected.

- Carbon Coefficients: The top-down methodology relies on several default carbon coefficients provided by IPCC (IPCC\OECD, 1994; Vol. 2), while the bottom-up methodology uses category specific coefficients that are likely to be more accurate. For example, in the top-down methodology default coefficients are used for coking coal, steam coal, coke and natural gas liquids. Also, as noted above, the carbon coefficient for crude oil is not an easy value to obtain given the many sources of crude oil for the U.S.

Although the two estimates using different methodologies are fairly close, the U.S. believes that the bottom-up methodology provides a more accurate assessment of CO_2 emissions for the U.S. This is largely a result of the data collection techniques used in the U.S., where there has been more emphasis on obtaining the detailed, products-based information used in the bottom-up methodology than obtaining the aggregated energy flow data used in the top-down methodology. However, the U.S. believes that it is important to understand fully the reasons for the differences between the two methods. At this time the U.S. is actively involved in evaluating the reasons for these differences. The U.S. will continue to work with the IPCC/OECD Greenhouse Gas Emission Inventory Programme as further information becomes available.

Table A-1: POTENTIAL CARBON EMISSIONS FROM ENERGY CONSUMPTION - 1990

Row	Sector	COAL								NATURAL GAS	PETROLEUM											TOTAL
		Res Coal	Comm Coal	Industrial Coking Coal	Industrial Other Coal	Coke Imports	Trans Coal	Utility Coal	Total Coal	Total Natural Gas	Asphalt& Road Oil	Aviation Gasoline	Distillate Fuel	Jet Fuel	Kerosene	LPG	Lubricants	Motor Gasoline	Residual Fuel	Other Petroleum	Total Petroleu	
	Fossil Fuel Consumption for Energy (Trillion Btu)																					
A	Residential	61.9							61.9	4534.4			837.4		63.9	365.0					1266.3	5862.6
B	Commercial		92.9						92.9	2707.5			487.0		11.8	64.4		110.6	233.1		906.9	3707.3
C	Industrial			1041.8	1648.00	4.8			2694.6	8549.4	1170.2		1180.9		12.3	1607.7	186.3	184.1	417.2	3559.2	8317.9	19562.0
D	Transportation						0.0		0.0	684.8		45.0	3830.5	3129.5		21.8	176.0	13577.1	1030.2		21810.1	22494.9
E	Utilities							16087.8	16087.8	2871.4			86.3						1139.4	24.7	1250.4	20209.6
F	TOTAL	61.9	92.9	1041.8	1648.0	4.8	0.0	16087.8	18937.2	19347.5	1170.2	45.0	6422.1	3129.5	88.0	2058.9	362.3	13871.8	2819.9	3583.9	33551.6	71836.4
	Carbon Coefficients (MMT/Quadrillion Btu)																					
G		26.05	26.05	25.46	25.47	27.85	NC	25.57		14.47	20.62	18.87	19.95	19.74	19.72	17.16	20.24	19.41	21.49	see Table A-1A		
	Potential Emissions from Consumption of Fossil Fuel for Energy (MMTCE)																					
H	Residential	1.6	0.0	0.0	0.0	0.0	0.0	0.0	1.6	65.6	0.0	0.0	16.7	0.0	1.3	6.3	0.0	0.0	0.0		24.2	91.5
I	Commercial	0.0	2.4	0.0	0.0	0.0	0.0	0.0	2.4	39.2	0.0	0.0	9.7	0.0	0.2	1.1	0.0	2.1	5.0		18.2	59.8
J	Industrial	0.0	0.0	26.5	42.7	0.1	0.0	0.0	69.3	123.7	24.1	0.0	23.6	0.0	0.2	27.6	3.8	3.6	9.0	72.0	163.8	356.8
K	Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	0.0	0.8	76.4	61.8	0.0	0.4	3.6	263.5	22.1		428.7	438.6
L	Utilities	0.0	0.0	0.0	0.0	0.0	0.0	411.4	411.4	41.5	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	24.5	0.7	26.9	479.8
M	TOTAL	1.6	2.4	26.5	42.7	0.1	0.0	411.4	484.7	280.0	24.1	0.8	128.1	61.8	1.7	35.3	7.3	269.3	60.6	72.7	661.8	1426.5

Sources: Coal consumption is from EIA (1994h and 1994b) as described in Rypinski (1994). Disaggregated "Other Petroleum" consumption was drawn form EIA, 1990-93b and converted to enregy units using thermal conversion factors from EIA (1994b). All remaing consumption data is from EIA, 1994b. Carbon Coefficients are derived by EIA based on detailed, fuel specific information (EIA, 1994g).

Note:
1. NC = Not Calculated
2. The above data include bunker fuels but do not include Puerto Rico and U.S. Territories.
3. Relatively small quantities of synthetic natural gas (64.1 TBtu) are produced from lignite coal and incorporated into the natural gas pipline. Since carbon from synthetic gas is accounted for in natural gas consumption, its consumption is deducted from coal consumption to avoid double-counting this carbon. Emission factors of 25.47 and 14.47 are used to convert the coal and synthetic gas numbers respectively.

Table A-2: CARBON SEQUESTRATION FROM NON-FUEL USE OF FOSSIL FUELS - 1990

	Consumption for Non-Fuel Use (Trillion Btu)														
A	Industrial	20.0	290.0	1090.0		Note 3			1280.0	190.0		Note 3	1350.0	3910.0	4220.0
B	Transportation									180.0				180.0	180.0
C	Carbon Coefficient (MMT/Quadrillion Btu)	25.46	14.47	20.62	18.87	19.95	19.74	19.72	17.16	20.24	19.41	21.49	see Table A-1A		
	Carbon Content (MMTCE)														
D	Industrial	0.5	4.2	22.5	0.0	0.0	0.0	0.0	22.0	3.8	0.0	0.0	27.9	76.2	80.9
E	Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	0.0	0.0	3.6	3.6
F	Fraction Sequestered	0.75	1.00	1.00					0.80	0.50			see Table A-1A		
	Carbon Sequestered (MMTCE)														
G	Industrial	0.4	4.2	22.5	0.0	0.0	0.0	0.0	17.6	1.9	0.0	0.0	17.3	59.2	63.8
H	Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	1.8	1.8
I	TOTAL	0.4	4.2	22.5	0.0	0.0	0.0	0.0	17.6	3.7	0.0	0.0	17.3	61.1	65.6

Sources: All non-fuel use is from Table 1.15 of Annual Energy Review 1993 (EIA, 1994h). The percents sequestered are from IPCC/OECD (1994; Vol. 1) and EIA estimates described in Rypinski (1994).

Notes:
1. The data above do not include Puerto Rico and U.S. Territories.
2. Since all non-fuel use of coal is coking coal the carbon coefficient for coal is the same as that for coking coal. All other carbon coefficients are the same as those used for energy combustion in Table A-1.
3. Residual and Distillate Fuels have small non-fuel uses which are included in the "Other "Wax/Misc" category of Table A1-A.

Table A-3: NET EMISSIONS FROM FOSSIL FUEL CONSUMPTION FOR ENERGY - 1990

		Coal	Natural Gas	Petroleum	Total
A	Net Carbon Emissions (MMTCE)	484.4	275.8	600.7	1360.8
B	Fraction Oxidized	0.990	0.995	0.990	
C	Actual Emissions (MMTCE)	479.5	274.4	594.7	1348.6
D	Actual Emissions from Territories (MMTCE)	0.1	-	9.0	9.1
E	Actual Emissions from Bunker Fuels (MMTC	-	-	22.6	22.6
	Total Actual Emissions from Fossil Fuel Consumption for Energy (MMTCE)				
F		479.6	274.4	581.1	1335.1

Source: The fraction oxidized for coal is from Bechtel (1993). Natural gas and petroleum fractions are from the IPCC methodology (IPCC/OECD, 1994; Vol. 1). All other information was drawn from Tables A-1, A-2, A-4, and A-5.

TABLE A-1A: EMISSIONS OF OTHER PETROLEUM FROM ENERGY CONSUMPTION - 1990

Other Petroleum Consumption (in Trillion Btu)

Row	Sector	AvGas Blend Components	Crude Oil	MoGas Blend Components	Misc. Products	Naphtha (<401 deg. F)	Other Oil (>401 deg. F)	Pentanes Plus	Petrochemical Feed	Petroleum Coke	Still Gas	Special Naphtha	Unfinished Oils	Waxes	Other Wax/Misc	TOTALS
A	Residential															0.00
B	Commercial															0.00
C	Industrial	0.24	50.88	53.70	137.83	347.80	753.92	250.32	Note 2	719.90	1473.21	107.09	-368.96	33.30	Note 3	3559.23
D	Transportation															0.00
E	Utilities									24.70						24.70
F	TOTAL	0.24	50.88	53.70	137.83	347.80	753.92	250.32	0.00	744.60	1473.21	107.09	-368.96	33.30	0.00	3583.93
G	**Carbon Coef. (MMT/QBtu)**	18.87	20.29	19.41	20.31	18.14	19.95	18.24	19.37	27.85	17.51	19.86	20.21	19.81	19.81	

Potential Emissions from Other Petroleum (in MMT)

Row	Sector	AvGas Blend Components	Crude Oil	MoGas Blend Components	Misc. Products	Naphtha (<401 deg. F)	Other Oil (>401 deg. F)	Pentanes Plus	Petrochemical Feed	Petroleum Coke	Still Gas	Special Naphtha	Unfinished Oils	Waxes	Other Wax/Misc	TOTALS
H	Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	Commercial	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J	Industrial	0.00	1.03	1.04	2.80	6.31	15.04	4.57	0.00	20.05	25.80	2.13	-7.46	0.66	0.00	71.97
K	Transportation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L	Utilities	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.00	0.69
M	TOTAL	0.00	1.03	1.04	2.80	6.31	15.04	4.57	0.00	20.74	25.80	2.13	-7.46	0.66	0.00	72.66

Sequestration from Non-Fuel use of Other Petroleum

Row	Sector	AvGas Blend Components	Crude Oil	MoGas Blend Components	Misc. Products	Naphtha (<401 deg. F)	Other Oil (>401 deg. F)	Pentanes Plus	Petrochemical Feed	Petroleum Coke	Still Gas	Special Naphtha	Unfinished Oils	Waxes	Other Wax/Misc	TOTALS
N	Non-Fuel Use (TBtu)				Note 3	Note 2	Note 2		820.00	190.00		110.00		Note 3	230.00	1350.00
O	Carbon Coef. (MMT/QBtu)	18.87	20.29	19.41	20.31	18.14	19.95	18.24	19.37	27.85	17.51	19.86	20.21	19.81	19.81	
P	Carbon Content (MMTCE)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.88	5.29	0.00	2.18	0.00		4.56	27.92
Q	Fraction Sequestered								0.80	0.00		0.00			1.00	
R	Carbon Sequestered (MMTC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.71	0.00	0.00	0.00	0.00	0.00	4.56	17.26

Source: Other petroleum consumption is from EIA (1990-93b and 1994b). Carbon coefficients are from EIA (1994g).

Notes:
1. The "Petrochemical Feed" category reports aggregate non-fuel use data for Naphtha (<401 deg. F) and Other Oil (>401 deg. F). Energy Consumption for these products is given separately in the appropriate columns.
2. The "Other Wax/Misc" category reports aggregate non-fuel use data for Residual Fuel, Distillate Fuel, Waxes, and Miscellaneous Products. Energy Consumption for these products is given separately in the appropriate columns.
3. Their are four standard products in the "Other Petroleum" category which do not appear in this table because they exhibited no consumption during the period from 1990 to 1993. These are "Natural Gasoline," "Petrochemical Feed Still Gas," "Plant Condensate," and "Unfractionated Stream."

Table A-4: CO2 EMISSIONS FROM FOSSIL FUEL CONSUMPTION FOR ENERGY IN U.S. TERRITORIES - 1990

		COAL (1000 Short Tons)	PETROLEUM (1000 Barrels per day)								TOTAL
Row	TERRITORY	Total Coal	Distillate Fuel Oil	Jet Fuel & Kerosene	LPG	Lubricants	Motor Gasoline	Residual Fuel Oil	Other Petroleum	Total Petroleum	
	Territory Consumption of Fossil Fuel for Energy										
A	American Samoa		2.6	0.7	0.0	0.0	0.3	-	0.1	3.7	
B	Guam		4.8	5.1	0.2	0.0	2.3	0.2	0.1	12.7	
C	Puerto Rico		21.5	12.4	2.4	0.3	45.7	36.8	21.0	140.1	
D	U.S. Virgin Islands		4.5	4.7	7.7	0.0	3.9	16.0	18.2	55.0	
E	Other U.S. Pacific Island		1.1	0.4	0.0	0.0	0.5	0.0	0.0	2.0	
F	Wake Island		0.3	7.4	-	-	-	-	0.9	8.6	
G	TOTAL	220.0	34.8	30.7	10.3	0.3	52.7	53.0	40.3	222.1	NA
	Conversion Factors (Btu/Short Ton and Million Btu/Barrel)										
H		24.4	5.825	5.670	4.011	6.065	4.620	6.287	5.796		
	Territory Consumption of Fossil Fuel for Energy (trillion Btu)										
I	American Samoa		5.5	1.4	0.0	0.0	0.5	0.0	0.2	7.7	
G	Guam		10.2	10.6	0.3	0.0	3.9	0.5	0.2	25.6	
K	Puerto Rico		45.7	25.7	3.5	0.7	77.1	84.4	44.4	281.5	
L	U.S. Virgin Islands		9.6	9.7	11.3	0.0	6.6	36.7	38.5	112.4	
M	Other U.S. Pacific Island		2.3	0.8	0.0	0.0	0.8	0.0	0.0	4.0	
N	Wake Island		0.6	15.3	0.0	0.0	0.0	0.0	1.9	17.9	
O	TOTAL	5.4	74.0	63.5	15.1	0.7	88.9	121.6	85.3	449.0	454.4
	Carbon Coefficients (MMT/Quadrillion Btu)										
P		25.14	19.95	19.74	17.16	20.24	19.41	21.49	20.31		
	Territory Emissions from the Consumption of Fossil Fuel for Energy (MMTCE)										
Q	American Samoa		0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	
R	Guam		0.2	0.2	0.0	0.0	0.1	0.0	0.0	0.5	
S	Puerto Rico		0.9	0.5	0.1	0.0	1.5	1.8	0.9	5.7	
T	U.S. Virgin Islands		0.2	0.2	0.2	0.0	0.1	0.8	0.8	2.3	
U	Other U.S. Pacific Island		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	
V	Wake Island		0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.4	
W	TOTAL	0.1	1.5	1.3	0.3	0.0	1.7	2.6	1.7	9.1	9.2
S	Fraction Oxidized	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990		
	Actual Emissions from Territories (MMTCE)										
Y		0.1	1.5	1.2	0.3	0.0	1.7	2.6	1.7	9.0	9.1

Sources: All consumption data is from EIA (1992c). The thermal conversion factors for petroleum were taken from Appendix D of the State Energy Data Report 1992 (EIA, 1994b). The thermal conversion factor for coal was derived by EIA as described in Rypinski (1994). Carbon coefficients are the same as used for U.S. energy emissions in Table A-1 (the coal coefficient is for bituminous coal).

Notes:
1. As defined by EIA, "Petroleum Other" includes asphalt, coke, aviation gasoline, naphthas, paraffin wax, petrochemical feedstocks, unfinished oils, white spirits, blending components, and miscellaneous production. All territory consumption of "Other Petroleum" fell into the "Miscellaneous Production" category. A conversion factor of 5.796 million Btu per barrel for this category is given in Appendix D of the State Energy Data Report 1992 (EIA, 1994b). The carbon coefficient for this category is the same as that given for "Miscellaneous Products," in Table A-1-A.
2. "-" indicates consumption is less than 50 barrels per day, and thus not reported.
3. NA = Not Applicable
4. The conversion from barrels per day to trillion Btu is done as follows: (1000 barrels/day)(365 days/year)(millionBtu/Barrel)(1 trillionBtu/10^6 millionBtu)

Table A-5: EMISSIONS FROM BUNKER FUEL CONSUMPTION - 1990

		FUEL			
Row	TERRITORY	Jet Fuel	Residual Fuel Oil	Distillate Fuel Oil & Other Products	TOTAL
	Bunker Fuel Consumption (1000 Barrels)				
H	TOTAL	NA	113880.0	19345.0	
	Conversion Factors (Million Btu/Barrel)				
I		NA	6.287	5.825	
	Bunker Fuel Consumption (Trillion Btu)				
Q	TOTAL	263.8	716.0	112.7	1092.4
	Carbon Coefficients (MMT/QBtu)				
R		19.74	21.49	19.95	
	Emissions from Bunker Fuel Consumption (MMTCE)				
Z	TOTAL	5.2	15.4	2.2	22.8
AA	**Fraction Oxidized**	0.990	0.990	0.990	
	Actual Emissions from Bunker Fuel Consumption (MMTCE)				
BB		5.2	15.2	2.2	22.6

Sources: Residual and distillate fuel consumption are form EIA (1992c). Jet fuel consumption is from ORNL (1993). The barrels to Btu conversion factors are from EIA (1994b). Carbon coefficients are the same as used in Table A-1.

Table A-6: Summary of U.S. Emissions - 1990

	Column	A	B	C	D	E
Row	Sector	Coal (MMTCE)	Natural Gas (MMTCE)	Petroleum (MMTCE)	Total (MMTCE)	Total (MMTCO2)
A	Residential	1.6	65.3	24.0	90.9	333.2
B	Commercial	2.4	39.0	18.0	59.4	217.8
C	Industrial	68.3	118.9	103.5	290.7	1065.9
D	Transportation	0.0	9.9	399.9	409.8	1502.6
E	Utilities	407.3	41.3	26.6	475.2	1742.5
F	U.S. Territories	0.1	0.0	9.0	9.1	33.4
G	TOTAL	479.6	274.4	581.1	1335.1	4895.4
H	TOTAL (MMTCO2)	1758.7	1006.1	2130.7	4895.4	

Sources: Tables A-1 through A-3

Note: Bunker Fuels account for emissions of 24.6 MMTCE and are already subtracted in the above table.

Table A-7: END USE SECTOR EMISSIONS COMPARISON - 1990

Column	A	B	C	D	E	F
Sector	Electricity Consumption (Bkwhrs)	Fraction of Total Consumption	Utility Emissions (MMTCE)	Emissions from Electricity Consumption (MMTCE)	Non-Electricity Emissions (MMTCE)	Total Sector Emissions (MMTCE)
Residential	924.0	0.3406	475.2	161.9	90.9	252.7
Commercial	839.0	0.3093	475.2	147.0	59.4	206.4
Industrial	946.0	0.3487	475.2	165.7	290.7	456.4
Transportation	4.0	0.0015	475.2	0.7	409.8	410.5
U.S.Territories	0.0	0.0000	475.2	0.0	9.1	9.1
TOTAL	2713.0	1.0		475.2	859.9	1335.1

Sources: Electricity consumption by sector is from Tables 13-16 of State Energy Data Report, 1992 (EIA, 1994b). All other information is taken from Tables A-1 and A-2.

Table A-8. U.S. Energy Statistics -- Physical Units, 1990

	SOLID FUELS (1000 Short Tons)						Natural Gas (10^6 cubic feet)	Liquid Fuels (000 Barrels)												
	Coking Coal	Steam Coal	Sub-bit. Coal	Lignite	Coke	Total Solids		Crude Oil	Nat. Gas Liquids	Feedstocks	Gasoline	Kerosene	Jet Fuel	Gas/ Diesel	Residual Oil	LPG	Naphtha	Petroleum Coke	Other Oil	Total Liquids
Production	102,801	591,142	244,274	88,090	27,620	1,053,927	17,809,674	2,684,687	568,999	29,253	2,585,261	17,011	560,023	1,101,795	390,741	186,190	70,504	201,660	406,633	8,802,757
Imports		2,699			760	3,459	1,532,259	2,286,190	52,281	124,920	127,704	953	29,187	79,036	162,606	19,732	16,866	731	75,097	2,975,303
Exports	63,459	42,344			570	106,373	85,565	4,366	10,886	0	20,248	2,003	15,773	42,699	78,568	4,313	4,591	80,207	22,717	286,371
Stockchange	465	32,400				32,865	512,934	(10,068)	9,816	(6,738)	4,415	378	9,072	26,931	4,764	4,749	(492)	(1,419)	(3,403)	38,005
Bunkers														11,770	134,929					146,699

Sources: Coal data are from Coal Production 1990 (EIA, 1991b), Coal Data: A Reference (EIA, 1991a), and Quaterly Coal Report (EIA, 1993c). Natural gas data are from Natural Gas Annual 1990 (EIA, 1991d). Petroleum data are from Petroleum Supply Annual 1990 (1991e) and International Energy Annual 1991 (EIA, 1992).

Note: "Other Oil" includes lubricants, waxes, asphalt and road oil, miscellaneous products, and other oils for petrochemcial feedstock use. Jet Fuel and Gasoline are aggregate categories. Jet Fuel includes naphtha type fuel and kerosene type fuel. Gasoline contains motor gasoline and aviation gasoline.

Table A-9. Conversion Factors to Energy Units (Heat Equivalents)

	SOLID FUELS (Million Btu/Short Ton)						Natural Gas (10^6 Btu/cubic foot)	Liquid Fuels (Million Btu/Barrel)											
	Coking Coal	Steam Coal	Sub-bit. Coal	Lignite	Coke			Crude Oil	Nat. Gas Liquids	Feedstocks	Gasoline	Kerosene	Jet Fuel	Gas/ Diesel	Residual Oil	LPG	Naphtha	Petroleum Coke	Other Oil
Production	26.799	23.968	17.508	12.692	24.800		1,031	5.800	3.822	5.825	5.253 & 5.048	5.670	5.355 & 5.670	5.825	6.287	3.625	5.248	6.024	5.796
Imports	26.799	23.974	17.508	12.692	24.800		1,012	5.800	3.822	5.825	5.253 & 5.048	5.670	5.355 & 5.670	5.825	6.287	3.625	5.248	6.024	5.796
Exports	26.799	23.974	17.508	12.692	24.800		1,018	5.800	3.822	5.825	5.253 & 5.048	5.670	5.355 & 5.670	5.825	6.287	3.625	5.248	6.024	5.796
Stockchange	26.799	23.974	17.508	12.692	24.800		1,030	5.800	3.822	5.825	5.253 & 5.048	5.670	5.355 & 5.670	5.825	6.287	3.625	5.248	6.024	5.796
Bunkers	26.799	23.974	17.508	12.692	24.800									5.825	6.287				

Sources: Anthracite heat equivalents are from Quaterly Coal Report (EIA, 1994c). Other heat equivalents are from State Energy Data Report 1992 (EIA, 1994b) and Natural Gas Annual 1990 (EIA, 1991d).

Note: Heat equiavlents for steam coal are weighted averages of the heat equivalents for anthracite and bituminous coal. Similarly, Gasoline has two components (Motor Gasoline and Aviation Gasoline), Jet Fuel has two components (Kerosene and Nphtha Type Jet Fuels), and Naphtha has two components (Naptha for Feedstock and Special Naphtha).

Table A-10. U.S. Apparent Consumption of Fossil Fuels, 1990

Row		SOLID FUELS (Trillion Btu)						Natural Gas (Trillion Btu)	Liquid Fuels (Trillion Btu)												
		Coking Coal	Steam Coal	Sub-bit. Coal	Lignite	Coke	TOTAL Solids		Crude Oil	Nat. Gas Liquids	Feedstocks	Gasoline	Kerosene	Jet Fuel	Gas/ Diesel	Residual Oil	LPG	Naphtha	Petroleum Coke	Other Oil	TOTAL Liquids
A	Production	2,755	14,168	4,277	1,118	685	23,003	18,362	15,571	2,175	170	13,579	96	3,155	6,418	2,457	675	370	1,215	2,513	17,916
B	Imports		65			19	84	1,551	13,260	200	728	671	5	165	460	1,022	72	89	4	446	17,122
C	Exports	1,701	1,015			14	2,730	87	25	42	0	106	11	89	249	494	16	24	483	306	1,845
D	Stockchange	12	777				789	528	(58)	38	(39)	23	2	51	157	30	17	(3)	(9)	(22)	188
E	Bunkers													264	69	848					1,181
F	Apparent Consumption	1,042	12,441	4,277	1,118	5	18,882	19,297	28,864	2,295	937	541	(8)	24	55	498	39	67	(470)	162	33,006

TOTAL ENERGY:	71,185

Table A-11. Potential Carbon Emissions

	SOLID FUELS (MMTCE)						Natural Gas (MMTCE)	Liquid Fuels (MMTCE)												
	Coking Coal	Steam Coal	Sub-bit. Coal	Lignite	Coke	TOTAL Solids		Crude Oil	Nat. Gas Liquids	Feedstocks	Gasoline	Kerosene	Jet Fuel	Gas/ Diesel	Residual Oil	LPG	Naphtha	Petroleum Coke	Other Oil	TOTAL Liquids
Apparent Consumption	1,042	12,441	4,277	1,118	5	18,882	19,297	28,864	2,295	937	541	(8)	24	55	498	39	67	(470)	162	33,005
Carbon Coeff.	25.86	25.86	26.24	26.62	29.57		14.47	20.29	15.24	20.21	19.41	19.72	19.74	19.95	21.49	17.16	18.14	27.85	Various	
Potential Carbon Emis.	**27**	**322**	**112**	**30**	**0**	**491**	**279**	**586**	**35**	**19**	**11**	**(0)**	**0**	**1**	**11**	**1**	**1**	**(13)**	**3**	**654**
																			TOTAL CARBON:	1,424

Sources: Carbon coefficients for coal are IPCC default values converted to Btu's and lower heat value (IPCC\OECD, 1994; Vol. 2). Gas and petroleum coefficients are from EIA (1994g).

Notes: Gasoline has two components (Motor Gasoline and Aviation Gasoline), Jet Fuel has two components (Kerosene and Nphtha Type Jet Fuels), and Naphtha has two components (Naptha for Feedstock and Special Naphtha).

Table A-12. Estimating Carbon Stored in Products

	Coal	Natural Gas	Liquid Fuels							TOTAL
			Asphalt & Road Oil	LPG	Lubricants	Petro. Feedstocks	Petroleum Coke	Special Naphtha	Waxes	
Consumption for Non-Fuel Use (trillion Btu)	20.0	290.0	1,170.0	1,280.0	370.0	820.0	230.0	110.0	230.0	4,520.0
Carbon Coefficients	25.46	14.47	20.62	17.16	20.24	19.37	27.85	19.86	19.81	
Carbon Content (MMTCE)	0.5	4.2	24.1	22.0	7.5	15.9	6.4	2.2	4.6	87.3
Fraction Sequestered	0.75	1.00	1.00	0.80	0.50	0.80	0.00	0.00	1.00	
Carbon Sequestered (MMTCE)	**0.4**	**4.2**	**24.1**	**17.6**	**3.7**	**12.7**	**0.0**	**0.0**	**4.6**	**67.3**

Table A-13 Net Emissions from Fossil Fuel Consumption (MMTCE)

		Fuel Type			TOTAL
row		Coal	Oil	Gas	
A	Potential C Emissions	491	654	279	1,424
B	Carbon Sequestered	0	63	4	67
C	Bunker Fuels		25		25
D	Net C Emissions	490	567	275	1,332
E	Fraction Oxidized	0.99	0.99	0.995	
F	**Actual C Emissions**	**486**	**561**	**274**	**1,320**
G	**CO2 Emissions**	**1,780**	**2,057**	**1,003**	**4,840**

ANNEX B
EMISSIONS FROM MOBILE COMBUSTION

Greenhouse gas emissions from mobile sources in this section are reported by transport mode (*i.e.*, road, rail, air), vehicle type, and fuel type. The emissions estimates for NO_x, NMVOCs, and CO (U.S. criteria pollutants) in this section were taken directly from the U.S. EPA's *National Air Pollutant Emissions Trends, 1900 - 1992* (U.S. EPA, 1993b). This EPA report provides emission estimates for these gases by sector and fuel type using a "top down" estimating procedure: the emissions were calculated either for individual sources or for many sources combined using basic activity data (such as amount of fuel delivered, or miles travelled) as indicators of emissions.

Estimates for methane and nitrous oxide emissions from mobile combustion were calculated by multiplying the appropriate emission factors provided in OECD (1991) by the source numbers of each activity level. National activity data for individual source categories were obtained from a number of publications from U.S. agencies. Depending on the source category, these basic activity data may include fuel consumption or deliveries, total vehicle miles travelled, etc. Activity data used in conjunction with emission factors relate the quantity of emissions to the activity.

Estimates of NMVOCs, NO_x, and CO Emissions From Mobile Combustion

Estimates of NMVOCs, NO_x, and CO emissions from gasoline and diesel-powered motor vehicles reported by EPA (1993b) are based upon vehicle miles traveled (VMT) and emission factors. For NMVOCs, NO_x, and CO, emission factors were obtained from the MOBILE4 model, a model used by the U.S. EPA as a tool for estimating exhaust and running loss emissions from highway vehicles in nonattainment areas and urban air sheds. The emission factors developed by the Organization for Economic Co-Operation and Development of the IPCC (OECD, 1991) were derived from data used in this model. The MOBILE4 model requires information on ambient temperature, vehicle speeds, gasoline volatility, and other variables for emission calculation.

Emissions of NMVOCs, NO_x, and CO from aircraft reported by EPA (1993b) are based on the number of take-offs and landings reported by the Federal Aviation Administration (FAA, 1990-92 and 1992) and AP-42 emission factors for various types of aircraft.[4] Average emission factors were calculated which take into account the national mix of different types of aircraft used for general aviation, military, and commercial purposes.

Emissions from railroads are calculated by EPA based on diesel, coal, and residual fuel consumption by railroads, as reported by the Energy Information Administration (EIA) of the U.S. Department of Energy (U.S. DOE; EIA, 1993c). Average emission factors that are applicable to each type of fuel were used.

Emissions from vessels operating inside the U.S. boundaries are based on:

- diesel, residual fuel, and coal consumption data reported by the

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[4] Emission occurring when aircraft are above 3,000 feet are not included in these estimates.

U.S. Department of Energy (U.S. DOE)

- marine gasoline sales data reported by U.S. Department of Transportation (U.S. DOT)
- national boat and motor registration and usage factors
- AP-42 emission factors

Emissions from coal-fired vessels were based on an average emission factor for coal combustion in boilers. Emissions from off-highway vehicles were calculated from estimated fuel use (based on each equipment subcategory, population data, and an annual fuel use factor) along with fuel deliveries of diesel and gasoline reported by the U.S. DOE and U.S. DOT.

Estimates of CH_4 and N_2O Emissions From Mobile Combustion

Estimates of CH_4 and N_2O emissions from gasoline vehicles (motorcycles excepted) were determined by multiplying the appropriate emission factors provided in OECD (1991) by the source numbers of each activity level (the distance traveled by each vehicle category and emission control type). The source number of each activity level was determined from:

- travel fraction of each model year (the fraction of the vehicle miles travelled or VMT attributed to a particular model year)
- distribution of control technology in each model year
- total vehicle miles travelled by each vehicle category.

Data were obtained from the U.S. EPA's National Vehicle and Fuel Emissions Laboratory (Brezinski *et al.,* 1992; Carlson, 1994; Nizich, 1994; U.S. EPA, 1992b) and the U.S. Department of Transportation (FAA, 1990-1992; FAA, 1992; U.S. DOT, 1993). Data for all gasoline vehicles are presented in Table B-1. Given the uncertainty underlying these estimates, an arbitrary uncertainty range of ± 50 percent was assigned to the resulting emission totals.

Table B-1. Gasoline Vehicle Data

Data Category	Passenger Cars	Light Duty Trucks 1	Light Duty Trucks 2	Heavy Duty Vehicles
VMT (10^6 Miles)	1,503,000	323,000	157,000	33,000
3-Way Catalyst	45%	36%	30%	6%
Oxi-3-Way Catalyst	32%	17%	15%	0%
Oxi-Catalyst	18%	14%	14%	9%
Non-Catalyst	2%	2%	3%	35%
Uncontrolled	4%	31%	39%	50%

Source:
1. VMT are from U.S. Department of Transportation, Federal Highway Administration, and U.S. EPA (Brezinski, 1992).
2. Distribution of control technologies are calculated from U.S. EPA data (Brezinski, 1992).

Because the travel fraction and control technology data for diesel vehicles and motorcycles are currently not available from the U.S. EPA, emissions for these vehicle types were calculated as a range by multiplying the total source activity level (i.e., the total vehicle miles travelled) available from the U.S. EPA by the high (uncontrolled) and low (advanced) emission factors provided for each category (OECD, 1991). The emission estimate reported in the inventory for diesel vehicles and motorcycles is the midpoint of this range. The data used are included in Table B-2.

Table B-2. Diesel Vehicle and Motorcycle Data

Vehicle Type	Vehicle Miles Travelled (10^6 Miles)
Diesel Passenger Cars	12,000
Light Duty Diesel	4,000
Heavy Duty Diesel	106,000
Motorcycles	11,000

Source: U.S. Department of Transportation, Federal Highway Administration and U.S. EPA (Brezinski, 1992).

Emissions from locomotives and off-highway vehicles were calculated using (1) emissions factors from OECD (1991) and (2) estimated consumption by vehicle and fuel type (Brezinski, *et. al.;* Carlson, 1994; Nizich, 1994; FAA, 1990-92 and 1992; and U.S. DOT, 1993). Emissions from (marine) vessels were calculated using (1) U.S. EPA data on quantity and type of fuel used and emissions factors provided for bunkers and boats (OECD, 1991). Emissions from aircraft were estimated using (1) emission factors[5] (OECD, 1991) and (2) fuel use by subcategory (U.S. DOT, 1992; FAA 1990-92 and 1992). The data used are included in Tables B-3 and B-4.

Table B-3. Data for Bunkers, Boats, and Locomotives

Fuel Category	Fuel Quantity (U.S. Gallons)		
	Residual	Diesel	Other
Bunkers	4,686,100,000	549,200,000	NA
Boats	1,562,000,000	1,647,000,000	1,300,400,000[a]
Locomotives	28,000,000	3,210,100,000	+

Source: U.S. EPA (Brezinski, 1992).
Notes: a. Gasoline.
"+" Denotes insignificant; "NA" denotes not applicable.

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[5] N_2O emission for jet and turboprop were not available from OECD.

ANNEX C
ESTIMATION OF 1990 METHANE EMISSIONS FROM ENTERIC FERMENTATION IN CATTLE AND FROM ANIMAL MANURE MANAGEMENT

This annex presents a detailed explanation of the methodologies and data used to estimate 1990 methane emissions from enteric fermentation in cattle and from animal manure management. This information is provided in order to enable the reader to verify the emission estimates presented in Part 4 of the inventory. All of the information contained in this annex is taken from U.S. EPA (1993a), to which the reader is referred for more detail.

Methane Emissions from Enteric Fermentation in Cattle

To estimate 1990 methane emissions from enteric fermentation in cattle, detailed analyses of rumen digestion and animal production were performed using a mechanistic model of cattle digestion. This model, originally described in Baldwin et al. (1987), explicitly models the fermentation of feed within the rumen, and estimates the amount of methane formed and emitted as a result. Since the original model of Baldwin et al. was developed for application to lactating cows, it was revised to enable evaluations of a wider range of animal types, sizes, and stages of maturity, as well as a wider range of diets.

To apply the model, representative cattle types and diets for five geographic regions of the U.S. were defined. The cattle type categories represent the different sizes, ages, feeding systems, and management systems that are typically found in the U.S. Representative diets were defined for each category of cattle, reflecting the diversity of diets that are found in each of the five regions (Figure C-1). Each cattle type within each region was evaluated using the model, resulting in emission factors (kilograms CH_4/head/year) for each type in each region.

The following animal types were defined for the cattle population:

Dairy Animal Types
- Replacement heifers 0-12 months of age[1]
- Replacement heifers 12-24 months of age
- Mature dairy cows (over 24 months of age)

Beef Animal Types
- Replacement heifers 0-12 months of age
- Replacement heifers 12-24 months of age
- Mature beef cows (over 24 months of age)
- Weanling system heifers and steers[2]

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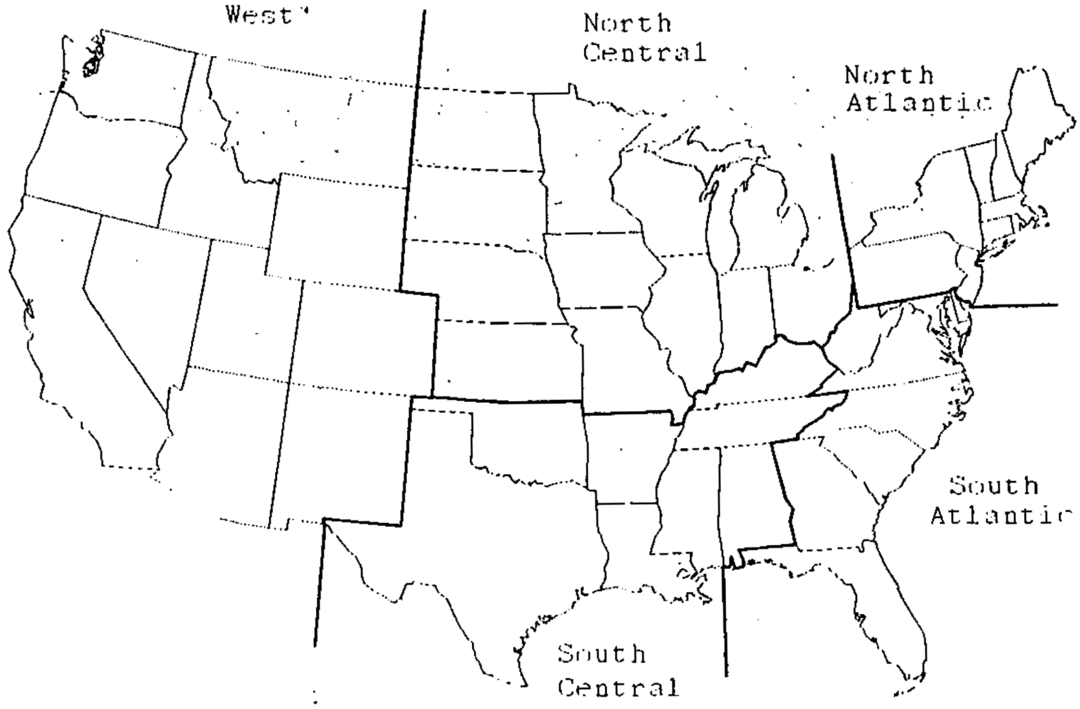
[1] "Replacements" are the offspring that are retained to replace mature cows that die or are removed from the herd (culled) each year.

[2] In "weanling systems", calves are moved directly from weaning to confined feeding programs. This system represents a very fast movement of cattle through to marketing for slaughter. Weanling system cattle are marketed at about 420 days of age (14 months).

Figure C-1: Geographic Regions Used in the Analysis



* Includes Alaska and Hawaii

Source: U.S. EPA (1993a)

Yearling system heifers and steers[3]
Mature bulls

Due to their small number, mature dairy bulls were not evaluated. Dairy calves that are not kept as replacements are generally fed for slaughter. Therefore, these animals were included in the total for weanling and yearling system heifers and steers (*i.e.*, heifers and steers grown for slaughter). Tables C-1 and C-2 summarize the size, age, and production characteristics used to simulate each of the representative animal types.

A total of 32 different diets were defined to represent the diverse feeds and forages consumed by cattle in the U.S. Fourteen diets were defined for dairy cattle: six for dairy cows and four each for replacement heifers 0-12 months and 12-24 months. Eighteen diets were defined for beef cattle: three each for beef cows, replacements 0-12 months, weanling system heifers and steers, and yearling system heifers and steers; four for replacements 12-24 months; and two for beef bulls.

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[3] "Yearling systems" represent a relatively slow movement of cattle through to marketing for slaughter. These systems include a wintering over, followed by a summer of grazing on pasture. Yearling system cattle are marketed at 565 days of age (18.8 months).

Table C-1. Representative Animal Characteristics: Heifers and Cattle Fed for Slaughter

Animal Type	Initial Weight (kg)[a]	Final Weight (kg)	Initial Age (days)	Final Age (days)	Other
Replacement Heifers:					
Dairy Replacement Heifers: 0-12 months	170	285	165	365	--
Dairy Replacement Heifers: 12-24 months	285	460	365	730	Pregnant
Beef Replacement Heifers: 0-12 months	165	270	165	365	--
Beef Replacement Heifers: 12-24 months	270	390	365	730	Pregnant
Feedlot Fed Cattle for Slaughter:					
Yearling System[b]	170	480	165	565	fed to 26-27% carcass fat
Weanling System[c]	170	480	165	422	fed to 29-30% carcass fat

a All weights reported as empty body weight.
b Includes 260 day stocker period principally on forages and a 140 day feedlot period with a high grain ration.
c Includes a 257 day feeding period; initially at 30 to 50 percent concentrate (125 days), followed by 132 days of a high grain ration.

Source: U.S. EPA (1993a)

Table C-2. Representative Animal Characteristics: Dairy Cows and Beef Cows

Animal Type	Initial and Final Weight (kg)[a]	Lactation/Dry Periods (days)	Milk Production/ Lactation (kg)	Other
Dairy Cows	550	305/60	5,570-7,190[b]	Pregnant
Beef Cows	450	205/160	1,400	Pregnant
Beef Bulls	650	NA	NA	NA

a All weights reported as empty body weight.
b Milk production per lactation varies by region.

Source: U.S. EPA (1993a)

To derive emission factors for each of the cattle types in each region, the extent to which each diet is used in each region was specified for each cattle type. For example, in the North Atlantic region, it was estimated that one third of the mature dairy cows are fed Dairy Cow Diet 1, one third Dairy Cow Diet 3, and one third Dairy Cow Diet 5 (Table C-3). The specification of the regional diet mixes was based on comments from cattle experts in different regions throughout the U.S. and on data on regional feed availability.

Table C-3. Dairy Cow Diet Descriptions

	Lactating Cow Diets					
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6
Description	50% alfalfa hay, 50% corn-SBM[a] concentrate	60% alfalfa hay, 40% corn-cottonseed meal concentrate (15% CP)[b]	69% corn silage, 16% corn meal, 14% SBM	50% alfalfa hay, 50% barley-SBM concentrate	40% timothy hay, 45% corn meal, 15% SBM-cane molasses concen.	Early timothy hay supplemented to 14.5% CP
ME (Mcal/kg)	2.61	2.56	2.65	2.57	2.69	2.41
Regional Distribution of Diets[c]						
North Atlantic	33%		33%		33%	
South Atlantic	40%				30%	30%
North Central	50%		50%			
South Central		33%			33%	33%
West		75%		25%		

[a] SBM = soybean meal

[b] CP = crude protein

[c] Regional distributions show the extent to which each diet is simulated to be used in each region. The percentages for each region sum to 100 percent.

Source: U.S. EPA (1993a)

The regional emission factors for mature dairy cows were estimated by applying the cattle digestion model to the average diet and the average annual milk production per head in each region (Table C-4). For the other dairy cattle types and all of the beef cattle types, emission factors were simulated for each of the defined diet types, and then using the diet percentages assigned for each region, weighted average emission factors were calculated for each animal type in each region. The statistics used in these simulations, and the resultant regional emission factors are summarized in Tables C-5 through C-11.

Table C-4. Regional Estimates of Methane Emissions from Mature Dairy Cows Statistics for the Average Animal Modeled

	N. Atlantic	S. Atlantic	N. Central	S. Central	West
Feed consumed per year (kg DM)	5735	5460	5805	5182	6032
ME[a] consumed per year (Mcal)	15,224	13,421	15,012	12,975	15,190
Diet ME (Mcal/kg)	2.65	2.46	2.59	2.50	2.52
Average feed digestibility (%)[b]	68	66	66	64	66
Methane emissions per year (kg/cow)	117.5	126.5	109.4	114.8	119.3
Milk Production per cow per year (kg)	6710	6110	6830	5570	7190
Methane emissions per kg of milk produced (g/kg)	17.5	20.7	16.0	20.6	16.6

a ME = metabolizable energy

b Digestibility is reported as simulated digestible energy divided by gross energy intake.

Note: Regional diets are weighted averages of the diets shown in Table C-3.

Source: U.S. EPA (1993a)

To estimate national emissions for each cattle type, the regional emission factors were multiplied by regional populations of each type (Tables C-12 and C-13). For all but the feedlot cattle, the average 1990 regional populations were taken from published statistics (Schoeff and Castaldo, 1991; USDA, 1992a). Emission factors for the feedlot fed cattle (*i.e.*, for yearling system and weanling system cattle) are based on the entire model simulation period, which is greater than 365 days for both systems. Therefore, the yearling system and weanling system cattle populations were derived from 1990 slaughter statistics (USDA, 1992b; CF Resources, 1991). National emissions from the entire cattle population are estimated by summing the emission estimates for all cattle types.[4]

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[4] The total number of cattle marketed for slaughter from feedlots in 1990 was estimated at 26.3 million. This figure was used to estimate emissions from feedlot fed cattle assuming that 80% of the cattle were produced using the yearling system and 20% were produced using the weanling system. Using the

Table C-5. Regional Estimates of Emissions from Dairy Replacement Heifers: 0-12 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4
Diet Description	Alfalfa hay	75% alfalfa hay, 25% concen.[a]	High quality grass forage (CP=18%)[b]	Corn silage with protein to 14% CP
Feed consumed per year (kg DM)	1116	1080	967	904
ME[c] consumed (Mcal)	2623	2684	2613	2432
Diet ME (Mcal/kg)	2.35	2.48	2.70	2.69
Average feed digestibility (%)[d]	62	65	67	69
Methane emissions (kg/head/yr)	21.4	20.0	20.1	14

Regional Distribution of Diets (%)[e]					Emissions (kg/head/yr)
North Atlantic	25%		60%	15%	19.5
South Atlantic	33%		67%		20.5
North Central	25%		50%	25%	18.9
South Central	15%		85%		20.3
West	50%	25%	25%		20.7

a Concentrate of corn meal and soybean meal
b CP = crude protein
c ME = metabolizable energy
d Digestibility is reported as simulated digestible energy divided by gross energy intake.
e Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

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simulated lifetimes for the yearling system cattle (565 days) and the weanling system cattle (422 days), the implied total annual average population of cattle needed to support this level of feedlot fed cattle slaughter is estimated as 38.6 million as follows:

$$\frac{(80\%\,yearling\,system \times 565\,days) + (20\%\,weanling\,system \times 422\,days)}{365\,days} \times 26.3\,million = 38.6\,million$$

When added to the annual average populations for the other cattle types, the total annual average U.S. cattle population is estimated at 103.8 million, which is consistent with the January 1 and July 1 population estimates reported by USDA (1992a) for 1990. This method for estimating the population and emissions from feedlot fed cattle is appropriate because the population of feedlot fed cattle has been stable in recent years.

Table C-6. Regional Estimates of Emissions from Dairy Replacement Heifers: 12-24 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4	
Diet Description	Alfalfa hay	75% alfalfa hay, 25% concen.[a]	Grass forage of declining quality[b]	Corn silage with protein to 14% CP[c]	
Feed consumed per year (kg DM)	3184	3018	3172	2540	
ME[c] consumed (Mcal)	7419	7437	7183	6801	
Diet ME (Mcal/kg)	2.33	2.46	2.25	2.68	
Average feed digestibility (%)[d]	62	64	58	67	
Methane emissions (kg/head/yr)	63.0	57.3	61.4	47.9	
Regional Distribution of Diets (%)[f]					Emissions (kg/head/yr)
North Atlantic	25%		50%	25%	58.4
South Atlantic	25%	10%	45%	20%	58.7
North Central	33%		33%	33%	57.4
South Central	20%		80%		61.7
West	50%	25%	25%		61.2

a Concentrate of corn and cottonseed meal

b High quality grass forage for 100 days (ME=2.8 Mcal/kg). Intermediate quality grass forage for 100 days (ME=2.5 Mcal/kg). Lower quality grass forage for 165 days (ME=2.1 Mcal/kg).

c CP = crude protein

d ME = metabolizable energy

e Digestibility is reported as simulated digestible energy divided by gross energy intake.

f Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table C-7. Regional Estimates of Methane Emissions from Beef Cows Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	Pasture for 7 mos; mixed hay for 5 mos[a]	Pasture of varying quality[b]	Pasture with 4 mos of supplement[c]	
Feed consumed per year (kg DM)	3029	3172	2700	
ME[d] consumed (Mcal)	7370	7731	7047	
Diet ME (Mcal/kg)	2.43	2.44	2.61	
Average feed digestibility (%)[e]	63	63	65	
Methane emissions (kg/head/yr)	63.4	71.7	53.7	
Regional Distribution of Diets (%)[f]				Emissions (kg/head/yr)
North Atlantic	80%		20%	60.5
South Atlantic	20%	80%		70.0
North Central	60%		40%	59.5
South Central	10%	90%		70.9
West	10%	80%	10%	69.1

[a] Seven months of pasture declining in quality as the seasons progress. Five months of mixed hay, grass with some legumes.

[b] Pasture quality varies with the seasons.

[c] Pasture with four months of supplementation using a mixed forage (80 percent) and concentrate (20 percent) supplement.

[d] ME = metabolizable energy

[e] Digestibility is reported as simulated digestible energy divided by gross energy intake.

[f] Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table C-8. Regional Estimates of Emissions from Beef Replacements: 0-12 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	Legume pasture with supplement[a]	Very high quality grass (18% CP)[b]	Corn silage supplemented to 14% CP	
Feed consumed per year (kg DM)	984	1011	922	
ME[c] consumed (Mcal)	2443	2614	2454	
Diet ME (Mcal/kg)	2.48	2.58	2.66	
Average feed digestibility (%)[d]	65	68	68	
Methane emissions (kg/head/yr)	18.1	27.2	15.8	
Regional Distribution of Diets (%)[e]				Emissions (kg/head/yr)
North Atlantic	50%	20%	30%	19.2
South Atlantic	50%	50%		22.7
North Central	33%	33%	33%	20.4
South Central	40%	60%		23.6
West	50%	50%		22.7

a Concentrate = 25 percent of ration

b CP = Crude protein

c ME = metabolizable energy

d Digestibility is reported as simulated digestible energy divided by gross energy intake.

e Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table C-9. Regional Estimates of Emissions from Beef Replacement Heifers: 12-24 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4	
Diet Description	Varying quality grass forage[a]	Varying quality grass forage[b]	Varying quality grass with winter supplement[c]	Varying quality grass with winter supplement[d]	
Feed consumed per year (kg DM)	2454	2675	2359	2305	
ME[e] consumed (Mcal)	6356	6524	5990	6000	
Diet ME (Mcal/kg)	2.59	2.49	2.54	2.60	
Average feed digestibility (%)[f]	67	66	66	67	
Methane emissions (kg/head/yr)	66.9	71.0	56.5	54.8	
Regional Distribution of Diets (%)[g]					Emissions (kg/head/yr)
North Atlantic		50%	50%		63.8
South Atlantic	50%	40%	10%		67.5
North Central		33%	33%	33%	60.8
South Central	80%	20%			67.7
West	33%	33%	33%		64.8

a 165 days of high quality grass followed by 200 days of intermediate quality grass.

b 120 days of high quality grass followed by 125 days of intermediate quality grass -- grass hay provided for 120 days during winter

c 120 days of high quality grass followed by 125 days of intermediate quality grass -- medium quality alfalfa with a corn:soybean meal concentrate (25 percent) provided for 120 days during winter

d 120 days of high quality grass followed by 125 days of intermediate quality grass -- corn silage supplemented to 14 percent CP provided for 120 days during winter

e ME = metabolizable energy

f Digestibility is reported as simulated digestible energy divided by gross energy intake.

g Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table C-10. Regional Estimates of Emissions from Feedlot Fed Cattle: Yearling System Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	All diets include forages during the stocker phase followed by high grain diets during feedlot feeding[a]			
Feed consumed per year (kg DM)	2865	2775	2755	
ME[b] consumed (Mcal)	7588	7383	7366	
Diet ME (Mcal/kg)	2.65	2.66	2.67	
Average feed digestibility (%)[c]	67	67	68	
Methane emissions (kg/head/yr)	50.0	54.1	52.9	
Adjustment for ionophores and hormone implants	90%	90%	90%	
Methane emissions (kg/head/yr)	45.0	48.7	47.6	
Regional Distribution of Diets (%)[d]				Emissions (kg/head/yr)
North Central	30%	20%	50%	47.0
South Central			100%	47.6
West	20%	50%	30%	47.6

[a] All three diets include a high quality mixed hay (legume and grass) for the first winter (90 days). The three diets then include:

Diet 1: mixed pasture (legume and grass) to 425 days of age; 50 percent alfalfa:50 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

Diet 2: grass pasture to 425 days of age; 50 percent alfalfa:50 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

Diet 3: grass pasture to 425 days of age; 70 percent corn silage:30 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

[b] ME = metabolizable energy

[c] Digestibility is reported as simulated digestible energy divided by gross energy intake.

[d] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages. Only the three regions with feedlots are shown.

Source: U.S. EPA (1993a)

Table C-11. Regional Estimates of Emissions from Feedlot Fed Cattle: Weanling System Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3
Diet Description	All diets include mixed rations with increasing amounts of high grain concentrates[a]		
Feed consumed per year (kg DM)	1935	1763	1742
ME[b] consumed (Mcal)	5232	5184	5059
Diet ME (Mcal/kg)	2.70	2.94	2.90
Average feed digestibility (%)[c]	68	71	71
Methane emissions (kg/head/yr)	31.2	25.3	25.4
Adjustment for ionophores and hormone implants	85%	85%	85%
Methane emissions (kg/head/yr)	26.5	21.5	21.6

Regional Distribution of Diets (%)[d]				Emissions (kg/head/yr)
North Central	20%	20%	60%	22.6
South Central	50%	50%		24.0
West	40%	30%	30%	23.5

[a] The following diets were simulated:
Diet 1: 60 percent alfalfa:40 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.
Diet 2: 50 percent alfalfa:50 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.
Diet 3: 69 percent corn silage:31 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.

[b] ME = metabolizable energy

[c] Digestibility is reported as simulated digestible energy divided by gross energy intake.

[d] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages. Only the three regions with feedlots are shown.

Source: U.S. EPA (1993a)

Table C-12. Methane Emissions From Enteric Fermentation in U.S. Dairy Cattle

Region/Animal Type	Emissions Factor (kg/head/yr)	Population (000 Head)	Emissions (Tg/yr)
North Atlantic			
Replacements 0-12 months	19.5	712	0.014
Replacements 12-24 months	58.4	712	0.042
Mature Cows	117.5	1,795	0.211
South Atlantic			
Replacements 0-12 months	20.5	268	0.005
Replacements 12-24 months	58.7	268	0.016
Mature Cows	126.5	710	0.090
North Central			
Replacements 0-12 months	18.9	1,987	0.038
Replacements 12-24 months	57.4	1,987	0.114
Mature Cows	109.4	4,497	0.492
South Central			
Replacements 0-12 months	20.3	405	0.008
Replacements 12-24 months	61.7	405	0.025
Mature Cows	114.8	1,156	0.133
West			
Replacements 0-12 months	20.7	833	0.017
Replacements 12-24 months	61.2	833	0.051
Mature Cows	119.3	1,972	0.235
National Total			
Replacements 0-12 months	19.6	4,205	0.082
Replacements 12-24 months	58.8	4,205	0.247
Mature Cows	114.6	10,130	1.161
Total	80.4	18,540	1.490

Source: U.S. EPA (1993a)

Methane Emissions from Animal Manure Management

Estimates of 1990 methane emissions from animal manure management were derived using the approach of Safley et al. (1992a). This approach is as follows:

(1) Estimate annual methane emissions for each animal type *i* and manure system *j* in each state *k*:

$$TM_{ijk} = N_{ik} \times TAM_i \times vs_i \times B_{0i} \times MCF_{jk} \times WS\%_{ijk}$$

Where TM_{ijk} = annual methane emissions for each animal type *i* and manure management system *j* in each state *k*
N_{ik} = number of animals of type *i* in state *k*
TAM_i = typical animal mass of animal *i*
vs_i = average annual volatile solids production per unit of animal mass for animal *i*
B_{0i} = maximum methane producing capacity of the manure of animal *i*
MCF_{jk} = the methane conversion factor of the manure system *j* in the state *k*
$WS\%_{ijk}$ = the percent of animal *i*'s manure managed in manure system *j* in state *k*

(2) Estimate total annual methane emissions for animal *i* by summing annual emissions over all applicable manure management systems *j* and states *k*.

(3) Estimate total annual methane emissions from all animals by summing over all animal types *i*.

Table C-13. Methane Emissions From Enteric Fermentation in U.S. Beef Cattle

Region/Animal Type	Emissions Factor (kg/head/yr)	Population (000 Head)[a]	Emissions (Tg/yr)
North Atlantic			
Replacements 0-12 months	19.2	87	0.002
Replacements 12-24 months	63.8	87	0.006
Mature Cows	61.5	337	0.021
South Atlantic			
Replacements 0-12 months	22.7	594	0.013
Replacements 12-24 months	67.5	594	0.040
Mature Cows	70.0	3,418	0.239
North Central			
Replacements 0-12 months	20.4	1,546	0.032
Replacements 12-24 months	60.8	1,546	0.094
Mature Cows	59.5	10,592	0.630
Weanling System Steers/Heifers[b]	22.6	2,963	0.067
Yearling System Steers/Heifers	47.0	11,852	0.557
South Central			
Replacements 0-12 months	23.6	2,079	0.049
Replacements 12-24 months	67.7	2,079	0.141
Mature Cows	70.9	12,359	0.876
Weanling System Steers/Heifers	24.0	1,164	0.028
Yearling System Steers/Heifers	47.6	4,656	0.222
West			
Replacements 0-12 months	22.7	1,229	0.028
Replacements 12-24 months	64.8	1,229	0.080
Mature Cows	69.1	6,772	0.468
Weanling System Steers/Heifers	23.5	1,133	0.027
Yearling System Steers/Heifers	47.6	4,532	0.216
Bulls: Nationally	100.0	2,200	0.220
National Total			
Replacements 0-12 months	22.3	5,535	0.124
Replacements 12-24 months	65.0	5,535	0.360
Mature Cows	66.7	33,478	2.234
Weanling System Steers/Heifers	23.1	5,260	0.122
Yearling System Steers/Heifers	47.3	21,040	0.994
Bulls	100.0	2,200	0.220
Total[d]	47.5	85,398[c]	4.054

a Population for slaughter steers and heifers in each region is the number slaughtered annually.

b The emissions from Yearling and Weanling System steers and heifers are assigned to the regions in which they are managed in feedlots.

c The national population is estimated using the average annual population of Yearling and Weanling System cattle: 38.65 million. See text.

d Total may not add due to rounding.

Source: U.S. EPA (1993a)

To implement this methodology, twenty types of animals were defined for the U.S., and data were collected on the 1990 populations of each animal type in each state, their typical animal mass, and their average annual volatile solids production per unit of animal mass. These data and their sources are listed in Table C-14. The cattle populations and weights are equal to those used in the previous section of this annex to estimate emissions from enteric fermentation.[5]

The maximum amount of methane that can be produced per kilogram of volatile solids, or the maximum methane producing capacity of each animal's manure (B_0), varies by animal type and diet. Appropriate B_0 values were chosen from the scientific literature depending on the typical diet of each animal type. For animal types without B_0 measurements, the B_0 was estimated based on similarities with other animals and the experience of the authors of Safley et al. (1992a). Table C-15 lists the values selected for the analysis.

The extent to which the maximum methane producing capacity of each animal's manure is realized, or the methane conversion factor (MCF), depends upon the management system and climate conditions in which the manure is managed. Ten categories of manure management systems were identified for the U.S., and based upon estimates in the scientific literature and research sponsored by U.S. EPA, MCFs for each system were identified (Table C-16). The MCF for each management system in each state was calculated by:

- estimating the average monthly temperature in each climate division of each state;[6]
- estimating the MCF value for each month using the average temperature data and the MCF values listed in Table C-16;
- estimating the annual MCF by averaging the monthly division estimates; and
- estimating the state-wide MCF by weighting the average MCF for each division by the fraction of the state's dairy population represented in each division.[7]

Table C-17 summarizes the resultant MCF estimates by management system for each state.

Livestock manure management system usage in the U.S. was determined by obtaining information from Extension Service personnel in each state. The U.S. was divided into eleven geographic regions based on similarities of climate and livestock production. For states that did not provide information, the regional average manure system usage was assumed. The results are summarized in Table C-18.

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[5] Tables C-1 and C-2 (in the enteric fermentation section) list weights on an empty body weight basis. These values were converted to live weight for purposes of estimating emissions from animal manure management.

[6] The average temperature in each climate division of each state was calculated for the normal period of 1951 to 1980 using the National Climatic Data Center time-bias corrected Historical Climatological Series Divisional Data (NCDC, 1991).

[7] The dairy populations in each climate division were estimated using the dairy population in each county (Bureau of the Census, 1987) and detailed county and climate division maps (NCDC, 1991). Using the dairy population as a weighting factor may slightly over or underestimate the MCFs for other livestock populations.

Table C-14. U.S. Animal Populations, Average Size, and VS Production

Animal Type		Population[a,b] N_i	Typical Animal Mass (TAM_i)[c] Kg	Manure per day[d] (kg/day per 1000 kg mass)	
				Total Manure	Volatile Solids vs_i
Feedlot Beef Cattle	Steers/Heifers	10,088,000	415	58	7.2
Other Beef Cattle	Calves	36,040,000	180	58	7.2
	Heifers	5,535,0000	360	58	7.2
	Steers	2,162,000	360	58	7.2
	Cows	33,478,000	500	58	7.2
	Bulls	2,200,000	720	58	7.2
	Total	79,205,000			
Dairy Cattle	Heifers	4,205,000	410	86	10
	Cows	10,130,000	610	86	10
	Total	14,335,000			
Swine	Market	48,259,000	46	84	8.5
	Breeding	7,040,000	181	84	8.5
	Total	55,299,000			
Poultry[c]	Layers	355,469,000	1.6	64	12
	Broilers	951,914,000	0.7	85	17
	Ducks	7,000,000	1.4	107	18.5
	Turkeys	53,783,000	3.4	47	9.1
Other	Sheep	10,639,000	70	40	9.2
	Goats	2,396,000	64	41	9.5
	Donkeys	4,000	300	51	10
	Horses and Mules	2,405,000	450	51	10

[a] Population data for swine, poultry, and sheep from USDA (1989a-f). Goat and horse population data from Bureau of Census (1987). Population data for cattle are the same as those used to estimate emissions from enteric fermentation in cattle in 1990. Population data as of January 1, 1988 for poultry, and sheep and as of December 1, 1987 for swine, goats, and horses. Cattle populations represent an average for 1990.

[b] Broiler/turkey populations estimated yearly based on number of flocks per year (North 1978; Carter 1989).

[c] Source: Taiganides and Stroshine (1971).

[d] Source: ASAE (1988).

Source: U.S. EPA (1993a)

Table C-15. Maximum Methane Producing Capacity Adopted For U.S. Estimates

Animal Type, Category		Maximum Potential Emissions (B_o)	Reference
Cattle:	Beef in Feedlots	0.33	Hashimoto et al. (1981)
	Beef Not in Feedlots	0.17	Hashimoto et al. (1981)
	Dairy	0.24	Morris (1976)
Swine:	Breeder	0.36	Summers & Bousfield (1980)
	Market	0.47	Chen (1983)
Poultry:	Layers	0.34	Hill (1982 & 1984)
	Broilers	0.30	Safley et al. (1992a)
	Turkeys	0.30	Safley et al. (1992a)
	Ducks	0.32	Safley et al. (1992a)
Sheep:	In Feedlots	0.36	Safley et al. (1992a)
	Not in Feedlots	0.19	Safley et al. (1992a)
Goats:		0.17	Safley et al. (1992a)
Horses, Mules, and Donkeys:		0.33	Ghosh (1984)

Source: U.S. EPA (1993a)

Table C-16. Methane Conversion Factors for U.S. Livestock Manure Systems

MCFs based on laboratory measurement	MCF at 30°C	MCF at 20°C	MCF at 10°C
Pasture, Range, Paddocks[a]	2 %	1.5 %	1 %
Liquid/Slurry[a]	65 %	35 %	10 %
Pit Storage < 30 days[a]	33 %	18 %	5 %
Pit Storage > 30 days[a]	65 %	35 %	10 %
Drylot[b]	5 %	1.5%	1 %
Solid Storage[a]	2 %	1.5 %	1 %
Daily Spread[a]	1 %	0.5 %	0.1 %
MCF measured by long term field monitoring	**Average Annual MCF**		
Anaerobic Lagoons[c]	90 %		
MCFs estimated by Safley et al.	**Average Annual MCF**		
Litter[d]	10 %		
Deep Pit Stacking[d]	5 %		

a Hashimoto (1992)
b Based on Hashimoto (1992).
c Safley et al. (1992a) and Safley and Westerman (1992b).
d Safley et al. (1992a).

Source: U.S. EPA (1993a)

Table C-17. Methane Conversion Factors for U.S. Livestock Manure Systems

State	Pasture, Range & Paddocks	Drylot	Solid Storage	Daily Spread	Liquid/ Slurry
Alabama	1.4%	1.9%	1.4%	0.4%	29.0%
Arizona	1.4%	1.9%	1.4%	0.4%	28.9%
Arkansas	1.3%	1.8%	1.3%	0.4%	27.6%
California	1.2%	1.4%	1.2%	0.3%	21.9%
Colorado	0.9%	1.0%	0.9%	0.2%	18.2%
Connecticut	0.9%	1.0%	0.9%	0.2%	18.5%
Delaware	1.2%	1.4%	1.2%	0.3%	22.6%
Florida	1.5%	2.4%	1.5%	0.6%	38.6%
Georgia	1.4%	1.8%	1.4%	0.4%	29.0%
Idaho	0.8%	0.8%	0.8%	0.2%	15.5%
Illinois	1.1%	1.3%	1.1%	0.3%	22.8%
Indiana	1.0%	1.2%	1.0%	0.3%	21.5%
Iowa	0.9%	1.1%	0.9%	0.2%	20.7%
Kansas	1.1%	1.5%	1.1%	0.3%	24.7%
Kentucky	1.2%	1.5%	1.2%	0.3%	23.8%
Louisiana	1.4%	2.1%	1.4%	0.5%	32.5%
Maine	0.8%	0.8%	0.8%	0.2%	15.5%
Maryland	1.1%	1.2%	1.1%	0.3%	21.0%
Massachusetts	0.9%	1.0%	0.9%	0.2%	18.1%
Michigan	0.8%	0.9%	0.8%	0.2%	17.0%
Minnesota	0.8%	0.8%	0.8%	0.2%	18.0%
Mississippi	1.4%	1.9%	1.4%	0.4%	29.3%
Missouri	1.1%	1.4%	1.1%	0.3%	24.1%
Montana	0.7%	0.8%	0.7%	0.2%	15.8%
Nebraska	1.0%	1.1%	1.0%	0.2%	20.8%
Nevada	1.2%	1.4%	1.2%	0.3%	22.1%
New Hampshire	0.8%	0.8%	0.8%	0.2%	16.3%
New Jersey	1.0%	1.1%	1.0%	0.3%	20.6%
New Mexico	1.2%	1.3%	1.2%	0.3%	21.3%
New York	0.9%	0.9%	0.9%	0.2%	18.1%
North Carolina	1.3%	1.5%	1.3%	0.3%	24.5%
North Dakota	0.7%	0.7%	0.7%	0.2%	16.8%
Ohio	1.0%	1.1%	1.0%	0.2%	20.2%
Oklahoma	1.4%	1.9%	1.4%	0.4%	28.7%
Oregon	1.1%	1.1%	1.1%	0.2%	16.2%
Pennsylvania	0.9%	1.0%	0.9%	0.2%	18.7%
Rhode Island	1.0%	1.1%	1.0%	0.2%	18.7%
South Carolina	1.3%	1.7%	1.3%	0.4%	27.3%
South Dakota	0.8%	0.9%	0.8%	0.2%	19.1%
Tennessee	1.3%	1.6%	1.3%	0.3%	24.8%
Texas	1.4%	2.1%	1.4%	0.5%	31.7%
Utah	0.9%	1.0%	0.9%	0.2%	17.4%
Vermont	0.8%	0.8%	0.8%	0.2%	16.6%
Virginia	1.2%	1.4%	1.2%	0.3%	22.5%
Washington	1.0%	1.0%	1.0%	0.2%	15.5%
West Virginia	1.2%	1.3%	1.2%	0.3%	21.4%
Wisconsin	0.8%	0.8%	0.8%	0.2%	17.0%
Wyoming	0.8%	0.8%	0.8%	0.2%	15.9%

Other Systems: Pit Storage for less than 30 days is assumed to have an MCF equal to 50 percent of the MCF for Liquid/Slurry. Pit Storage for more than 30 days is assumed to have an MCF equal to liquid/slurry. Anaerobic lagoons are assumed to have an MCF of 90 percent; litter and deep pit stacks an MCF of 10 percent.

Source: U.S. EPA (1993a)

Table C-18. Livestock Manure System Usage for the U.S.

Animal	Anaerobic Lagoons	Liquid/Slurry and Pit Storage	Daily Spread	Solid Storage & Drylot	Pasture, Range & Paddock	Litter, Deep Pit Stacks and Other
Non-Dairy Cattle	<1%	<1%	0%	10%	89%	0%
Dairy	11%	21%	41%	18%	0%	8%
Poultry[b]	4%	3%	0%	0%	<1%	93%
Sheep	0%	0%	0%	0%	92%	8%
Swine	29%	44%	0%	20%	0%	7%
Other Animals[c]	0%	0%	0%	0%	89%	11%

Note: Totals may not add due to rounding.
a Includes liquid/slurry storage and pit storage.
b Includes chickens, turkeys, and ducks.
c Includes goats, horses, mules, and donkeys.

Source: Safley et al. (1992a).

Point estimates of emissions were calculated using the previously described data. Emissions were estimated for each animal type by summing annual emissions over all applicable manure management systems and states. Total annual methane emissions from all animals were estimated by summing over all animal types.

Uncertainties in the point estimates result from uncertainties in the data used to make these estimates, in particular:

- The estimated MCF values for pasture, range, drylots, solid storage, and paddocks are based on dry manure. This may underestimate the MCFs for regions with significant rainfall. Because a large fraction of animal manure is managed in these systems, total emissions may be underestimated.

- The methane producing potential of liquid/slurry and pit storage manure systems may be greater than assumed. These systems are widespread, so total emissions may be underestimated.

The greatest uncertainty results from the MCF assumptions. Therefore, "high" and "low" case emission estimates were defined based on varying the MCFs used for the various manure management systems in the base case:

- High Case. The MCFs for liquid/slurry, pit storage, litter, and deep pit stacking systems were assumed to be double the base case. The MCFs for solid systems (except litter and deep stack pits) were assumed to be *five times* the base case. The MCFs for anaerobic lagoons were the same as the base case.

- Low Case. The MCFs for each of the major solid systems (pasture/range, solid storage, and drylots) were assumed to be 80 percent of the base case. The MCFs for liquid/slurry and pit storage were assumed to be 90 percent of the base case. The MCFs for litter and deep pits were assumed to be half the base case. The MCFs for anaerobic lagoons, estimated using a lagoon methanogenesis model prepared for U.S. EPA[8], were 40 to 100 percent of the base case.

These assumptions are summarized in Table C-19.

Table C-19. Base, High, and Low Case Emission Estimate Assumptions

Management System	MCF	
	High Case	Low Case
Pasture, Range, Paddock, Drylot, Daily Spread	Five Times Base Case	80 percent of Base Case
Liquid/Slurry, Pit Storage	Two Times Base Case	90 percent of Base Case
Litter, Deep Pits	Two Times Base Case	50 percent of Base Case
Anaerobic Lagoons	Same as Base Case	Model Estimates 40 to 100 percent of Base Case

Source: U.S. EPA (1993a)

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[8] The model estimates methane production based on loading rates, lagoon characteristics, and climate. The model estimates are "conservative" because the model focuses on the amount of methane that can be recovered reliably for use as an energy source.

ANNEX D
IPCC REPORTING TABLES: 1990

Minimum Data Tables 1 A Energy

SOURCE AND SINKS	ACTIVITY DATA		EMISSIONS ESTIMATES						AGGREGATE EMISSION FACTORS					
Sector Specific Data (TBtu)	A Consumption [a]		B (Gg of full mass)						C (kg pollutant /GJ)					
	(TBtu)	(PJ)							C = B/A					
			CO2	CH4 [c]	N20	NOx	CO	NMVOC	CO2	CH4	N20	NOx	CO	NMVOC
1-A-1 Energy & Transformation Activitie														
(Electric Utilities)	20,210	21,323	1,742,471	13.3	14.0	6,826.1	285.7	31.7	81.717	6.23E-04	6.55E-04	3.20E-01	1.34E-02	1.49E-03
Oil	1,250	1,319	97,630	-	-	-	-	-	74.001	-	-	-	-	-
Gas	2,871	3,030	151,586	-	-	-	-	-	50.034	-	-	-	-	-
Coal	16,088	16,974	1,493,255	-	-	-	-	-	87.972	-	-	-	-	-
1-A-2 Industry (ISIC)	19,562	20,640	1,065,905	9.1	16.3	3,206.2	648.5	257.6	51.643	4.38E-04	7.91E-04	1.55E-01	3.14E-02	1.25E-02
Oil	8,318	8,776	379,569	-	-	-	-	-	43.250	-	-	-	-	-
Gas	8,549	9,021	436,027	-	-	-	-	-	48.337	-	-	-	-	-
Coal	2,695	2,843	250,309	-	-	-	-	-	88.042	-	-	-	-	-
1-A-3 Transportation	22,495	23,734	1,502,626	220.7	92.3	9,667.7	67,520.0	8,251.9	63.310	9.30E-03	3.89E-03	4.07E-01	2.84E+00	3.48E-01
Oil	21,810	23,012	1,466,475	-	-	-	-	-	63.727	-	-	-	-	-
Gas	685	723	36,151	-	-	-	-	-	50.034	-	-	-	-	-
Coal	0	0	0	-	-	-	-	-	-	-	-	-	-	-
1-A-4 Commercial	3,707	3,912	217,816	1.1	1.0	283.9	120.6	14.5	55.686	2.84E-04	2.58E-04	7.26E-02	3.08E-02	3.71E-03
Oil	907	957	66,101	-	-	-	-	-	69.080	-	-	-	-	-
Gas	2,707	2,857	142,931	-	-	-	-	-	50.034	-	-	-	-	-
Coal	93	98	8,785	-	-	-	-	-	89.623	-	-	-	-	-
1- A-5 Residential	5,863	6,186	333,186	368.7	3.8	379.1	5,072.9	380.9	53.864	5.96E-02	6.11E-04	6.13E-02	8.20E-01	6.16E-02
Oil	1,266	1,336	87,954	-	-	-	-	-	65.830	-	-	-	-	-
Gas	4,534	4,784	239,379	-	-	-	-	-	50.034	-	-	-	-	-
Coal	62	65	5,853	-	-	-	-	-	89.623	-	-	-	-	-
1-A-6 Agriculture / Forestry	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Oil	NE	NE	NE											
Gas	NE	NE	NE											
Coal	NE	NE	NE											
1-A-8 Territories	454	479	33,428	NE	NE	NE	NE	NE	69.727	NE	NE	NE	NE	NE
Oil	449	474	32,934						69.516					
Gas	0	0	0						NA					
Coal	5	6	495						87.366					
1-A-8 Traditional Biomass [b]	2,267	2,392	180,710						75.550					
Wood	2,185	2,305	175,000	772	5	125	6,783	NE	75.909	3.35E-01	2.31E-03	5.42E-02	2.94E+00	NE
Ethanol	82	87	5,710	NE	NE	NE	NE	NE	65.998	NE	NE	NE	NE	NE
TOTAL	72,291	76,274	4,895,433	646	127	20,363	73,648	8,937						

NA = Not Available; NE = Not Estimated

"-" = Value is not estimated separately, but included in an aggregate figure.

Note Totals may not equal sum of components due to independent rounding.

[a] Estimates other than CO2 were often calculated via methodologies other than the IPCC default and do not necessarily use the activity data listed in this table. For CO2 calculations a detailed bottom-up approach was implemented using activity data disaggregated by sector and fuel type.

[b] Emissions from traditional biomass are presented for informational purposes only, and are not included when computing total national emissions.

[c] Total methane emissions include 32 Gg from natural gas consumption which was not sector specific. For years after 1990, the 1990 figure was used as a rough estimate, since 1990 was the most recent available number.

1 B 1 Fugitive Emissions (Oil and Gas)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES		AGGREGATE EMISSION FACTORS	
	Fuel Quantity [e] (PJ)	CH4 [f] (Gg)	CO2 [g] (Gg)	CH4 (g/GJ)	CO2 (kg/GJ)
1 B 1 a Crude Oil (Total)	**47,822**	**271**	**NA**		
i Production [a]	17,758	253 [h]	NA	14.25	NA
ii Transportation	NE	6	NA	NE	NA
iii Refined [b]	30,064	12	NA	0.40	NA
1 B 1 b Natural Gas (Total)	**36,008**	**2,970**	**6,560**		
i Production [c]	17,542	1,080	6,560	61.57	373.96
ii Consumption [d]	18,466	1,890	NA	102.35	NA

NA = Not Applicable; NE = Not Estimated

Note Totals may not equal sum of components due to independent rounding.

[a] Fugitive, routine maintenance, and venting and flaring emissions from oil production.

[b] Emissions from refineries and storage tanks.

[c] All emissions from gas production facilities including fugitive emissions from gas producing oil wells.

[d] Emissions from natural gas processing, transmission; and distribution.

[e] Source: "UN Energy Statistics Yearbook," United Nations, New York, New York.

[f] Source: "Anthropogenic Methane Emissions in the United States: Estimates for 1990: Report to Congress" - USEPA, 1993, Washington, D.C.

[g] Consists exclusively of flared natural gas.

[h] This includes 22.3 Gg of fugitive emissions from oil wells, 0.05 Gg of routine maintenance emissions, and 231 Gg of venting and flaring emissions. Venting and flaring emissions were estimated by Radian (1992) at about 4% of total venting and flaring reported each year, or 92.5 Gg. Bams and Edmonds (1990) estimated venting and flaring emissions at 29% of total venting and flaring, reported each year, or 462 Gg. A point estimate of 10%, or 231 Gg, is chosen for this table.

1 B 2 Fugitive Emissions (Coal Mining)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES			AGGREGATE EMISSIONS FACTORS	
	Production [a] (MMT)	Total CH4 [b] (Gg)	Production (Gg)	Post Processing (Gg)	Production (Gg CH4 / MMT)	Post Processing (Gg CH4 / MMT) [c
1 B 2 Coal Mining (Total) [b]	**931**	**4,400**	**3,800**	**800**		
a Surface	547	600	500	100	0.91	0.18
b Underground	384	4,000	3,300	700	8.59	1.82

Note: Totals may not equal sum of components due to independent rounding.

[a] Production figures are from Table 2 of EIA, 1990, "Coal Production 1990."

[b] 4,400 is a point estimate of total CH4 emissions and does not match the sum of its components due to independent rounding.

[c] Emission factors given as kg CH4 per metric tonne of coal produced.

Minimum Data Tables 2 Industrial Processes

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES (shaded boxes not applicable)						AGGREGATE EMISSION FACTORS (shaded boxes not applicable)					
Sector Specific Data	A Production Quantity	B Full Mass of Pollutant (Gg)						C (kg pollutant per tonne of product) C = B/A					
	(000 t)	CO	CO2	CH4	N2O	NOx	NMVOC	CO	CO2	CH4	N2O	NOx	NMVOC
2 INDUSTRIAL PROCESSES (Total)		**4,346**	**55,030**	**NE**	**96**	**716**	**3,488**						
A Iron and Steel	NE	[a]	NE	NE	[a]		[a]	[a]	NE	NE	NE		[a]
B Non-Ferrous Metals													
Aluminum Production [b]	4,048	[a]	7,489		NE		[a]	[a]	1.850		NE		[a]
C Inorganic Chemicals (excluding. solven													
Nitric Acid	7,260				39.9						0.005		
Fertilizer Production	NE				NE	[a]					NE	[a]	
Carbon Dioxide Production	4,000	[a]	1,200		NE	[a]		[a]	0.300		NE	[a]	
D Organic Chemicals													
Adipic Acid	735				56.2		[a]				0.076		[a]
E Non-Metallic Mineral Products													
Cement	67,267	[a]	32,691	NE				[a]	0.486	NE			
Lime	15,859	[a]	11,927	NE				[a]	0.752	NE			
Soda Ash Production	14,734	[a]	1,435	NE				[a]	0.097	NE			
Soda Ash Use	6,527	[a]	2,710	NE				[a]	0.415	NE			
Limestone Use	11,436	[a]	5,067	NE				[a]	0.443	NE			
F Other Industry [c]													
Chemical & Allied Products	NE	1,716				361	1,607	NE				NE	NE
Metals Processing	NE	1,887				73	65	NE				NE	NE
Other Industrial	NE	651				279	433	NE				NE	NE
Storage and Transport	NE	92				3	1,383	NE				NE	NE

NA = Not Available; NE = Not Estimated

Note: Totals may not equal sum of components due to independent rounding.

[a] These estimates are encompassed in 2 F, "Other Industry" (see [b]).

[b] CO2 emissions from aluminum production are included in this table for informational purposes, but is not included in the national total in order to prevent double counting these emissions, which are included under non-fuel industrial uses in the Energy section.

[c] The "Other Industry" category is used to report NOx, CO, and NMVOC emissions for industry. Since these emissions estimates were taken directly from another report, no activity data or aggregate emissions factors are presented.

Minimum Data Tables 3 Solvents

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES (shaded boxes not applicable)			AGGREGATE EMISSION FACTORS		
Sector Specific Data	A Quantity Consumed (kt)	B Full Mass of Pollutant (Gg)			C Pollutant per tonne of product (kg pollutant /GJ) C = B/A		
		CO	NMVOC	NOx	CO	NMVOC	NOx
3 Solvents (Total)	**NA**	**2**	**5,740**	**2**	**NA**	**NA**	**NA**
A. Degreasing	NA	1	682	-	NA	NA	NA
B. Dry Cleaning	NA	NA	190	NA	NA	NA	NA
C. Graphic Arts	NA	-	621	-	NA	NA	NA
D. Surface Coating (including. Paint)	NA	1	2,375	2	NA	NA	NA
E. Other Industrial	NA	-	149	-	NA	NA	NA
F. Non-Industrial	NA		1,723			NA	

NA = Not Available.

"-" = less than 0.0004535 Gg (453.5 metric tonnes).

Note: Totals may not equal sum of components due to independent rounding.

Minimum Data Tables 4 Agriculture

4 A & B Enteric Fermentation and Manure Management

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSIONS ESTIMATES		AGGREGATE EMISSIONS FACTOR	
Sector Specific Data	A		B		C	
	Number of Animals					
	Enteric Fermentation	Manure Management	Enteric Fermentation	Manure Management	Enteric Fermentation	Manure Management
	(1000 head)		(Gg CH4)		(kg CH4 per animal) C = (B/A) X 1000	
4 Agriculture						
A & B Enteric Fermentation & Manure Management (Total)	**176,269**	**174,371**	**5,814**	**2,274**		
1.i Beef Cattle [a]	85,398	89,293	4,054	170	47.5	1.9
1.ii Dairy Cattle [a]	18,540	14,335	1,490	730	80.4	50.9
2. Goats [b]	1,900	2,396	10	2	5.3	0.7
3. Sheep [b]	11,364	10,639	90	6	7.9	0.6
4. Pigs [b]	53,852	55,299	80	1,120	1.5	20.3
5. Horses/Mules/Asses [b]	5,215	2,409	90	16	17.3	6.7
6. Buffalo	NE	NE	NE	NE	NA	NA
7. Camels and Llamas	NO	NO	NO	NO	NA	NA
8. Poultry	NA	1,368,166	NA	230	NA	0.2

NA = Not Applicable; NE = Not Estimated; NO = Not Occurring

Note: Totals may not equal sum of components due to independent rounding.

[a] Replacements 0 - 12 months are included in the "Beef Cattle" category for animal waste systems, and are included in the "Dairy Cattle" category for enteric fermentation.

[b] Populations used for enteric fermentation emission estimates differ from those used for manure management emission estimates because different population data sources were used (USEPA, 1993a).

4 C Rice Cultivation

SOURCE AND SINK CATEGORIES	ACTIVITY DATA [a]		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTOR
Sector Specific Data	A Area Harvested [a] (Mha)	B Hectare-Days of Cultivation (Mha-days)	C Emissions of Methane (Gg CH4)	D Average Emission Factor (kg CH4 per ha-day)
				D = C/B
C Rice Cultivation (Total)	**1.246**	**117.602**	**429.0**	**3.65**
1. Flooded Regime (Total)	1.246	117.602	429.0	3.65
Arkansas	0.486	42.493	156.3	3.68
California	0.156	21.501	77.4	3.60
Florida: primary	0.006	0.670	2.5	3.73
rantoon	0.003	0.335	1.2	3.58
Louisiana: primary	0.208	21.813	80.2	3.68
rantoon	0.063	6.580	24.2	3.68
Mississippi	0.095	7.466	25.8	3.46
Missouri	0.034	3.047	11.0	3.61
Texas: primary	0.139	9.764	35.9	3.68
rantoon	0.056	3.933	14.5	3.69
2. Intermittent Regime	NO	NO	NO	NO
3. Dry Regime	NO	NO	NO	NO

NO = Not occurring in the U.S.

Note: Totals may not equal sum of components due to independent rounding.

[a] Area harvested is given as a three year average centered around 1990.

4 D. Agricultural Soils

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTORS	
Sector Specific Data	A Amount of Nitrogen Applied in Fertilizer and Manure [a] (tonnes N)	B Area Cultivated [b] (ha)	C (Gg N2O)	D Nitrous Oxide Released per tonne Nitrogen Applied (g N2O/ g N) D = C/A	E Amount of Biological Fixation of Nitrogen (tonnes N)
4 D Agricultural Soils					
1. Fertilizer Use	9,965,700	NE	183	0.0184	NE

[a] Amount of nitrogen applied is given as a three year average centered around 1990.

[b] Since the estimate was made directly from the total amount of nitrogen applied, the area cultivated was not calculated.

4 E Agricultural Waste Burning

SOURCE AND SINK CATEGORIES	ACTIVITY DATA			EMISSION ESTIMATE				AGGREGATE EMISSION FACTORS			
Sector Specific Data	A Annual Burning of Crop Residues [a]	B		C Full Mass of Pollutant (Gg)				D Pollutant per tonne of dry matter (kg / t dm) D = C/A			
		Carbon Fraction	Nitrogen Fraction								
	(kt dm)	(t C / t dm)	(t N / t dm)	CH4	N20	NOx	CO	CH4	N20	NOx	CO
E Agricultural Waste Burning (Total)	**41,979**			**78.8**	**4.9**	**114.7**	**2,756.8**	**1.88**	**0.12**	**2.73**	**65.67**
1. Cereals (Total)	30,841			58.8	2.5	58.5	2,056.6	1.91	0.08	1.90	66.68
Wheat	5,939	0.4853	0.004	11.5	0.3	6.2	403.5	1.94	0.04	1.04	67.94
Barley	832	0.4567	0.006	1.5	0.1	1.3	53.2	1.83	0.07	1.56	63.94
Maze	13,986	0.4709	0.0081	26.3	1.2	29.4	922.0	1.88	0.09	2.10	65.93
Oats	454	0.4853	0.007	0.9	+	0.8	30.9	1.94	0.08	1.82	67.94
Rye	33	0.4853	0.007	0.1	+	0.1	2.3	1.94	0.08	1.82	67.94
Rice	730	0.4144	0.0067	1.2	0.1	1.3	42.3	1.66	0.07	1.74	58.02
Millet	19	0.4853	0.007	+	+	+	1.3	1.94	0.08	1.82	67.94
Sorghum	8,849	0.4853	0.0085	17.2	0.8	19.5	601.2	1.94	0.09	2.20	67.94
2. Pulse (Total)	8,364			15.1	2.1	49.9	526.9	1.80	0.25	5.96	63.00
Soya	8,126	0.45	0.023	14.6	2.1	48.5	511.9	1.80	0.25	5.96	63.00
Beans	207	0.45	0.023	0.4	0.1	1.2	13.1	1.80	0.25	5.96	63.00
Peas	23	0.45	0.023	+	+	0.1	1.4	1.80	0.25	5.96	63.00
Lentils	9	0.45	0.023	+	+	0.1	0.5	1.80	0.25	5.96	63.00
3. Tubers / Roots (Total)	1,209			2.0	0.2	5.1	70.4	1.66	0.18	4.22	58.20
Sugarbeet	540	0.4072	0.0228	0.9	0.1	3.2	30.8	1.63	0.25	5.91	57.01
Artichoke	3	0.4226	0.011	+	+	+	0.2	1.69	0.12	2.85	59.16
Peanut	140	0.4226	0.011	0.2	+	0.4	8.3	1.69	0.12	2.85	59.16
Potatoes	511	0.4226	0.011	0.9	0.1	1.5	30.2	1.69	0.12	2.85	59.16
Other	15	0.4226	0.011	+	+	+	0.9	1.69	0.12	2.85	59.16
4. Sugar Cane (Total)	1,565	0.4695	0.003	2.9	0.1	1.2	102.9	1.88	0.03	0.78	65.73

"+" = value less than 0.05.

Note: Totals may not equal sum of components due to independent rounding.

[a] "Annual Burning of Crop Residues," or total biomass burned as given in Column H, Sheet A, Worksheet 4-4, in the IPCC Workbook (IPCC/OECD, 1994) is computed by multiplying crop production by the residue to crop ratio, the burning efficiency, and the combustion efficiency.

5 D 3 Managed Forests: Net Emissions/Removals

SOURCE AND SINK CATEGORIES	EMISSIONS / REMOVALS
	(Gg CO2)
Total Growth Increment	NE
Total Harvest	NE
Net Emissions (+) or Removals (-)	(436,000)

NE = Not Estimated

[a] The methodology used by the U.S. determines net emissions and removals via direct timber inventory, so growth increment and harvest are not calculated.

Minimum Data Tables 6 Waste

6 A Waste: Landfills

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE REMOVAL FACTORS	
	A Total MSW [a] (kg per year)	B MSW Landfilled [b] (kg)	C Methane Emissions [b] (kg)	D Emission Factor (kg CH4 / kg MSW Landfilled) D = C/B	E Quantity of CH4 recovered [c] (kg CH4)
A Landfills	2.81E+11	1.90E+11	1.00E+10	0.053	1.50E+09

[a] Source: Biocycle, 1992.
[b] Source: USEPA, 1993a.
[c] Recovered methane is flared or used for energy production.

6 B Wastewater (Sewage Treatment)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTORS	
	A Quantity BOD in Wastewater (kg BOD)	B Quantity of BOD anaerobically digested. (kg BOD)	C CH4 Emissions Emissions (kg)	D Emission Factor (kg CH4 / kg BOD) [a D = C/B	E Quantity of CH4 recovered (kg CH4)
B Wastewater					
Municipal	4.54E+09	6.82E+08	1.50E+08	0.22	NE
Industrial	NE	NE	NE	NE	NE

[a] The Emissions factor is given as kg of CH4 emitted per kg of BOD anaerobically digested.

Table 7 A Overview Table for National Greenhouse Gas Inventories

OVERVIEW TABLE															
GREENHOUSE GAS SOURCE AND SINK CATEGORIES	CO2		CH4		N2O		NOx		CO		NMVOC		Documentation	Dissaggregation	Footnotes
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality			
1 All Energy (Fuel Combustion + Fugitive)															
A Fuel Combustion	ALL	H	ALL	M	ALL	L	ALL	M	ALL	M	ALL	M	H	2	[a]
B Fugitive															
1 Coal Production	-	-	ALL	H	-	-	-	-	-	-	-	-	H	3	
2 Oil and Gas Systems	ALL	M	ALL	L	-	-	All	M	All	M	All	M	M	3	
2 Industrial Processes	ALL	H	-	-	ALL	H	All	M	All	M	All	M	M	3	
3 Solvent Use and Other Product Use	-	-	-	-	-	-	All	M	All	M	All	M	L	3	
4 Agriculture															
A Enteric Fermentation	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
B Manure Management	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
C Rice Cultivation	-	-	ALL	L	-	-	-	-	-	-	-	-	H	3	
D Agricultural Soils	-	-	-	-	PART	L	-	-	-	-	-	-	M	1	
E Agricultural Waste Burning	-	-	ALL	L	ALL	L	ALL	L	ALL	L	-	-	H	3	
F Savannah Burning	NO	-	NO	-	NO	-	NO	-	NO	-	NO	-			
5 Land Use Change and Forestry	PART	L	-	-	-	-	-	-	-	-	-	-	M	1	[b]
6 Waste	-	-	-	-	-	-	-	-	-	-	-	-			
A Landfills	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
B Wastewater	-	-	PART	L	-	-	-	-	-	-	-	-	H	2	

[a] Some of the combustion calculations are based on currently unpublished data, which will be published by December, 1994.

[b] Neither soil carbon flux, nor forest product carbon storage and decay, are included.

Table 8 B Short Summary Report for National Greenhouse Gas Inventories [a]

Short Summary Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	CO2	CH4	N2O	NOx	CO	NMVOC
Total National Sources and Sinks [b]	**4,520,993**	**27,032**	**411**	**21,362**	**82,673**	**19,123**
Total National Sources	4,956,993	27,032	411	21,362	82,673	19,123
Total National Sinks	(436,000)	0	0	0	0	0
1 All Energy (Fuel Combustion + Fugitives)	4,901,993	8,286	127	20,455	74,041	9,605
A Fuel Combustion	4,895,433	645	127	20,363	73,648	8,937
B Fugitive Fuel Emission	6,560	7,641	0	92	393	668
2 Industrial Processes	55,000	-	96	716	4,346	3,488
3 Solvent and Other Product Use	-	-	-	2	2	5,740
4 Agriculture (Total)	0	8,596	188	115	2,756	0
A Enteric Fermentation	-	5,814	-	-	-	-
B Manure Management	-	2,274	-	-	-	-
C Rice Cultivation	-	429	-	-	-	-
D Agricultural Soils	-	-	183	-	-	-
E Agricultural Waste Burning	-	79	5	115	2,756	-
F Savannah Burning	NO	NO	NO	NO	NO	NO
5 Land Use Change and Forestry	(436,000)	-	-	-	-	-
6 Waste	-	10,150	-	74	1,528	290

NO = Emissions from this category do not occur in the U.S.

"-" = Information not applicable.

Note: Totals may not equal sum of components due to independent rounding.

[a] This table is referred to as "Table 6B" in the IPCC guidelines (IPCC/OECD, 1994; Vol. 1) but is referred to herein as "Table 8B" in order to maintain continuity with the other reporting tables.

[b] The total represents net emissions and may not be equivalent to the sum of components due to independent rounding.

ANNEX E
SULFUR DIOXIDE: EFFECTS ON RADIATIVE FORCING AND SOURCES OF EMISSIONS

Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through photochemical transformation into sulfate particles that (i) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (ii) possibly increase the number of cloud condensation nuclei, thereby potentially altering the physical characteristics of clouds, and (iii) affect atmospheric chemical composition, e.g. stratospheric O_3, by providing surfaces for heterogeneous chemical processes. As a result of these activities, the effect of these gases on radiative forcing may be negative (IPCC, 1992). Therefore, since their effects are uncertain and opposite from the other criteria pollutants, emissions of SO_2 have been presented separately below in Table E-1.

Table E-1. Emissions of Sulfur Dioxide: 1990
(Million Metric Tonnes)

Source	Emissions
Fossil Fuel Combustion	**22.69**
Electric Utilities	17.49
Industrial	3.42
Commercial	0.45
Residential	0.20
Transportation	1.21
Industrial Processes	**1.91**
Metals Processing	1.001
Chemical and Allied Manufacturing	0.467
Asphalt Manufacturing	0.001
Agriculture, Food, Kindred Prod.	0.003
Wood, Pulp, Paper, and Publishing	0.151
Mineral Products	0.283
Solvent Use	**0.001**
Waste Incineration	**0.04**
Fossil Fuel Production, Distribution and Storage	**0.51**
Total	**25.15**

Source: U.S. EPA, 1993b
Note: Total may not add to the sum of the individual source categories due to independent rounding.

The major source of SO_2 emissions in the U.S. is the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also release significant quantities of SO_2. As a result, the largest contributor to overall U.S. emissions of SO_2 are electric utilities, accounting for about 70 percent. Coal combustion accounted for approximately 96 percent of SO_2 emissions from electric utilities. The second largest source is industrial fuel combustion, which produced about 14 percent of 1990 SO_2 emissions. Table E-2 provides SO_2 emissions disaggregated by fuel source.

Table E-2. Emissions of SO_2 from Fossil Fuel Combustion by Fuel Source: 1990 (Million Metric Tonnes)

Fuel Source	Emissions
Coal	19.01
Fuel Oil	3.14
Natural Gas	0.38
Wood[a]	0.01
Internal Combustion	0.04
Other Fuels[b]	0.10
Total	**22.69**

Source: U.S. EPA (1993b)

Notes: Total may not add to the sum of the independent source categories due to independent rounding.

a. Residential sector only.

b. Other fuels include: LPG, waste oil, coke oven gas, coke, and wood from sectors other than the residential sector.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of SO_2 can cause significant increases in acute and chronic respiratory diseases. In addition, once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, as well as cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the U.S. has regulated the emissions of SO_2 in the Clean Air Act of 1970 and in the amendments of 1990. The U.S. EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Program, which protects air quality and public health on the local level; (2) New Source Performance Standards, which set emission limits for new sources; (3) the New Source Review/Prevention of Significant Deterioration Program, which protects air quality from deteriorating, especially in clean areas; and (4) the Acid Rain Program, which addressees regional environmental problems often associated with long-range transport of SO_2 and other pollutants.