

ANNEX L

Methodology for Estimating CH₄ Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for five livestock categories: cattle, horses, sheep, swine, and goats. Emissions from cattle represent the majority of U.S. emissions; consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle and the IPCC Tier 1 methodology was used to estimate emissions from the other types of livestock.

Estimate Methane Emissions from Cattle

This section describes the process used to estimate methane emissions from cattle enteric fermentation. A model based on recommendations provided in IPCC/UNEP/OECD/IEA (1997) and IPCC (2000) was developed that uses information on population, energy requirements, digestible energy, and methane conversion rates to estimate methane emissions. The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emissions profiles; (2) characterize cattle diets to generate information needed to estimate emissions factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

Each stage in the cattle lifecycle was modeled to simulate the cattle population from birth to slaughter. This level of detail accounts for the variability in methane emissions associated with each life stage. Given that the time in which cattle can be in a stage can be less than one year (e.g., beef calves are weaned at 7 months), the stages are modeled on a per month basis. The type of cattle use also impacts methane emissions (e.g., beef versus dairy). Consequently, cattle life stages were modeled for several categories of dairy and beef cattle. These categories are listed in Table L-1.

Table L-1: Cattle Population Categories Used for Estimating Methane Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots
	Cows
	Bulls

The key variables tracked for each of these cattle population categories (except bulls¹) are as follows:

- *Calving rates:* The number of animals born on a monthly basis was used to initiate monthly cohorts and to determine population age structure. The number of calves born each month was obtained by multiplying annual births by the percentage of births by month. Annual birth information for each year was taken from USDA (2002a, 2001a, 2000a, 1999a, 1995a). Average percentages of births by month for beef from USDA (USDA/APHIS/VS 1998, 1994, 1993) were used for 1990 through 2001. For dairy animals, birth rates were assumed constant throughout the year. Whether calves were born to dairy or beef cows was estimated using the dairy cow calving rate and the total dairy cow population to determine the percent of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows.
- *Average weights and weight gains:* Average weights were tracked for each monthly age group using starting weight and monthly weight gain estimates. Weight gain (i.e., pounds per month) was estimated based on weight gain needed to reach a set target weight, divided by the number of months remaining before target weight was achieved. Birth weight was assumed to be 88 pounds for both beef and dairy

¹ Only end-of-year census population statistics and a national emission factors are used to estimate methane emissions from the bull population.

animals. Weaning weights were estimated to range from 480 to 575 pounds. Other reported target weights were available for 12, 15, 24, and 36 month-old animals. Live slaughter weights were derived from dressed slaughter weight data for each year (USDA 2002c, 2001c, 2000c, 1999a, 1995a). Live slaughter weight was estimated as dressed weight divided by 0.63.

- *Feedlot placements:* Feedlot placement statistics were available that specify placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model used these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported placement data. After animals are placed in feedlots they progress through two steps. First, animals spend time on a step-up diet to become acclimated to the new feed type. Animals are then switched to a finishing diet for a period of time before they are slaughtered. The length of time an animal spends in a feedlot depends on the start weight (i.e., placement weight), the rate of weight gain during the start-up and finishing phase of diet, and the end weight (as determined by weights at slaughter). Weight gain during start-up diets is estimated to be 2.8 to 3 pounds per day. Weight gain during finishing diets is estimated to be 3 to 3.3 pounds per day (Johnson 1999). All animals are estimated to spend 25 days in the step-up diet phase (Johnson 1999). Length of time finishing was calculated based on start weight, weight gain per day, and target slaughter weight.
- *Pregnancy and lactation:* Energy requirements and hence, composition of diets, level of intake, and emissions for particular animals, are greatly influenced by whether the animal is pregnant or lactating. Information is therefore needed on the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate methane emissions. A weighted average percent of pregnant cows each month was estimated using information on births by month and average pregnancy term. For beef cattle, a weighted average total milk production per animal per month was estimated using information on typical lactation cycles and amounts (NRC 1999), and data on births by month. This process results in a range of weighted monthly lactation estimates expressed as lbs/animal/month. The monthly estimates from January to December are 3.33, 5.06, 8.70, 12.01, 13.58, 13.32, 11.67, 9.34, 6.88, 4.45, 3.04, and 2.77 lbs milk/animal/month. Monthly estimates for dairy cattle were taken from USDA monthly milk production statistics.
- *Death rates:* This factor is applied to all heifer and steer cohorts to account for death loss within the model on a monthly basis. The death rates are estimated by determining the death rate that results in model estimates of the end-of-year population for cows that match the published end-of-year population census statistics.
- *Number of animals per category each month:* The population of animals per category is calculated based on number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to the next category (including feedlot placements). These monthly age groups are tracked in the enteric fermentation model to estimate emissions by animal type on a regional basis.
- *Animal characteristic data:* Dairy lactation estimates for 1990 through 2001 are shown in Table L-2. Table L-3 provides the target weights used to track average weights of cattle by animal type. Table L-4 provides a summary of the reported feedlot placement statistics for 2001. Data on feedlot placements were available for 1996 through 2001. Data for 1990 to 1995 were based on the average of monthly placements from the 1996 to 1998 reported figures.

Cattle population data were taken from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) reports. A summary of the annual average populations upon which all livestock-related emissions are based is provided in Table M-1 of Annex M, Methodology for Estimating CH₄ and N₂O Emissions from Manure Management. The USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Cattle and calf populations, feedlot placement statistics (e.g., number of animals placed in feedlots by weight class), slaughter numbers, and lactation data were obtained from the USDA (2002a, 2002c, 2001a, 2002c, 2000a, 2000c, 1999a, 1995a). Beef calf birth percentages were obtained from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993).

Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digestible to the animal) and methane conversion rate (Y_m , the fraction of gross energy converted to methane) values for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals and animals being fed mixed rations, representative regional diets were estimated using information collected from state livestock specialists and from USDA (1996a). The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine chemical composition for use in estimating digestible energy and Y_m for each animal type. Additional detail on the regional diet characterization is provided in EPA (2000).

Digestible energy and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. Given the availability of detailed diet information for different regions and animal types in the United States, digestible energy and Y_m values unique to the United States² were developed. Table L-7 shows the regional digestible energy, the Y_m , and percent of total U.S. cattle population in each region based on 2001 data. Digestible energy and Y_m values were estimated for each cattle population category, for each year in the time series based on physiological modeling, published values, and/or expert opinion.

Digestible energy and Y_m values for dairy cows were estimated using a model (Donovan and Baldwin 1999) that represents physiological processes in the ruminant animals. The three major categories of input required by the model are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage). Data used to simulate ruminant digestion is provided for a particular animal that is then used to represent a group of animals with similar characteristics. The model accounts for differing diets (i.e., grain-based, forage-based, range-based), so that Y_m values for the variable feeding characteristics within the U.S. cattle population can be estimated.

To calculate the digestible energy values for grazing beef cattle, the diet descriptions were used to estimate weighted digestible energy values for a combination of forage only and supplemented diets. Where digestible energy values were not available for specific feed types, total digestible nutrients (TDN) as a percent of dry matter (DM) intake was used as a proxy for digestible energy as it is essentially the same as the digestible energy value. For forage diets, two separate regional digestible energy values were used to account for the generally lower forage quality in the western US. For non-western grazing animals, the forage digestible energy was an average of the seasonal “TDN percent DM” for Grass Pasture diets listed in Appendix Table 1 of the NRC (2000). This average digestible energy for the non-western grazing animals was 64.7 percent. This value was used for all regions except the west. For western grazing animals, the forage digestible energy was calculated as the average “TDN percent DM” for meadow and range diets listed in Appendix Table 1 of the NRC (2000). The calculated digestible energy for western grazing animals was 58.5 percent. The supplemental diet digestible energy values were estimated for each specific feed component, as shown in Table L-5, along with the percent of each feed type in each region. Finally, weighted averages were developed for digestible energy values for each region using both the supplemental diet and the forage diet³. For beef cows, the digestible energy value was adjusted downward by two percent to reflect the reduced diet of the mature beef cow. The percent of each diet that is assumed to be supplemental and the digestible energy values for each region are shown in Table L-6. Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002).

For feedlot animals, digestible energy and Y_m values for 1996 through 2001 were taken from Johnson (1999). Values for 1990 through 1995 were linearly extrapolated from the 1996 value based on Johnson (1999). In response to peer reviewer comments (Johnson 2000), values for dairy replacement heifers are based on EPA (1993).

² In some cases, the Y_m values used for this analysis extend beyond the range provided by the IPCC. However, EPA believes that these values are representative for the U.S. due to the research conducted to characterize the diets of U.S. cattle and to assess the Y_m values associated with different animal performance and feed characteristics in the United States.

³ For example, in California the forage DE of 64.7 was used for 95 percent of the grazing cattle diet and a supplemental diet DE of 65.2 percent was used for five percent of the diet, for a total weighted DE of 64.9 percent.

Step 3: Estimate Methane Emissions from Cattle

Emissions were estimated in three steps: a) determine gross energy (GE) intake using the IPCC (2000) equations, b) determine an emissions factor using the GE values and other factors, and c) sum the daily emissions for each animal type. The necessary data values include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity (C_a)⁴
- Standard Reference Weight⁵ (Dairy = 1,324 kg; Beef = 1,195 kg)
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of gross energy intake digestible)
- Y_m (the fraction of gross energy converted to methane)

Step 3a: Gross Energy, GE

As shown in the following equation, gross energy (GE) is derived based on the net energy estimates and the feed characteristics. Only variables relevant to each animal category are used (e.g., estimates for feedlot animals do not require the NE_l factor). All net energy equations are provided in IPCC (2000).

$$GE = [((NE_m + NE_{mobilized} + NE_a + NE_l + NE_p) / \{NE_{ma}/DE\}) + (NE_g / \{NE_{ga}/DE\})] / (DE / 100)$$

Where:

GE = gross energy (MJ/day)

NE_m = net energy required by the animal for maintenance (MJ/day)

$NE_{mobilized}$ = net energy due to weight loss (mobilized) (MJ/day)

NE_a = net energy for animal activity (MJ/day)

NE_l = net energy for lactation (MJ/day)

NE_p = net energy required for pregnancy (MJ/day)

$\{NE_{ma}/DE\}$ = ratio of net energy available in a diet for maintenance to digestible energy consumed

NE_g = net energy needed for growth (MJ/day)

$\{NE_{ga}/DE\}$ = ratio of net energy available for growth in a diet to digestible energy consumed

DE = digestible energy expressed as a percentage of gross energy (percent)

Step 3b: Emission Factor

The emissions factor (DayEmit) was determined using the gross energy value and the methane conversion factor (Y_m) for each category. This is shown in the following equation:

$$\text{DayEmit} = [GE \times Y_m] / [55.65 \text{ MJ/kg CH}_4]$$

Where:

DayEmit = emission factor (kg CH₄/head/day)

⁴ Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, 0.36 for extensive open range or hilly terrain grazing conditions. C_a factor for dairy cows is weighted to account for the fraction of the population in the region that grazes during the year.

⁵ Standard Reference Weight is used in the model to account for breed potential.

GE = gross energy intake (MJ/head/day)

Y_m = methane conversion rate which is the fraction of gross energy in feed converted to methane (percent)

The daily emission factors were estimated for each animal type, weight and region.

Step 3c: Estimate Total Emissions

Emissions were summed for each month and for each population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

$$\text{Emissions} = \text{DayEmit} \times \text{Days/Month} \times \text{SubPop}$$

Where:

DayEmit = the emission factor for the subcategory (kg CH₄/head/day)

Days/Month = the number of days in the month

SubPop = the number of animals in the subcategory during the month

This process was repeated for each month, and the totals for each subcategory were summed to achieve an emissions estimate for the entire year. The estimates for each of the 10 subcategories of cattle are listed in Table L-8. The emissions for each subcategory were then summed to estimate total emissions from beef cattle and dairy cattle for the entire year.

Emission Estimates from Other Livestock

All livestock population data, except for horses, were taken from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) reports. Table M-1 of Annex M shows the population data for all livestock species that were used for estimating all livestock-related emissions. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Recent reports were obtained from the USDA Economics and Statistics System, while historical data were downloaded from the USDA-NASS. The Food and Agriculture Organization (FAO) publishes horse population data. These data were accessed from the FAOSTAT database at <http://apps.fao.org/>. Methane emissions from sheep, goats, swine, and horses were estimated by multiplying published national population estimates by the national emission factor for each year. Table L-9 shows the emission factors used for these other livestock.

A complete time series of enteric fermentation emissions from all livestock types is shown in Table L-10 (Tg CO₂ Eq.) and Table L-11 (Gg).

Table L-2: Dairy Lactation by Region (lbs· year/cow)*

Year	California	West	Northern Great		Southcentral	Northeast	Midwest	Southeast
			Plains					
1990	18,443	17,293	13,431		13,399	14,557	14,214	12,852
1991	18,522	17,615	13,525		13,216	14,985	14,446	13,053
1992	18,709	18,083	13,998		13,656	15,688	14,999	13,451
1993	18,839	18,253	14,090		14,027	15,602	15,086	13,739
1994	20,190	18,802	14,686		14,395	15,732	15,276	14,111
1995	19,559	18,708	14,807		14,294	16,254	15,680	14,318
1996	19,148	19,076	15,040		14,402	16,271	15,651	14,232
1997	19,815	19,537	15,396		14,330	16,519	16,116	14,517
1998	19,461	19,814	15,922		14,722	16,865	16,676	14,404
1999	20,763	20,495	16,378		14,986	17,271	16,966	14,860
2000	21,134	20,782	17,297		15,314	17,484	17,426	15,196
2001	20,898	20,656	17,347		14,813	17,602	17,218	15,303

Source: USDA (2002d, 2001d, 2000d, 1999a, 1995a).

* Beef lactation data were developed using the methodology described in the text.

Table L-3: Target Weights for Use in Estimating Average Weights and Weight Gains (lbs)

Cattle Type	Typical Weights
Beef Replacement Heifer Data	
Replacement Weight at 15 months	715
Replacement Weight at 24 months	1,078
Mature Weight at 36 months	1,172
Dairy Replacement Heifer Data	
Replacement Weight at 15 months	800
Replacement Weight at 24 months	1,225
Mature Weight at 36 months	1,350
Stockers Data – Grazing/Forage Based Only	
Steer Weight Gain/Month to 12 months	45
Steer Weight Gain/Month to 24 months	35
Heifer Weight Gain/Month to 12 months	35
Heifer Weight Gain/Month to 24 months	30

Source: Feedstuffs (1998), Western Dairyman (1998), Johnson (1999), NRC (1999).

Table L-4: Feedlot Placements in the United States for 2001¹ (Number of animals placed in Thousand Head)

Weight When Placed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
< 600 lbs	499	336	329	334	499	419	469	510	528	891	655	418	5,887
600 - 700 lbs	716	402	414	384	509	442	444	472	448	758	588	475	6,052
700 - 800 lbs	664	517	614	494	799	631	606	667	561	592	381	413	6,939
> 800 lbs	384	325	485	339	565	473	467	555	604	461	284	272	5,214
Total	2,263	1,580	1,842	1,551	2,372	1,965	1,986	2,204	2,141	2,702	1,908	1,578	22,184

Source: USDA (2002f, 2001f, 2000f, 1999a, 1995a).

Note: Totals may not sum due to independent rounding.

Table L-5: DE Values and Representative Regional Diets (Percent of Diet for each Region) for the Supplemental Diet of Grazing Beef Cattle

Feed	Source of TDN (NRC 2000)	Unweighted TDN or DE	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 11-1, feed #4	59.6%	65%	30%	30%	29%	12%	30%	
Barley	Table 11-1, feed #12	86.3%	10%	15%					
Bermuda	Table 11-1, feed #17	48.5%							35%
Bermuda Hay	Table 11-1, feed #17	48.5%				40%			
Corn	Table 11-1, feed #38	88.1%	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 11-1, feed #39	71.2%			25%		20%	20%	
Cotton Seed Meal	Table 11-1, feed #42	74.4%				7%			
Grass Hay	Table 1a, feed #129, 147, 148	53.7%		40%				30%	
Orchard	Table 11-1, feed #61	53.5%							40%
Soybean Meal Supplement	Table 11-1, feed #70	83.1%		5%	5%				5%
Sorghum	Table 11-1, feed #67	81.3%							20%
Soybean Hulls	Table 11-1, feed #69	76.4%						7%	
Timothy Hay	Table 11-1, feed #77	55.5%					50%		
Whole Cotton Seed	Table 11-1, feed #41	89.2%	5%				5%		
Wheat Middlings	Table 1a, feed #433	83.0%			15%	13%			
Wheat	Table 11-1, feed #83	87.2%	10%						
Weighted Total			65.2%	65.1%	62.4%	65.0%	74.3%	58.8%	69.3%

Source of representative regional diets: Donovan (1999)

L-6 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001

Table L-6: Percent of each Diet that is Supplemental, and the Resulting DE Values for each Region

Region	Percent Supplement	Percent Forage	Calculated Weighted Average DE
West	10	90	59.2%
Northeast	15	85	64.7%
Southcentral	10	90	64.4%
Midwest	15	85	64.7%
Northern Great Plains	15	85	66.1%
Southeast	5	95	64.4%
California	5	95	64.9%

Source of percent of total diet that is supplemental diet: Donovan (1999)

Table L-7: Regional Digestible Energy (DE), Methane Conversion Rates (Y_m), and population percentages for Cattle in 2001

Animal Type	Data	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Beef Repl. Heif.	DE ^a	65	59	66	64	65	65	64
	Y _m ^b	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
	Pop. ^c	3%	10%	31%	23%	2%	14%	17%
Dairy Repl. Heif.	DE	66	66	66	64	68	66	66
	Y _m	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
	Pop.	18%	12%	5%	4%	18%	36%	7%
Steer Stockers	DE	65	59	66	64	65	65	64
	Y _m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
	Pop.	4%	8%	42%	22%	2%	18%	5%
Heifer Stockers	DE	65	59	66	64	65	65	64
	Y _m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
	Pop.	2%	7%	50%	22%	1%	15%	4%
Steer Feedlot	DE	85	85	85	85	85	85	85
	Y _m	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
	Pop.	3%	8%	48%	24%	1%	16%	1%
Heifer Feedlot	DE	85	85	85	85	85	85	85
	Y _m	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
	Pop.	3%	8%	48%	24%	1%	16%	1%
Beef Cows	DE	63	57	64	62	63	63	62
	Y _m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
	Pop.	2%	8%	28%	26%	2%	14%	19%
Dairy Cows	DE	69	66	69	68	69	69	68
	Y _m	4.8%	5.8%	5.8%	5.7%	5.8%	5.8%	5.6%
	Pop.	17%	13%	5%	6%	18%	33%	8%
Steer Step-Up	DE	73	73	73	73	73	73	73
	Y _m	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
Heifer Step-Up	DE	73	73	73	73	73	73	73
	Y _m	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%

^a Digestible Energy in units of percent GE (MJ/Day).

^b Methane Conversion Rate is the fraction of GE in feed converted to methane.

^c Percent of each subcategory population present in each region.

Table L-8: CH₄ Emissions from Cattle (Gg)

Cattle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Dairy	1,375	1,378	1,375	1,316	1,314	1,320	1,254	1,255	1,251	1,266	1,284	1,282
Cows	1,142	1,148	1,143	1,082	1,082	1,088	1,024	1,028	1,026	1,038	1,059	1,055
Replacements 7-11 months	49	49	49	49	49	49	48	48	48	48	48	48
Replacements 12-23 months	184	181	183	185	183	183	181	179	177	180	177	179
Beef	3,961	3,920	4,031	4,070	4,147	4,272	4,227	4,124	4,046	4,035	3,976	3,936
Cows	2,428	2,432	2,468	2,494	2,585	2,628	2,638	2,574	2,531	2,520	2,506	2,492
Replacements 7-11 months	52	54	57	60	62	61	60	56	54	53	53	54
Replacements 12-23 months	190	196	203	216	229	232	225	216	206	198	198	200
Steer Stockers	430	402	464	482	435	479	455	430	418	393	369	372
Heifer Stockers	231	220	233	240	231	249	239	241	236	227	213	215
Feedlot Cattle	413	397	384	353	374	383	371	375	378	420	416	384
Bulls	218	220	222	224	231	239	239	233	223	224	220	219
Total	5,336	5,298	5,406	5,385	5,461	5,591	5,481	5,379	5,297	5,300	5,260	5,218

Note: Totals may not sum due to independent rounding.

Table L-9: Emission Factors for Other Livestock (kg CH₄/head/year)

Livestock Type	Emission Factor
Sheep	8
Goats	5
Horses	18
Swine	1.5

Source: IPCC (2000).

Table L-10: CH₄ Emissions from Enteric Fermentation (Tg CO₂ Eq.)

Livestock Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	83.2	82.3	84.7	85.5	87.1	89.7	88.8	86.6	85.0	84.7	83.5	82.7
Dairy Cattle	28.9	28.9	28.9	27.6	27.6	27.7	26.3	26.4	26.3	26.6	27.0	26.9
Horses	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.9	1.8	1.7	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.2
Swine	1.7	1.8	1.8	1.8	1.9	1.9	1.8	1.8	2.0	1.9	1.9	1.9
Goats	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	117.9	117.1	119.4	118.8	120.4	123.0	120.5	118.3	116.7	116.6	115.7	114.8

Table L-11: CH₄ Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	3,961	3,920	4,031	4,070	4,147	4,272	4,227	4,124	4,046	4,035	3,976	3,936
Dairy Cattle	1,375	1,378	1,375	1,316	1,314	1,320	1,254	1,255	1,251	1,266	1,284	1,282
Horses	91	92	92	92	92	92	93	93	94	93	94	95
Sheep	91	89	86	82	79	72	68	64	63	58	56	56
Swine	81	85	88	87	90	88	84	88	93	90	88	88
Goats	13	13	13	12	12	11	10	10	10	10	10	10
Total	5,612	5,576	5,685	5,658	5,733	5,855	5,737	5,635	5,557	5,551	5,509	5,468

ANNEX M

Methodology for Estimating CH₄ and N₂O Emissions from Manure Management

This annex presents a discussion of the methodology used to calculate methane and nitrous oxide emissions from manure management systems. More detailed discussions of selected topics may be found in supplemental memoranda in the supporting docket to this inventory.

The following steps were used to estimate methane and nitrous oxide emissions from the management of livestock manure. Nitrous oxide emissions associated with pasture, range, or paddock systems and daily spread systems are included in the emissions estimates for Agricultural Soil Management (see Annex N).

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2001 for all livestock types, except horses and goats, were obtained from the USDA National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f, 2002 a-f). The actual population data used in the emissions calculations for cattle and swine were downloaded from the USDA National Agricultural Statistics Service Population Estimates Data Base (<<http://www.usda.gov/nass/>>). Horse population data were obtained from the FAOSTAT database (FAO 2002). Goat population data for 1992 and 1997 were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000).

A summary of the livestock population characterization data used to calculate methane and nitrous oxide emissions is presented in Table M-1.

Dairy Cattle: The total annual dairy cow and heifer state population data for 1990 through 2001 are provided in various USDA National Agricultural Statistics Service reports (1995a, 1999a, 2000a-b, 2001a-b, 2002a-b). The actual total annual dairy cow and heifer state population data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<<http://www.usda.gov/nass/>>) for Cattle and Calves. The specific data used to estimate dairy cattle populations are “Cows That Calved – Milk” and “Heifers 500+ Lbs – Milk Repl.”

Beef Cattle: The total annual beef cattle population data for each state for 1990 through 2001 are provided in various USDA National Agricultural Statistics Service reports (1995a, 1999a, 2000a-b, 2001a-b, 2002a-b). The actual data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<<http://www.usda.gov/nass/>>), Cattle and Calves. The specific data used to estimate beef cattle populations are: “Cows That Calved—Beef,” “Heifers 500+ Lbs—Beef Repl,” “Heifers 500+ Lbs—Other,” and “Steers 500+ Lbs.” Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

For all beef cattle groups (cows, heifers, steer, bulls, and calves), the USDA data provide cattle inventories from January and July of each year. Cattle inventories change over the course of the year, sometimes significantly, as new calves are born and as fattened cattle are slaughtered; therefore, to develop the best estimate for the annual animal population, the average inventory of cattle by state was calculated. USDA provides January inventory data for each state; however, July inventory data is only presented as a total for the United States. In order to estimate average annual populations by state, a “scaling factor” was developed that adjusts the January state-level data to reflect July inventory changes. This factor equals the average of the US January and July data divided by the January data. The scaling factor is derived for each cattle group and is then applied to the January state-level data to arrive at the state-level annual population estimates.

Swine: The total annual swine population data for each state for 1990 through 2001 are provided in various USDA National Agricultural Statistics Service reports (USDA 1994a, 1998a, 2000c, 2001c, 2002c). The USDA data provides quarterly data for each swine subcategory: breeding, market under 60 pounds (less than 27 kg), market 60 to 119 pounds (27 to 54 kg), market 120 to 179 pounds (54 to 81 kg), and market 180 pounds and over (greater than 82 kg). The average of the quarterly data was used in the emissions calculations. For states where only

December inventory is reported, the December data were used directly. The actual data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<<http://www.usda.gov/nass/>>), Hogs and Pigs.

Sheep: The total annual sheep population data for each state for 1990 through 2001 were obtained from USDA National Agricultural Statistics Service (USDA 1994b, 1999c, 2000f, 2001f, 2002f). Population data for lamb and sheep on feed are not available after 1993. The number of lamb and sheep on feed for 1994 through 2001 were calculated using the average of the percent of lamb and sheep on feed from 1990 through 1993. In addition, all of the sheep and lamb “on feed” are not necessarily on “feedlots”; they may be on pasture/crop residue supplemented by feed. Data for those animals on feed that are on feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb on feedlots for all years, it was assumed that the percentage of sheep and lamb on feed that are on feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

Goats: Annual goat population data by state were available for only 1992 and 1997 (USDA 1999d). The data for 1992 were used for 1990 through 1992 and the data for 1997 were used for 1997 through 2001. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

Poultry: Annual poultry population data by state for the various animal categories (hens 1 year and older, total pullets, other chickens, broilers, and turkeys) were obtained from USDA National Agricultural Statistics Service (USDA 1995b, 1998b, 1999b, 2000d-e, 2000g, 2001d-e, 2002d-e). The annual population data for boilers and turkeys were adjusted for turnover (i.e., slaughter) rate (Lange 2000).

Horses: The Food and Agriculture Organization (FAO) publishes annual horse population data, which were accessed from the FAOSTAT database at <<http://apps.fao.org/>> (FAO 2002).

Step 2: Waste Characteristics Data

Methane and nitrous oxide emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids excretion rate (VS)
- Maximum methane producing capacity (B_0) for U.S. animal waste
- Nitrogen excretion rate (N_{ex})
- Typical animal mass (TAM)

Table M-2 presents a summary of the waste characteristics used in the emissions estimates. Published sources were reviewed for U.S.-specific livestock waste characterization data that would be consistent with the animal population data discussed in Step 1. The USDA’s National Engineering Handbook, Agricultural Waste Management Field Handbook (USDA 1996a) is one of the primary sources of waste characteristics. In some cases, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) were used to supplement the USDA data. The volatile solids (VS) and nitrogen excretion data for breeding swine are a combination of the types of animals that make up this animal group, namely gestating and farrowing swine and boars. It is assumed that a group of breeding swine is typically broken out as 80 percent gestating sows, 15 percent farrowing swine, and 5 percent boars (Safley 2000).

The method for calculating volatile solids production from beef and dairy cows, heifers, and steer is based on the relationship between animal diet and energy utilization, which is modeled in the enteric fermentation portion of the inventory. Volatile solids content of manure equals the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material which, when combined with urinary excretions, constitutes manure. The enteric fermentation model requires the estimation of gross energy intake and its fractional digestibility, digestible energy, in the process of estimating enteric methane emissions (see Appendix K for details on the enteric energy model). These two inputs were used to calculate the indigestible energy per animal unit as gross energy minus digestible energy plus an additional 2 percent of gross energy for urinary energy excretion per animal unit. This was then converted to volatile solids production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 20.1 MJ/kg (Garrett and Johnson, 1983). The equation used for calculating volatile solids is as follows:

$$\text{VS production (kg)} = [\text{GE} - \text{DE} + (0.02 * \text{GE})] / 20.1 \text{ (MJ/kg)}$$

Where:

GE= gross energy intake (MJ)

DE= digestible energy (MJ)

This equation was used to calculate volatile solids rates for each region, cattle type, and year, with state-specific volatile solids excretion rates assigned based on which region of the country the state is located in (Peterson et al., 2002).

Table M-3 presents the state-specific volatile solids production rates used for 2001.

Step 3: Waste Management System Usage Data

Estimates were made of the distribution of wastes by management system and animal type using the following sources of information:

- State contacts to estimate the breakout of dairy cows on pasture, range, or paddock, and the percent of wastes managed by daily spread systems (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, Wright 2000)
- Data collected for EPA's Office of Water, including site visits, to medium and large beef feedlot, dairy, swine, and poultry operations (EPA 2001a)
- Contacts with the national USDA office to estimate the percent of beef steer and heifers on feedlots (Milton 2000)
- Survey data collected by USDA (USDA 1998d, 2000h) and re-aggregated by farm size and geographic location, used for small operations
- Survey data collected by the United Egg Producers (UEP 1999) and USDA (2000i) and previous EPA estimates (EPA 1992) of waste distribution for layers
- Survey data collected by Cornell University on dairy manure management operations in New York (Poe 1999)
- Previous EPA estimates of waste distribution for sheep, goat, and horse operations (EPA 1992)

Beef Feedlots: Based on EPA site visits and state contacts, beef feedlot manure is almost exclusively managed in drylots. Therefore, 100 percent of the manure excreted at beef feedlots is expected to be deposited in drylots and generate emissions. In addition, a portion of the manure that is deposited in the drylot will run off the drylot during rain events and be captured in a waste storage pond. An estimate of the runoff has been made by EPA's Office of Water for various geographic regions of the United States. These runoff numbers were used to estimate emissions from runoff storage ponds located at beef feedlots (EPA 2001a).

Dairy Cows: Based on EPA site visits and state contacts, manure from dairy cows at medium (200 through 700 head) and large (greater than 700 head) operations are managed using either flush systems or scrape/slurry systems. In addition, they may have a solids separator in place prior to their storage component. Estimates of the percent of farms that use each type of system (by geographic region) were developed by EPA's Office of Water, and were used to estimate the percent of wastes managed in lagoons (flush systems), liquid/slurry systems (scrape systems), and solid storage (separated solids) (EPA 2001a). Manure management system data for small (fewer than 200 head) dairies were obtained from USDA (USDA 2000h). These operations are more likely to use liquid/slurry and solid storage management systems than anaerobic lagoon systems. The reported manure management systems were deep pit, liquid/slurry (also includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (also includes manure pack, outside storage, and inside storage).

The percent of wastes by system was estimated using the USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992 and 1997 Census of Agriculture (USDA 1999e) were used to determine the percentage of all dairies using the various manure management systems. Due to lack of

additional data for other years, it was assumed that the data provided for 1992 were the same as that for 1990 and 1991, and data provided for 1997 were the same as that for 1998, 1999, 2000, and 2001. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations. These organizations include state NRCS offices, state extension services, state universities, USDA National Agricultural Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Contacts at Cornell University provided survey data on dairy manure management practices in New York (Poe 1999). Census of Agriculture population data for 1992 and 1997 (USDA 1999e) were used in conjunction with the state data obtained from personal communications to determine regional percentages of total dairy cattle and dairy wastes that are managed using these systems. These percentages were applied to the total annual dairy cow and heifer state population data for 1990 through 2001, which were obtained from the National Agricultural Statistics Service (USDA 1995a, 1999a, 2000a-b, 2001a-b, 2002a-b).

Of the dairies using systems other than daily spread and pasture, range, or paddock systems, some dairies reported using more than one type of manure management system. Therefore, the total percent of systems reported by USDA for a region and farm size is greater than 100 percent. Typically, this means that some of the manure at a dairy is handled in one system (e.g., a lagoon), and some of the manure is handled in another system (e.g., drylot). However, it is unlikely that the same manure is moved from one system to another. Therefore, to avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100 percent, using the same distribution of systems. For example, if USDA reported that 65 percent of dairies use deep pits to manage manure and 55 percent of dairies use anaerobic lagoons to manage manure, it was assumed that 54 percent (i.e., 65 percent divided by 120 percent) of the manure is managed with deep pits and 46 percent (i.e., 55 percent divided by 120 percent) of the manure is managed with anaerobic lagoons (ERG 2000).

Dairy Heifers: The percent of dairy heifer operations that are pasture, range, or paddock or that operate as daily spread was estimated using the same approach as dairy cows. Similar to beef cattle, dairy heifers are housed on drylots when not pasture based. Based on data from EPA's Office of Water (EPA 2001a), it was assumed that 100 percent of the manure excreted by dairy heifers is deposited in drylots and generates emissions. Estimates of runoff have been made by EPA's Office of Water for various geographic regions of the US (EPA 2001a).

Swine: Based on data collected during site visits for EPA's Office of Water (ERG 2000), manure from swine at large (greater than 2000 head) and medium (200 through 2000 head) operations are primarily managed using deep pit systems, liquid/slurry systems, or anaerobic lagoons. Manure management system data were obtained from USDA (USDA 1998d). It was assumed those operations with less than 200 head use pasture, range, or paddock systems. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992 and 1997 Census of Agriculture (USDA 1999e) were used to determine the percentage of all swine utilizing the various manure management systems. The reported manure management systems were deep pit, liquid/slurry (also includes above- and below-ground slurry), anaerobic lagoon, and solid storage (also includes solids separated from liquids).

Some swine operations reported using more than one management system; therefore, the total percent of systems reported by USDA for a region and farm size is greater than 100 percent. Typically, this means that some of the manure at a swine operation is handled in one system (e.g., liquid system), and some of the manure is handled in another system (e.g., dry system). However, it is unlikely that the same manure is moved from one system to another. Therefore, to avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100 percent, using the same distribution of systems, as explained under "Dairy Cows".

Sheep: It was assumed that all sheep wastes not deposited on feedlots were deposited on pasture, range, or paddock lands (Anderson 2000).

Goats/Horses: Estimates of manure management distribution were obtained from EPA's previous estimates (EPA 1992).

Poultry – Layers: Waste management system data for layers for 1990 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). The percentage of layer operations using a shallow pit flush house with anaerobic lagoon or high-rise house without bedding was obtained for 1999 from United Egg Producers, voluntary survey, 1999 (UEP 1999). These data were augmented for key poultry states (AL, AR, CA, FL, GA, IA, IN, MN, MO, NC, NE, OH, PA, TX, and WA) with USDA data (USDA 2000i). It was

assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. It was assumed that system usage in 2000 and 2001 was equal to that estimated for 1999. It was also assumed that 1 percent of poultry wastes are deposited on pasture, range, or paddock lands (EPA 1992).

Poultry - Broilers/Turkeys: The percentage of turkeys and broilers on pasture or in high-rise houses without bedding was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA1992). It was assumed that 1 percent of poultry wastes are deposited in pastures, range, and paddocks (EPA 1992).

Step 4: Emission Factor Calculations

Methane conversion factors (MCFs) and nitrous oxide emission factors (EFs) used in the emission calculations were determined using the methodologies shown below:

Methane Conversion Factors (MCFs)

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000) for anaerobic lagoon systems published default methane conversion factors of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. Therefore, a climate-based approach was identified to estimate MCFs for anaerobic lagoon and other liquid storage systems.

The following approach was used to develop the MCFs for liquid systems, and is based on the van't Hoff-Arrhenius equation used to forecast performance of biological reactions. One practical way of estimating MCFs for liquid manure handling systems is based on the mean ambient temperature and the van't Hoff-Arrhenius equation with a base temperature of 30°C, as shown in the following equation (Safley and Westerman 1990):

$$f = \exp \left[\frac{E(T_2 - T_1)}{RT_1T_2} \right]$$

Where:

$T_1 = 303.16\text{K}$

$T_2 = \text{ambient temperature (K) for climate zone (in this case, a weighted value for each state)}$

$E = \text{activation energy constant (15,175 cal/mol)}$

$R = \text{ideal gas constant (1.987 cal/K mol)}$

The factor “f” represents the proportion of volatile solids that are biologically available for conversion to methane based on the temperature of the system. The temperature is assumed equal to the ambient temperature. For colder climates, a minimum temperature of 5°C was established for uncovered anaerobic lagoons and 7.5°C for other liquid manure handling systems. For those animal populations using liquid systems (i.e., dairy cow, dairy heifer, layers, beef on feedlots, and swine) monthly average state temperatures were based on the counties where the specific animal population resides (i.e., the temperatures were weighted based on the percent of animals located in each county). The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2001), and the county population data were based on 1992 and 1997 Census data (USDA 1999e). County population data for 1990 and 1991 were assumed to be the same as 1992; county population data for 1998 through 2001 were assumed to be the same as 1997; and county population data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

Annual MCFs for liquid systems are calculated as follows for each animal type, state, and year of the inventory:

- 1) Monthly temperatures are calculated by using county-level temperature and population data. The weighted-average temperature for a state is calculated using the population estimates and average monthly temperature in each county.
- 2) Monthly temperatures are used to calculate a monthly van't Hoff-Arrhenius “f” factor, using the equation presented above. A minimum temperature of 5°C is used for anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems.

- 3) Monthly production of volatile solids that are added to the system is estimated based on the number of animals present and, for lagoon systems, adjusted for a management and design practices factor. This factor accounts for other mechanisms by which volatile solids are removed from the management system prior to conversion to methane, such as solids being removed from the system for application to cropland. This factor, equal to 0.8, has been estimated using currently available methane measurement data from anaerobic lagoon systems in the United States (ERG 2001).
- 4) The amount of volatile solids available for conversion to methane is assumed to be equal to the amount of volatile solids produced during the month (from Step 3). For anaerobic lagoons, the amount of volatile solids available also includes volatile solids that may remain in the system from previous months.
- 5) The amount of volatile solids consumed during the month is equal to the amount available for conversion multiplied by the “f” factor.
- 6) For anaerobic lagoons, the amount of volatile solids carried over from one month to the next is equal to the amount available for conversion minus the amount consumed.
- 7) The estimated amount of methane generated during the month is equal to the monthly volatile solids consumed multiplied by the maximum methane potential of the waste (B_0).
- 8) The annual MCF is then calculated as:

$$MCF_{(annual)} = CH_4 \text{ generated}_{(annual)} / (VS \text{ generated}_{(annual)} \times B_0)$$

Where:

$MCF_{(annual)}$ = Methane conversion factor

$VS \text{ generated}_{(annual)}$ = Volatile solids excretion rate

B_0 = Maximum methane producing potential of the waste

In order to account for the carry-over of volatile solids from the year prior to the inventory year for which estimates are calculated, it is assumed in the MCF calculation for lagoons that a portion of the volatile solids from October, November, and December of the year prior to the inventory year are available in the lagoon system starting January of the inventory year.

Following this procedure, the resulting MCF accounts for temperature variation throughout the year, residual volatile solids in a system (carry-over), and management and design practices that may reduce the volatile solids available for conversion to methane. The MCFs presented in Table M-4 by state and waste management system represent the average MCF for 2001 by state for all animal groups located in that state. However, in the calculation of methane emissions, specific MCFs for each animal type in the state are used.

Nitrous Oxide Emission Factors

Nitrous oxide emission factors for all manure management systems were set equal to the default IPCC factors (IPCC 2000).

Step 5: Weighted Emission Factors

For beef cattle, dairy cattle, swine, and poultry, the emission factors for both methane and nitrous oxide were weighted to incorporate the distribution of wastes by management system for each state. The following equation was used to determine the weighted MCF for a particular animal type in a particular state:

$$MCF_{animal, state} = \sum_{system} (MCF_{system, state} \times \%Manure_{animal, system, state})$$

Where:

$MCF_{animal, state}$ = Weighted MCF for that animal group and state

$MCF_{system, state} = \text{MCF for that system and state (see Step 4)}$

$\% \text{ Manure}_{animal, system, state} = \text{Percent of manure managed in the system for that animal group in that state (expressed as a decimal)}$

The weighted nitrous oxide emission factor for a particular animal type in a particular state was determined as follows:

$$EF_{animal, state} = \sum_{system} (EF_{system} \times \% \text{ Manure}_{animal, system, state})$$

Where:

$EF_{animal, state} = \text{Weighted emission factor for that animal group and state}$

$EF_{system} = \text{Emission factor for that system (see Step 4)}$

$\% \text{ Manure}_{animal, system, state} = \text{Percent of manure managed in the system for that animal group in that state (expressed as a decimal)}$

Data for the calculated weighted factors for 1992 was taken from the 1992 Census of Agriculture, combined with assumptions on manure management system usage based on farm size, and were also used for 1990 and 1991. Data for the calculated weighted factors for 1997 was taken from the 1997 Census of Agriculture, combined with assumptions on manure management system usage based on farm size, and were also used for 1998, 1999, 2000, and 2001. Factors for 1993 through 1996 were calculated by interpolating between the two sets of factors. A summary of the weighted MCFs used to calculate beef feedlot, dairy cow and heifer, swine, and poultry emissions for 2001 are presented in Table M-5.

Step 6: Methane and Nitrous Oxide Emission Calculations

For beef feedlot cattle, dairy cows, dairy heifers, swine, and poultry, methane emissions were calculated for each animal group as follows:

$$\text{Methane}_{animal\ group} = \sum_{state} (\text{Population} \times VS \times B_o \times MCF_{animal, state} \times 0.662)$$

Where:

$\text{Methane}_{animal\ group} = \text{methane emissions for that animal group (kg CH}_4\text{/yr)}$

$\text{Population} = \text{annual average state animal population for that animal group (head)}$

$VS = \text{total volatile solids produced annually per animal (kg/yr/head)}$

$B_o = \text{maximum methane producing capacity per kilogram of VS (m}^3 \text{ CH}_4\text{/kg VS)}$

$MCF_{animal, state} = \text{weighted MCF for the animal group and state (see Step 5)}$

$0.662 = \text{conversion factor of m}^3 \text{ CH}_4 \text{ to kilograms CH}_4 \text{ (kg CH}_4\text{/m}^3 \text{ CH}_4\text{)}$

Methane emissions from other animals (i.e., sheep, goats, and horses) were based on the 1990 methane emissions estimated using the detailed method described in *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (EPA 1993). This approach is based on animal-specific manure characteristics and management system data. This process was not repeated for subsequent years for these other animal types. Instead, national populations of each of the animal types were used to scale the 1990 emissions estimates to the period 1991 through 2001.

Nitrous oxide emissions were calculated for each animal group as follows:

$$\text{Nitrous Oxide}_{\text{animal group}} = \sum_{\text{state}} (\text{Population} \times N_{\text{ex}} \times EF_{\text{animal, state}} \times 44 / 28)$$

Where:

Nitrous Oxide_{animal group} = nitrous oxide emissions for that animal group (kg/yr)

Population = annual average state animal population for that animal group (head)

N_{ex} = total Kjeldahl nitrogen excreted annually per animal (kg/yr/head)

EF_{animal, state} = weighted nitrous oxide emission factor for the animal group and state, kg N₂O-N/kg N excreted (see Step 5)

44/28 = conversion factor of N₂O-N to N₂O

Emission estimates are summarized in Table M-6 and Table M-7.

Table M-1: Livestock Population (1,000 Head)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Dairy Cattle	14,143	13,980	13,830	13,767	13,566	13,502	13,305	13,138	12,992	13,026	13,070	12,995
Dairy Cows	10,007	9,883	9,714	9,679	9,504	9,491	9,410	9,309	9,200	9,142	9,220	9,166
Dairy Heifer	4,135	4,097	4,116	4,088	4,062	4,011	3,895	3,829	3,793	3,884	3,850	3,828
Swine	53,941	56,478	58,532	58,016	59,951	58,899	56,220	58,728	61,991	60,245	58,892	58,960
Market Swine	47,043	49,247	51,276	50,859	52,669	51,973	49,581	51,888	55,150	53,871	52,658	52,772
Market <60 lbs.	18,359	19,212	19,851	19,434	20,157	19,656	18,851	19,886	20,691	19,928	19,582	19,628
Market 60-119 lbs.	11,734	12,374	12,839	12,656	13,017	12,836	12,157	12,754	13,552	13,256	12,933	12,940
Market 120-179 lbs.	9,440	9,840	10,253	10,334	10,671	10,545	10,110	10,480	11,235	11,043	10,753	10,747
Market >180 lbs.	7,510	7,822	8,333	8,435	8,824	8,937	8,463	8,768	9,672	9,645	9,390	9,457
Breeding Swine	6,899	7,231	7,255	7,157	7,282	6,926	6,639	6,840	6,841	6,374	6,233	6,188
Beef Cattle	86,087	87,267	88,548	90,321	92,571	94,391	94,269	92,290	90,730	90,032	89,215	88,598
Feedlot Steers	7,338	7,920	7,581	7,984	7,797	7,763	7,380	7,644	7,845	7,781	8,280	8,566
Feedlot Heifers	3,621	4,035	3,626	3,971	3,965	4,047	3,999	4,396	4,459	4,578	4,872	5,035
NOF Bulls ²	2,180	2,198	2,220	2,239	2,306	2,392	2,392	2,325	2,235	2,241	2,196	2,187
NOF Calves ²	23,909	23,853	24,118	24,209	24,586	25,170	25,042	24,363	24,001	23,895	23,508	22,953
NOF Heifers ²	8,872	8,938	9,520	9,850	10,469	10,680	10,869	10,481	9,998	9,725	9,353	9,224
NOF Steers ²	7,490	7,364	8,031	7,935	8,346	8,693	9,077	8,452	8,050	7,864	7,248	7,009
NOF Cows ²	32,677	32,960	33,453	34,132	35,101	35,645	35,509	34,629	34,143	33,948	33,760	33,624
Sheep	11,358	11,174	10,797	10,201	9,836	8,989	8,465	8,024	7,825	7,215	7,032	6,965
Sheep not on Feed	10,271	10,168	9,748	9,151	8,940	8,193	7,697	7,270	7,085	6,519	6,351	6,290
Sheep on Feed	1,088	1,055	1,049	1,050	896	797	768	754	740	696	681	675
Goats	2,516	2,516	2,516	2,410	2,305	2,200	2,095	1,990	1,990	1,990	1,990	1,990
Poultry	1,537,074	1,594,944	1,649,998	1,707,422	1,769,135	1,679,704	1,882,078	1,926,790	1,963,919	2,007,284	2,072,877	2,054,998
Hens >1 yr.	119,551	117,178	121,103	131,688	135,094	133,841	138,048	140,966	150,778	151,914	153,232	153,237
Pullets ¹	227,083	239,559	243,267	240,712	243,286	246,599	247,446	261,515	265,634	274,520	273,801	279,726
Chickens	6,545	6,857	7,113	7,240	7,369	7,637	7,243	7,549	7,682	9,659	8,088	8,126
Broilers	1,066,209	1,115,845	1,164,089	1,217,147	1,275,916	1,184,667	1,381,229	1,411,673	1,442,596	1,481,093	1,549,818	1,525,291
Turkeys	117,685	115,504	114,426	110,635	107,469	106,960	108,112	105,088	97,229	90,098	87,938	88,619
Horses	5,069	5,100	5,121	5,130	5,110	5,130	5,150	5,170	5,237	5,170	5,240	5,300

Note: Totals may not sum due to independent rounding.

¹Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

²NOF = Not on Feed

Table M-2: Waste Characteristics Data

Animal Group	Average TAM (kg) Source	Total Kjeldahl Nitrogen, N _{ex} (kg/day per 1,000 kg mass) Source	Maximum Methane Generation Potential, B ₀ (m ³ CH ₄ /kg VS added) Source	Volatile Solids, VS (kg/day per 1,000 kg mass) Source
Dairy Cow	604 Safley 2000	0.44 USDA 1996a	0.24 Morris 1976	Table M-3 Peterson et al., 2002
Dairy Heifer	476 Safley 2000	0.31 USDA 1996a	0.17 Bryant et. al. 1976	Table M-3 Peterson et al., 2002
Feedlot Steers	420 USDA 1996a	0.30 USDA 1996a	0.33 Hashimoto 1981	Table M-3 Peterson et al., 2002
Feedlot Heifers	420 USDA 1996a	0.30 USDA 1996a	0.33 Hashimoto 1981	Table M-3 Peterson et al., 2002
NOF Bulls	750 Safley 2000	0.31 USDA 1996a	0.17 Hashimoto 1981	6.04 USDA 1996a
NOF Calves	159 USDA 1998c	0.30 USDA 1996a	0.17 Hashimoto 1981	6.41 USDA 1996a
NOF Heifers	420 USDA 1996a	0.31 USDA 1996a	0.17 Hashimoto 1981	Table M-3 Peterson et al., 2002
NOF Steers	318 Safley 2000	0.31 USDA 1996a	0.17 Hashimoto 1981	Table M-3 Peterson et al., 2002
NOF Cows	590 Safley 2000	0.33 USDA 1996a	0.17 Hashimoto 1981	Table M-3 Peterson et al., 2002
Market Swine <60 lbs.	15.88 Safley 2000	0.60 USDA 1996a	0.48 Hashimoto 1984	8.80 USDA 1996a
Market Swine 60-119 lbs.	40.60 Safley 2000	0.42 USDA 1996a	0.48 Hashimoto 1984	5.40 USDA 1996a
Market Swine 120-179 lbs.	67.82 Safley 2000	0.42 USDA 1996a	0.48 Hashimoto 1984	5.40 USDA 1996a
Market Swine >180 lbs.	90.75 Safley 2000	0.42 USDA 1996a	0.48 Hashimoto 1984	5.40 USDA 1996a
Breeding Swine	198 Safley 2000	0.24 USDA 1996a	0.48 Hashimoto 1984	2.60 USDA 1996a
Sheep	27 ASAE 1999	0.42 ASAE 1999	NA NA	NA NA
Goats	64 ASAE 1999	0.45 ASAE 1999	NA NA	NA NA
Horses	450 ASAE 1999	0.30 ASAE 1999	NA NA	NA NA
Hens >= 1 yr	1.8 ASAE 1999	0.83 USDA 1996a	0.39 Hill 1982	10.8 USDA 1996a
Pullets	1.8 ASAE 1999	0.62 USDA 1996a	0.39 Hill 1982	9.7 USDA 1996a
Other Chickens	1.8 ASAE 1999	0.83 USDA 1996a	0.39 Hill 1982	10.8 USDA 1996a
Broilers	0.9 ASAE 1999	1.10 USDA 1996a	0.36 Hill 1984	15.0 USDA 1996a
Turkeys	6.8 ASAE 1999	0.74 USDA 1996a	0.36 Hill 1984	9.7 USDA 1996a

NA = Not Applicable. In these cases, methane emissions were projected based on animal population growth from base year.

Table M-3: Estimated Volatile Solids Production Rate By State for 2001

State	Dairy Cow kg/day/1000 kg	Dairy Heifer kg/day/1000 kg	NOF Cows kg/day/1000 kg	NOF Heifers kg/day/1000 kg	NOF Steers kg/day/1000 kg	Feedlot Heifers kg/day/1000 kg	Feedlot Steers kg/day/1000 kg
Alabama	8.56	6.82	6.74	7.16	7.47	3.33	3.26
Alaska	10.71	6.82	8.71	9.42	9.87	3.33	3.26
Arizona	10.71	6.82	8.71	9.43	9.87	3.33	3.26
Arkansas	8.06	7.57	6.72	7.13	7.45	3.36	3.30
California	9.36	6.82	6.57	6.95	7.27	3.32	3.26
Colorado	8.33	6.82	6.19	6.51	6.82	3.35	3.28
Connecticut	8.41	6.14	6.62	7.03	7.33	3.40	3.33
Delaware	8.41	6.14	6.62	7.01	7.33	3.40	3.33
Florida	8.56	6.82	6.74	7.17	7.47	3.33	3.26
Georgia	8.56	6.82	6.74	7.16	7.47	3.33	3.26
Hawaii	10.71	6.82	8.71	9.42	9.87	3.33	3.26
Idaho	10.71	6.82	8.71	9.40	9.87	3.33	3.26
Illinois	8.29	6.82	6.63	7.01	7.34	3.39	3.32
Indiana	8.29	6.82	6.63	7.01	7.34	3.39	3.32
Iowa	8.29	6.82	6.63	7.00	7.34	3.39	3.32
Kansas	8.33	6.82	6.19	6.51	6.82	3.35	3.28
Kentucky	8.56	6.82	6.74	7.16	7.47	3.33	3.26
Louisiana	8.06	7.57	6.72	7.14	7.45	3.36	3.30
Maine	8.41	6.14	6.62	7.04	7.33	3.40	3.33
Maryland	8.41	6.14	6.62	7.02	7.33	3.40	3.33
Massachusetts	8.41	6.14	6.62	7.02	7.33	3.40	3.33
Michigan	8.29	6.82	6.63	7.02	7.34	3.39	3.32
Minnesota	8.29	6.82	6.63	7.01	7.34	3.39	3.32
Mississippi	8.56	6.82	6.74	7.17	7.47	3.33	3.26
Missouri	8.29	6.82	6.63	7.02	7.34	3.39	3.32
Montana	8.33	6.82	6.19	6.54	6.82	3.35	3.28
Nebraska	8.33	6.82	6.19	6.51	6.82	3.35	3.28
Nevada	10.71	6.82	8.71	9.41	9.87	3.33	3.26
New Hampshire	8.41	6.14	6.62	7.04	7.33	3.40	3.33
New Jersey	8.41	6.14	6.62	7.03	7.33	3.40	3.33
New Mexico	10.71	6.82	8.71	9.40	9.87	3.33	3.26
New York	8.41	6.14	6.62	7.01	7.33	3.40	3.33
North Carolina	8.56	6.82	6.74	7.17	7.47	3.33	3.26
North Dakota	8.33	6.82	6.19	6.52	6.82	3.35	3.28
Ohio	8.29	6.82	6.63	7.02	7.34	3.39	3.32
Oklahoma	8.06	7.57	6.72	7.11	7.45	3.36	3.30
Oregon	10.71	6.82	8.71	9.42	9.87	3.33	3.26
Pennsylvania	8.41	6.14	6.62	7.02	7.33	3.40	3.33
Rhode Island	8.41	6.14	6.62	7.04	7.33	3.40	3.33
South Carolina	8.56	6.82	6.74	7.17	7.47	3.33	3.26
South Dakota	8.33	6.82	6.19	6.52	6.82	3.35	3.28
Tennessee	8.56	6.82	6.74	7.16	7.47	3.33	3.26
Texas	8.06	7.57	6.72	7.11	7.45	3.36	3.30
Utah	10.71	6.82	8.71	9.41	9.87	3.33	3.26
Vermont	8.41	6.14	6.62	7.02	7.33	3.40	3.33
Virginia	8.56	6.82	6.74	7.16	7.47	3.33	3.26
Washington	10.71	6.82	8.71	9.40	9.87	3.33	3.26
West Virginia	8.41	6.14	6.62	7.03	7.33	3.40	3.33
Wisconsin	8.29	6.82	6.63	7.01	7.34	3.39	3.32
Wyoming	8.33	6.82	6.19	6.53	6.82	3.35	3.28

Source: Peterson et al., 2002.

Table M-4: Methane Conversion Factors By State for Liquid Systems¹ for 2001

State	Liquid/Slurry and Deep Pit	Anaerobic Lagoon
Alabama	0.3511	0.7663
Alaska	0.1507	0.4845
Arizona	0.4673	0.7918
Arkansas	0.3760	0.7617
California	0.3630	0.7554
Colorado	0.2297	0.6668
Connecticut	0.2545	0.6763
Delaware	0.2823	0.6862
Florida	0.5195	0.7935
Georgia	0.3263	0.6578
Hawaii	0.5973	0.7728
Idaho	0.2311	0.6741
Illinois	0.2935	0.7202
Indiana	0.2792	0.7097
Iowa	0.2634	0.6986
Kansas	0.3401	0.7493
Kentucky	0.2726	0.6301
Louisiana	0.4542	0.7860
Maine	0.2119	0.6390
Maryland	0.2847	0.7190
Massachusetts	0.2448	0.6871
Michigan	0.2395	0.6751
Minnesota	0.2407	0.6785
Mississippi	0.4015	0.7722
Missouri	0.3252	0.7398
Montana	0.2153	0.6508
Nebraska	0.2815	0.7166
Nevada	0.2597	0.7009
New Hampshire	0.2191	0.6501
New Jersey	0.2778	0.7160
New Mexico	0.3210	0.7387
New York	0.2307	0.6683
North Carolina	0.3320	0.7473
North Dakota	0.2256	0.6612
Ohio	0.2652	0.6985
Oklahoma	0.3962	0.7681
Oregon	0.2120	0.6429
Pennsylvania	0.2610	0.7000
Rhode Island	0.2242	0.6032
South Carolina	0.3804	0.7690
South Dakota	0.2552	0.6970
Tennessee	0.2796	0.6343
Texas	0.4466	0.7817
Utah	0.2681	0.7116
Vermont	0.2134	0.6407
Virginia	0.2816	0.7142
Washington	0.2153	0.6498
West Virginia	0.2613	0.6968
Wisconsin	0.2353	0.6714
Wyoming	0.2244	0.6635

¹ As defined by IPCC (IPCC 2000).

Table M-5: Weighted Methane Conversion Factors for 2001

State	Beef Feedlot- Heifer	Beef Feedlot- Steer	Dairy Cow	Dairy Heifer	Swine - Market	Swine - Breeding	Layer	Broiler	Turkey
Alabama	0.0200	0.0170	0.1019	0.0189	0.4889	0.4912	0.3290	0.0150	0.0150
Alaska	0.0170	0.0170	0.1652	0.0165	0.0150	0.0150	0.1324	0.0150	0.0150
Arizona	0.0169	0.0166	0.6180	0.0165	0.5272	0.5272	0.4842	0.0150	0.0150
Arkansas	0.0199	0.0199	0.0754	0.0188	0.5499	0.5539	0.0150	0.0150	0.0150
California	0.0195	0.0197	0.5167	0.0184	0.5056	0.5022	0.1061	0.0150	0.0150
Colorado	0.0159	0.0159	0.4365	0.0157	0.2839	0.2835	0.4032	0.0150	0.0150
Connecticut	0.0175	0.0175	0.1082	0.0170	0.1443	0.1311	0.0492	0.0150	0.0150
Delaware	0.0181	0.0181	0.0967	0.0175	0.3315	0.3315	0.0329	0.0150	0.0150
Florida	0.0220	0.0220	0.4274	0.0204	0.2150	0.2160	0.3413	0.0150	0.0150
Georgia	0.0200	0.0200	0.1465	0.0188	0.0019	0.4957	0.3258	0.0150	0.0150
Hawaii	0.0228	0.0228	0.5474	0.0210	0.3966	0.3966	0.2045	0.0150	0.0150
Idaho	0.0159	0.0159	0.4509	0.0157	0.2101	0.2093	0.4043	0.0150	0.0150
Illinois	0.0167	0.0167	0.1219	0.0164	0.3354	0.3355	0.0293	0.0150	0.0150
Indiana	0.0167	0.0167	0.1002	0.0164	0.3230	0.3233	0.0150	0.0150	0.0150
Iowa	0.0166	0.0166	0.1009	0.0163	0.4187	0.4195	0.0150	0.0150	0.0150
Kansas	0.0170	0.0170	0.1236	0.0167	0.3638	0.3637	0.0297	0.0150	0.0150
Kentucky	0.0182	0.0182	0.0421	0.0175	0.0016	0.4517	0.0510	0.0150	0.0150
Louisiana	0.0209	0.0209	0.1121	0.0196	0.2039	0.2035	0.4777	0.0150	0.0150
Maine	0.0171	0.0171	0.0642	0.0167	0.0150	0.0150	0.0464	0.0150	0.0150
Maryland	0.0178	0.0177	0.0916	0.0172	0.2957	0.2956	0.0507	0.0150	0.0150
Massachusetts	0.0174	0.0175	0.0774	0.0169	0.1974	0.1968	0.0486	0.0150	0.0150
Michigan	0.0164	0.0164	0.1589	0.0162	0.2937	0.2927	0.0284	0.0150	0.0150
Minnesota	0.0164	0.0164	0.0916	0.0162	0.3064	0.3062	0.0150	0.0150	0.0150
Mississippi	0.0202	0.0202	0.0939	0.0190	0.5618	0.5622	0.4697	0.0150	0.0150
Missouri	0.0169	0.0169	0.1109	0.0166	0.3551	0.3550	0.0150	0.0150	0.0150
Montana	0.0159	0.0159	0.2602	0.0157	0.2625	0.2625	0.3985	0.0150	0.0150
Nebraska	0.0167	0.0167	0.1065	0.0164	0.3279	0.3275	0.0291	0.0150	0.0150
Nevada	0.0160	0.0160	0.5146	0.0157	0.0150	0.0150	0.0150	0.0150	0.0150
New Hampshire	0.0172	0.0172	0.0733	0.0167	0.1228	0.1221	0.0470	0.0150	0.0150
New Jersey	0.0178	0.0178	0.0831	0.0172	0.1894	0.1911	0.0500	0.0150	0.0150
New Mexico	0.0162	0.0162	0.5294	0.0159	0.0150	0.0150	0.4606	0.0150	0.0150
New York	0.0173	0.0173	0.0918	0.0168	0.2126	0.2119	0.0476	0.0150	0.0150
North Carolina	0.0182	0.0182	0.0656	0.0175	0.5841	0.5824	0.3209	0.0150	0.0150
North Dakota	0.0164	0.0164	0.0675	0.0161	0.2615	0.2618	0.0277	0.0150	0.0150
Ohio	0.0166	0.0166	0.1021	0.0163	0.3032	0.3034	0.0150	0.0150	0.0150
Oklahoma	0.0166	0.0166	0.3603	0.0162	0.5767	0.5811	0.4671	0.0150	0.0150
Oregon	0.0178	0.0178	0.2611	0.0172	0.1098	0.1096	0.1676	0.0150	0.0150
Pennsylvania	0.0175	0.0176	0.0603	0.0170	0.3196	0.3187	0.0150	0.0150	0.0150
Rhode Island	0.0176	0.0176	0.0394	0.0171	0.1953	0.1953	0.0143	0.0150	0.0150
South Carolina	0.0198	0.0198	0.1051	0.0187	0.5174	0.5149	0.4696	0.0150	0.0150
South Dakota	0.0165	0.0165	0.0949	0.0163	0.3058	0.3060	0.0285	0.0150	0.0150
Tennessee	0.0182	0.0182	0.0551	0.0176	0.0025	0.4238	0.0513	0.0150	0.0150
Texas	0.0167	0.0167	0.5148	0.0163	0.5367	0.5362	0.1075	0.0150	0.0150
Utah	0.0160	0.0160	0.3811	0.0158	0.3313	0.3290	0.4377	0.0150	0.0150
Vermont	0.0172	0.0172	0.0837	0.0167	0.0150	0.0150	0.0458	0.0150	0.0150
Virginia	0.0178	0.0177	0.0525	0.0172	0.4896	0.4901	0.0497	0.0150	0.0150
Washington	0.0178	0.0180	0.3206	0.0172	0.2133	0.2097	0.0888	0.0150	0.0150
West Virginia	0.0176	0.0176	0.0689	0.0171	0.2068	0.2062	0.0493	0.0150	0.0150
Wisconsin	0.0164	0.0164	0.1002	0.0162	0.2757	0.2753	0.0281	0.0150	0.0150
Wyoming	0.0159	0.0159	0.2385	0.0157	0.2863	0.2848	0.3997	0.0150	0.0150

Table M-6: CH₄ Emissions from Livestock Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Dairy Cattle	545	585	573	565	623	640	611	639	661	700	693	719
Dairy Cows	535	575	564	556	614	631	602	631	653	691	684	711
Dairy Heifer	9	9	9	9	9	9	9	8	8	9	9	9
Swine	623	675	638	679	740	763	729	781	876	838	813	815
Market Swine	484	524	500	534	584	608	581	626	716	683	665	666
Market <60 lbs.	102	110	103	109	119	121	116	125	140	131	128	128
Market 60-119 lbs.	101	111	104	110	119	123	117	127	143	136	132	132
Market 120-179 lbs.	136	147	140	151	165	170	164	175	200	191	185	184
Market >180 lbs.	145	156	152	165	182	193	185	198	233	225	220	221
Breeding Swine	139	151	138	146	156	155	148	156	160	156	148	150
Beef Cattle	161	160	161	161	164	164	164	161	158	158	157	155
Feedlot Steers	21	19	19	17	16	14	14	15	15	15	16	16
Feedlot Heifers	10	11	9	10	9	8	8	8	9	9	9	9
NOF Bulls	6	6	6	6	6	7	7	6	6	6	6	6
NOF Calves	15	15	15	15	15	16	16	15	15	15	15	14
NOF Heifers	16	17	18	18	19	20	20	19	18	18	17	17
NOF Steers	11	11	12	11	12	12	13	12	12	12	11	10
NOF Cows	80	81	82	84	86	87	87	85	84	83	83	82
Sheep	3	3	3	3	3	2	2	2	2	2	2	2
Goats	1	1	1	1	1	1	1	1	1	1	1	1
Poultry	128	129	125	129	129	124	125	127	130	124	125	128
Hens >1 yr.	33	31	33	34	34	33	32	31	33	31	31	31
Total Pullets	63	65	59	60	60	58	56	58	60	56	57	60
Chickens	4	4	4	4	4	4	3	3	4	3	3	3
Broilers	19	20	21	21	22	21	24	25	25	26	27	27
Turkeys	10	10	10	10	9	9	9	9	8	8	8	8
Horses	29	29	29	29	29	29	29	29	30	29	30	30

Table M-7: N₂O Emissions from Livestock Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Dairy Cattle	13.9	13.6	13.5	13.4	13.3	13.2	13.0	12.9	12.7	12.7	12.7	12.6
Dairy Cows	9.4	9.3	9.0	8.9	8.7	8.7	8.6	8.4	8.2	8.2	8.2	8.1
Dairy Heifer	4.4	4.4	4.4	4.5	4.6	4.6	4.5	4.5	4.5	4.6	4.6	4.6
Swine	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4
Market Swine	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1
Market <60 lbs.	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Market 60-119 lbs.	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Market 120-179 lbs.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Market >180 lbs.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Breeding Swine	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Beef Cattle	15.8	17.3	16.2	17.3	17.0	17.1	16.5	17.4	17.8	17.9	19.0	19.7
Feedlot Steers	10.6	11.5	11.0	11.5	11.3	11.2	10.7	11.1	11.3	11.3	12.0	12.4
Feedlot Heifers	5.2	5.8	5.2	5.7	5.7	5.9	5.8	6.4	6.4	6.6	7.0	7.3
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	20.5	20.9	21.3	21.6	22.1	20.9	23.2	23.3	23.2	23.2	23.8	23.6
Hens >1 yr.	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Pullets	1.0	1.0	1.0	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Chickens	+	+	+	+	+	+	+	+	+	+	+	+
Broilers	12.0	12.5	13.1	13.7	14.3	13.3	15.5	15.9	16.2	16.7	17.4	17.1
Turkeys	6.7	6.6	6.5	6.3	6.1	6.1	6.2	6.0	5.6	5.1	5.0	5.1
Horses	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7

+ Emission estimate is less than 0.1 Gg

ANNEX N

Methodology for Estimating N₂O Emissions from Agricultural Soil Management

Nitrous oxide (N₂O) emissions from agricultural soil management covers activities that add nitrogen to soils, and thereby enhance natural emissions of N₂O. The IPCC methodology (IPCC/UNEP/OECD/IEA 1997, IPCC 2000), which is used here, divides this source category into three components: (1) direct N₂O emissions from managed soils; (2) direct N₂O emissions from pasture, range, and paddock livestock manure; and (3) indirect N₂O emissions from soils induced by applications of nitrogen.

There are five steps in estimating N₂O emissions from agricultural soil management. First, the activity data are derived for each of the three components. Note that some of the data used in the first component are also used in the third component. In the second, third, and fourth steps, N₂O emissions from each of the three components are estimated. In the fifth step, emissions from the three components are summed to estimate total emissions. The remainder of this annex describes these steps, and data used in these steps, in detail.

Step 1: Derive Activity Data

The activity data for this source category are annual amounts of nitrogen added to soils for each relevant activity, except for histosol cultivation, for which the activity data are annual histosol areas cultivated.¹ The activity data are derived from statistics, such as fertilizer consumption data or livestock population data, and various factors used to convert these statistics to annual amounts of nitrogen, such as fertilizer nitrogen contents or livestock excretion rates. Activity data were derived for each of the three components, as described below.

Step 1a: Direct N₂O Emissions from Managed Soils

The activity data for this component include: a) the amount of nitrogen in synthetic and organic commercial fertilizers that are applied annually, b) the amount of nitrogen in livestock manure that is applied annually through both daily spread operations and the eventual application of manure that had been stored in manure management systems, c) the amount of nitrogen in sewage sludge that is applied annually, d) the amount of nitrogen in the aboveground biomass of nitrogen-fixing crops and forages that are produced annually, e) the amount of nitrogen in crop residues that are retained on soils annually, and f) the area of histosols cultivated annually.

Application of synthetic and organic commercial fertilizer: Annual commercial fertilizer consumption data for the United States were taken from annual publications of synthetic and organic fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b, 2002) and a recent AAPFCO database (AAPFCO 2000a). These data were manipulated in several ways to derive the activity data needed for the inventory. First, the manure and sewage sludge portions of the organic fertilizers were subtracted from the total organic fertilizer consumption data because these nitrogen additions are accounted for under “manure application” and “sewage sludge application.”² Second, the organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of nitrogen by multiplying by the average organic fertilizer nitrogen contents provided in the annual fertilizer publications. These nitrogen contents are weighted average values, so they vary from year-to-year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2001). The synthetic fertilizer data are recorded in units of nitrogen, so these data did not need to be converted. Lastly, both the synthetic and organic fertilizer consumption data are recorded in “fertilizer year” totals (i.e., July to June); therefore, the data were converted to calendar year totals. This was done by assuming that approximately 35 percent of fertilizer usage occurred from July to December, and 65 percent from January to June (TVA 1992b). July to December values were

¹ Histosols are soils with a high organic carbon content. All soils with more than 20 to 30 percent organic matter by weight (depending on the clay content) are classified as histosols (Brady and Weil 1999).

² Organic fertilizers included in these publications are manure, compost, dried blood, sewage sludge, tankage, and “other.” (Tankage is dried animal residue, usually freed from fat and gelatin). The manure and sewage sludge used as commercial fertilizer are accounted for elsewhere, so these were subtracted from the organic fertilizer statistics to avoid double counting.

not available for calendar year 2001, so a “least squares line” statistical extrapolation using the previous eleven years of data was used to arrive at an approximate value. Annual consumption of commercial fertilizers—synthetic and non-manure/non-sewage organic—in units of nitrogen and on a calendar year basis are presented in Table N-1.

Application of livestock manure: To estimate the amount of livestock manure nitrogen applied to soils, it was assumed that all of the manure produced by livestock would be applied to soils with two exceptions. These exceptions were: (1) the portion of poultry manure that is used as a feed supplement for ruminants, and (2) the manure that is deposited on soils by livestock on pasture, range, and paddock. In other words, all of the manure that is managed, except the portion of poultry manure that is used as a feed supplement, is assumed to be applied to soils. The amount of managed manure for each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed in order to collect and manage the manure. In some instances, the number of animals in managed systems was determined by subtracting the number of animals in pasture, range, and paddock from the total animal population for a particular animal type.

Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the USDA National Agricultural Statistics Service (USDA 1994b,c; 1995a,b; 1998a,c; 1999a-c; 2000a-g; 2001b-g; 2002b-g). Horse population data were obtained from the FAOSTAT database (FAO 2002). Goat population data for 1992 and 1997 were obtained from the Census of Agriculture (USDA 1999d); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the Census of Agriculture (USDA 1999e).

Information regarding the percentage of manure handled using various manure management systems for dairy cattle, beef cattle, and sheep was obtained from communications with personnel from state Natural Resource Conservation Service offices, state universities, National Agricultural Statistics Service, and other experts (Poe et al. 1999, Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Information regarding the percentage of manure handled using various manure management systems for swine, poultry, goats, and horses was obtained from Safley et al. (1992). A more detailed discussion of manure management system usage is provided in Annex M.

Once the animal populations for each livestock type and management system were estimated, these populations were then multiplied by an average animal mass constant (USDA 1996, USDA 1998d, ASAE 1999, Safley 2000) to derive total animal mass for each animal type in each management system. Total Kjeldahl nitrogen³ excreted per year for each livestock type and management system was then calculated using daily rates of nitrogen excretion per unit of animal mass (USDA 1996, ASAE 1999). The total poultry manure nitrogen in managed systems was reduced by the amount assumed to be used as a feed supplement (i.e., 4.2 percent of the managed poultry manure; Carpenter 1992). The annual amounts of Kjeldahl nitrogen were then summed over all livestock types and management systems to derive estimates of the annual manure nitrogen applied to soils (Table N-2).

Application of sewage sludge: Estimates of annual nitrogen additions from land application of sewage sludge were derived from periodic estimates of sludge generation and disposal rates that were developed by EPA. Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works. Based on a 1988 questionnaire returned from 600 publicly owned treatment works (POTWs), the EPA estimated that 5.4 million metric tons of dry sewage sludge were generated by POTWs in the United States in that year (EPA 1993). Of this total, 33.3 percent was applied to land, including agricultural applications, compost manufacture, forest land application, and the reclamation of mining areas. A subsequent EPA report (EPA 1999) compiled data from several national studies and surveys, and estimated that approximately 6.7 and 6.9 million metric tons of dry sewage sludge were generated in 1996 and 1998, respectively, from all treatment works, and projected that approximately 7.1 million metric tons would be generated in 2000. The same study concluded that 60 percent of the sewage sludge generated in 1998 was applied to land (based on the results of a 1995 survey), and projected that 63 percent would be land applied in 2000. These EPA estimates of sludge generation and percent land applied were linearly interpolated to derive estimates for each year in the 1990 to 2000 period. To estimate annual amounts of nitrogen applied, the annual amounts of dry sewage sludge applied were multiplied by an average nitrogen content of 3.3 percent (Metcalf and Eddy, Inc. 1991). Estimates for the year 2001 were held constant at the year 2000 level,

³ Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen in both the solid and liquid wastes.

as no new data were available (Bastian 2002). Final estimates of annual amounts of sewage sludge nitrogen applied to land are presented in Table N-1.

Production of nitrogen-fixing crops and forages: Annual production statistics for beans, pulses, and alfalfa were taken from U.S. Department of Agriculture crop production reports (USDA 1994a, 1998b, 2000i, 2001a, 2002). Annual production statistics for the remaining nitrogen-fixing forages (i.e., the major non-alfalfa forage crops, specifically red clover, white clover, birdsfoot trefoil, arrowleaf clover, and crimson clover) were derived from information in a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Evers 2000, Gerrish 2000, Hoveland 2000, and Pederson 2000).

The production statistics for beans, pulses, and alfalfa were in tons of product, which needed to be converted to tons of aboveground biomass nitrogen. This was done by multiplying the production statistics by one plus the aboveground residue to crop product mass ratios, dry matter fractions, and nitrogen contents. The residue to crop product mass ratios for soybeans and peanuts, and the dry matter content for soybeans, were obtained from Strehler and Stützel (1987). The dry matter content for peanuts was obtained through personal communications with Ketzi (1999). The residue to crop product ratios and dry matter contents for the other beans and pulses were estimated by taking averages of the values for soybeans and peanuts. The dry matter content for alfalfa was obtained through personal communications with Karkosh (2000). The IPCC default nitrogen content of 3 percent (IPCC/UNEP/OECD/IEA 1997) was used for all beans, pulses, and alfalfa.⁴

The production statistics for the non-alfalfa forage crops were derived by multiplying estimates of areas planted by estimates of annual yields, in dry matter mass units. These derived production statistics were then converted to units of nitrogen by applying the IPCC default nitrogen content of 3 percent (IPCC/UNEP/OECD/IEA 1997).

The final estimates of annual aboveground biomass production, in units of nitrogen, are presented in Table N-3. The residue to crop product mass ratios and dry matter fractions used in these calculations are presented in Table N-6.

Retention of crop residue: It was assumed that 90 percent of residues from corn, wheat, barley, sorghum, oats, rye, millet, soybeans, peanuts, and other beans and pulses are left on the field after harvest (e.g., rolled into the soil, chopped and disked into the soil, or otherwise left behind) (Karkosh 2000).⁵ It was also assumed that 100 percent of unburned rice residue is left on the field.⁶

The derivation of crop residue nitrogen activity data was very similar to the derivation of nitrogen-fixing crop activity data. Crop production statistics were multiplied by aboveground residue to crop product mass ratios, residue dry matter fractions, residue nitrogen contents, and the fraction of residues left on soils. Annual production statistics for all crops except rice in Florida were taken from U.S. Department of Agriculture reports (USDA 1994a, 1998b, 2001a, 2002). Production statistics for rice in Florida, which are not recorded by USDA, were estimated by applying an average rice crop yield for Florida (Smith 2001) to annual Florida rice areas (Schueneman 1999, 2001, Deren 2002). Residue to crop product ratios for all crops were obtained from, or derived from, Strehler and Stützel (1987). Dry matter contents for wheat, rice, corn, and barley residue were obtained from Turn et al. (1997). Soybean and millet residue dry matter contents were obtained from Strehler and Stützel (1987). Peanut, sorghum, oat, and rye residue dry matter contents were obtained through personal communications with Ketzi (1999). Dry matter contents for all other beans and pulses were estimated by averaging the values for soybeans and peanuts. The residue nitrogen contents for wheat, rice, corn, and barley are from Turn et al. (1997). The nitrogen content of soybean residue is from Barnard and Kristoferson (1985), the nitrogen contents of peanut, sorghum, oat, and rye residue are from Ketzi (1999), and the nitrogen content of millet residue is from Strehler and Stützel (1987).

⁴ This nitrogen content may be an overestimate for the residue portion of the aboveground biomass of the beans and pulses. Also, the dry matter fractions used for beans and pulses were taken from literature on crop residues, and so may be underestimates for the product portion of the aboveground biomass.

⁵ Although the mode of residue application would likely affect the magnitude of N₂O emissions, an emission estimation methodology that accounts for this has not been developed.

⁶ Some of the rice residue may be used for other purposes, such as for biofuel or livestock bedding material. Research to obtain more detailed information regarding final disposition of rice residue, as well as the residue of other crops, will be undertaken for future inventories.

Nitrogen contents of all other beans and pulses were estimated by averaging the values for soybeans and peanuts. Estimates of the amounts of rice residue burned annually were derived using information obtained from agricultural extension agents in each of the rice-growing states (see Agricultural Residue Burning section of the Agriculture Chapter for more detail).

The final estimates of residue retained on soil, in units of nitrogen, are presented in Table N-4. The residue to crop product mass ratios, residue dry matter fractions, and residue nitrogen contents used in these calculations are presented in Table N-6.

Cultivation of histosols: Estimates of the areas of histosols cultivated in 1982, 1992, and 1997 were obtained from the USDA's 1997 *National Resources Inventory* (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002).⁷ These areas were grouped by broad climatic region⁸ using temperature and precipitation estimates from Daly et al. (1994, 1998), and then further aggregated to derive a temperate total and a sub-tropical total. These final areas were then linearly interpolated to obtain estimates for 1990 through 1996, and linearly extrapolated to obtain area estimates for 1998 through 2001 (Table N-5).

Step 1b: Direct N₂O Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of N₂O emissions from this component were based on livestock manure that is not managed in manure management systems, but instead is deposited directly on soils by animals in pasture, range, and paddock. The livestock included in this component were: dairy cattle, beef cattle, swine, sheep, goats, poultry, and horses.

Dairy Cattle: Information regarding dairy farm grazing was obtained from communications with personnel from state Natural Resource Conservation Service offices, state universities, and other experts (Poe et al. 1999, Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, Wright 2000). Because grazing operations are typically related to the number of animals on a farm, farm-size distribution data reported in the 1992 and 1997 *Census of Agriculture* (USDA 1999e) were used in conjunction with the state data obtained from personal communications to determine the percentage of total dairy cattle that graze. An overall percent of dairy waste that is deposited in pasture, range, and paddock was developed for each region of the United States. This percentage was applied to the total annual dairy cow and heifer state population data for 1990 through 2001, which were obtained from the USDA National Agricultural Statistics Service (USDA 1995a; 1999a; 2000a,b; 2001b,c; 2002b,c).

Beef Cattle: To determine the population of beef cattle that are on pasture, range, and paddock, the following assumptions were made: 1) beef cows, bulls, and calves were not housed on feedlots; 2) a portion of heifers and steers were on feedlots; and 3) all beef cattle that were not housed on feedlots were located on pasture, range, and paddock (i.e., total population minus population on feedlots equals population of pasture, range, and paddock) (Milton 2000). Information regarding the percentage of heifers and steers on feedlots was obtained from USDA personnel (Milton 2000) and used in conjunction with the USDA National Agricultural Statistics Service population data (USDA 1995a; 1999a; 2000a,b; 2001b,c; 2002b,c) to determine the population of steers and heifers on pasture, range, and paddock.

Swine: Based on the assumption that smaller facilities are less likely to utilize manure management systems, farm-size distribution data reported in the 1992 and 1997 *Census of Agriculture* (USDA 1999e) were used to determine the percentage of all swine whose manure is not managed (i.e., the percentage on pasture, range, and paddock). These percentages were applied to the average of the quarterly USDA National Agricultural Statistics Service population data for swine (USDA 1994b, 1998a, 2000e, 2001d; 2002d) to determine the population of swine on pasture, range, and paddock.

Sheep: It was assumed that all sheep and lamb manure not deposited on feedlots was deposited on pasture, range, and paddock (Anderson 2000). Sheep population data were obtained from the USDA National Agricultural Statistics Service (USDA 1994c, 1999c, 2000g, 2001f, 2002f). However, population data for lamb and sheep on feed were not available after 1993. The number of lamb and sheep on feed from 1994 through 2001 were calculated using the average of the percent of lamb and sheep on feed from 1990 through 1993. In addition, all of the sheep

⁷ These areas do not include Alaska, but Alaska's cropland area accounts for less than 0.1 percent of total U.S. cropland area, so this omission is not significant.

⁸ These climatic regions were: 1) cold temperate, dry, 2) cold temperate, moist, 3) sub-tropical, dry, 4) sub-tropical, moist, 5) warm temperate, dry, and 6) warm temperate, moist.

and lamb “on feed” were not necessarily on “feedlots”; they may have been on pasture/crop residue supplemented by feed. Data for those feedlot animals versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb on feedlots for all years, it was assumed that the percentage of sheep and lamb on feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

Goats: It was assumed that 92 percent of goat manure was deposited on pasture, range, and paddock (Safley et al. 1992). Annual goat population data by state were available for only 1992 and 1997 (USDA 1999d). The data for 1992 were used for 1990 through 1992 and the data for 1997 were used for 1997 through 2001. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

Poultry: It was assumed that one percent of poultry manure was deposited on pasture, range, and paddock (Safley et al. 1992). Poultry population data were obtained from USDA National Agricultural Statistics Service (USDA 1995b, 1998a, 1999b, 2000c, 2000d, 2000f, 2001f, 2002f). The annual population data for boilers and turkeys were adjusted for turnover (i.e., slaughter) rate (Lange 2000).

Horses: It was assumed that 92 percent of horse manure was deposited on pasture, range, and paddock (Safley et al. 1992). Horse population data were obtained from the FAOSTAT database (FAO 2002).

For each animal type, the population of animals within pasture, range, and paddock systems was multiplied by an average animal mass constant (USDA 1996, ASAE 1999, USDA 1998d, Safley 2000) to derive total animal mass for each animal type. Total Kjeldahl nitrogen excreted per year was then calculated for each animal type using daily rates of nitrogen excretion per unit of animal mass (USDA 1996, ASAE 1999). Annual nitrogen excretion was then summed over all animal types to yield total nitrogen in pasture, range, and paddock manure (Table N-2).

Step 1c: Indirect N₂O Emissions from Soils Induced by Applications of Nitrogen

This component accounts for N₂O that is emitted indirectly from nitrogen applied as commercial fertilizer, sewage sludge, and livestock manure. Through volatilization, some of this nitrogen enters the atmosphere as NH₃ and NO_x, and subsequently returns to soils through atmospheric deposition, thereby enhancing N₂O production. Additional nitrogen is lost from soils through leaching and runoff, and enters groundwater and surface water systems, from which a portion is emitted as N₂O. These two indirect emission pathways are treated separately, although the activity data used, except for livestock manure, are identical. The activity data for commercial fertilizer and sewage sludge are the same as those used in the calculation of direct emissions from managed soils (Table N-1). The activity data for livestock manure are different from those used in other calculations. Here, total livestock manure (i.e., the sum of applied manure, manure in pasture, range, and paddock, and manure used as a livestock feed supplement) is used in the volatilization and deposition calculation; and livestock manure applied or deposited on soils (i.e., the sum of applied manure and manure in pasture, range, and paddock) in the leaching and runoff calculation. These data are presented in Table N-2.

Table N-1: Commercial Fertilizer Consumption & Land Application of Sewage Sludge (Gg N)

Fertilizer Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Synthetic	10,104	10,275	10,352	10,719	11,160	10,798	11,156	11,172	11,193	11,237	10,898	10,684
Other Organics*	5	9	6	5	8	11	13	15	13	11	10	9
Sewage Sludge	77	87	97	107	118	129	133	135	137	142	148	148

* Excludes manure and sewage sludge used as commercial fertilizer.

Table N-2: Livestock Manure Nitrogen (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Applied to Soils	2,675	2,746	2,735	2,791	2,811	2,782	2,814	2,875	2,910	2,907	2,959	2,972
Pasture, Range, & Paddock	4,148	4,167	4,256	4,304	4,412	4,474	4,467	4,331	4,244	4,199	4,136	4,100
Total Manure	6,855	6,945	7,024	7,130	7,258	7,290	7,317	7,243	7,191	7,143	7,133	7,110

Table N-3: Aboveground Biomass Nitrogen in Nitrogen-Fixing Crops and Forages (Gg)

Crop Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Soybeans	4,241	4,374	4,823	4,117	5,538	4,788	5,241	5,921	6,036	5,844	6,073	6,365
Peanuts	84	115	100	79	99	81	86	83	93	90	76	99
Dry Edible Beans	98	102	68	66	87	93	84	89	92	100	80	59
Dry Edible Peas	7	11	8	10	7	14	8	17	18	14	11	11

Austrian Winter Peas	+	+	+	+	+	+	+	+	+	+	+	+
Lentils	3	5	5	6	6	7	4	7	6	7	9	9
Wrinkled Seed Peas	3	3	2	3	2	3	2	2	2	2	2	2
Alfalfa	1,730	1,729	1,642	1,662	1,683	1,746	1,642	1,655	1,708	1,740	1,642	1,646
Red Clover	513	513	513	513	513	513	513	513	513	513	513	513
White Clover	2,735	2,735	2,735	2,735	2,735	2,735	2,735	2,735	2,735	2,735	2,735	2,735
Birdsfoot Trefoil	99	99	99	99	99	99	99	99	99	99	99	99
Arrowleaf Clover	67	67	67	65	63	61	58	56	54	52	48	50
Crimson Clover	21	21	21	19	18	17	16	14	13	12	11	9
Total	9,600	9,774	10,082	9,375	10,850	10,156	10,488	11,192	11,368	11,207	11,298	11,598

+ Less than 0.5 Gg N.

Note: Totals may not sum due to independent rounding.

Table N-4: Nitrogen in Crop Residues Retained on Soils (Gg)

Product Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Corn	957	902	1,143	765	1,213	893	1,114	1,111	1,177	1,138	1,196	1,147
Wheat	501	364	453	440	426	401	418	456	468	422	410	359
Barley	71	78	77	67	63	61	66	61	59	47	54	42
Sorghum	180	184	275	168	203	144	250	199	164	187	148	162
Oats	39	27	32	23	25	18	17	18	18	16	16	13
Rye	2	2	2	2	2	2	1	1	2	2	1	1
Millet	3	3	3	3	3	3	3	3	3	3	1	3
Rice	51	53	61	52	65	60	57	66	69	75	69	89
Soybeans	1,982	2,045	2,254	1,924	2,588	2,238	2,450	2,767	2,821	2,731	2,839	2,975
Peanuts	13	18	16	13	16	13	14	13	15	14	12	16
Dry Edible Beans	11	12	8	7	10	10	10	10	10	11	9	7
Dry Edible Peas	1	1	1	1	1	2	1	2	2	2	1	1
Austrian Winter Peas	+	+	+	+	+	+	+	+	+	+	+	0
Lentils	+	1	1	1	1	1	+	1	1	1	1	1
Wrinkled Seed Peas	+	+	+	+	+	+	+	+	+	+	+	0
Total	3,814	3,689	4,326	3,466	4,616	3,845	4,402	4,709	4,810	4,650	4,758	4,817

+ Less than 0.5 Gg N.

Note: Totals may not sum due to independent rounding.

Table N-5: Cultivated Histosol Area (Thousand Hectares)

Year	Temperate Area	Sub-Tropical Area
1990	432	192
1991	431	193
1992	429	194
1993	431	194
1994	433	195
1995	435	195
1996	437	196
1997	439	196
1998	441	197
1999	443	197
2000	445	197
2001	447	198

Table N-6: Key Assumptions for Nitrogen-Fixing Crop Production and Crop Residue

Crop	Residue/Crop Ratio	Residue Dry	
		Matter Fraction	Residue Nitrogen Fraction
Soybeans	2.1	0.87	0.023
Peanuts	1.0	0.86	0.0106
Dry Edible Beans	1.55	0.87	0.0062
Dry Edible Peas	1.55	0.87	0.0062
Austrian Winter Peas	1.55	0.87	0.0062
Lentils	1.55	0.87	0.0062
Wrinkled Seed Peas	1.55	0.87	0.0062

Alfalfa	0	0.85	NA
Corn	1.0	0.91	0.0058
Wheat	1.3	0.93	0.0062
Barley	1.2	0.93	0.0077
Sorghum	1.4	0.91	0.0108
Oats	1.3	0.92	0.007
Rye	1.6	0.90	0.0048
Millet	1.4	0.89	0.007
Rice	1.4	0.91	0.0072

Note: For the derivation of activity data for nitrogen-fixing crop production, the IPCC default nitrogen content of aboveground biomass (3 percent) was used.

Step 2: Estimate Direct N₂O Emissions from Managed Soils Due to Nitrogen Additions and Cultivation of Histosols

In this step, N₂O emissions were calculated for each of two parts (direct N₂O emissions due to nitrogen additions and direct N₂O emissions due to histosol cultivation), which were then summed to yield total direct N₂O emissions from managed soils (Table N-7).

Step 2a: Direct N₂O Emissions Due to Nitrogen Additions

To estimate these emissions, the amounts of nitrogen applied were each reduced by the IPCC default fraction of nitrogen that is assumed to volatilize, the unvolatilized amounts were then summed, and the total unvolatilized nitrogen was multiplied by the IPCC default emission factor of 0.0125 kg N₂O-N/kg N (IPCC/UNEP/OECD/IEA 1997). The volatilization assumptions are described below.

- *Application of synthetic and organic commercial fertilizer:* The total amounts of nitrogen applied in the form of synthetic commercial fertilizers and non-manure/non-sewage organic commercial fertilizers were reduced by 10 percent and 20 percent, respectively, to account for the portion that volatilizes to NH₃ and NO_x (IPCC/UNEP/OECD/IEA 1997).
- *Application of livestock manure:* The total amount of livestock manure nitrogen applied to soils was reduced by 20 percent to account for the portion that volatilizes to NH₃ and NO_x (IPCC/UNEP/OECD/IEA 1997).
- *Application of sewage sludge:* The total amount of sewage sludge nitrogen applied to soils was reduced by 20 percent to account for the portion that volatilizes to NH₃ and NO_x (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).
- *Production of nitrogen-fixing crops:* None of the nitrogen in the aboveground biomass of nitrogen-fixing crops was assumed to volatilize.
- *Retention of crop residue:* None of the nitrogen in retained crop residue was assumed to volatilize.

Step 2b: Direct N₂O Emissions Due to Cultivation of Histosols

To estimate annual N₂O emissions from histosol cultivation, the temperate histosol area was multiplied by the IPCC default emission factor for temperate soils (8 kg N₂O-N/ha cultivated; IPCC 2000), and the sub-tropical histosol area was multiplied by the average of the temperate and tropical IPCC default emission factors (12 kg N₂O-N/ha cultivated; IPCC 2000).

Step 3: Estimate Direct N₂O Emissions from Pasture, Range, and Paddock Livestock Manure

To estimate direct N₂O emissions from soils due to the deposition of pasture, range, and paddock manure, the total nitrogen excreted by these animals was multiplied by the IPCC default emission factor (0.02 kg N₂O-N/kg N excreted) (see Table N-8).

Step 4: Estimate Indirect N₂O Emissions Induced by Applications of Nitrogen

In this step, N₂O emissions were calculated for each of two parts (indirect N₂O emissions due to volatilization of applied nitrogen and indirect N₂O emissions due to leaching and runoff of applied nitrogen), which were then summed to yield total direct N₂O emissions from managed soils.

Step 4a: Indirect Emissions Due to Volatilization

To estimate these emissions, first the amounts of commercial fertilizer nitrogen and sewage sludge nitrogen applied, and the total amount of manure nitrogen produced, were each multiplied by the IPCC default fraction of nitrogen that is assumed to volatilize to NH₃ and NO_x (10 percent for synthetic fertilizer nitrogen; and 20 percent for nitrogen in organic fertilizer, sewage sludge, and livestock manure). Next, the volatilized amounts of nitrogen were summed, and then the total volatilized nitrogen was multiplied by the IPCC default emission factor of 0.01 kg N₂O-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in Table N-9.

Step 4b: Indirect Emissions Due to Leaching and Runoff

To estimate these emissions, first the amounts of commercial fertilizer nitrogen and sewage sludge nitrogen applied, and the total amount of manure nitrogen applied or deposited, were each multiplied by the IPCC default fraction of nitrogen that is assumed to leach and runoff (30 percent for all nitrogen). Next, the leached/runoff amounts of nitrogen were summed, and then the total nitrogen was multiplied by the IPCC default emission factor of 0.025 kg N₂O-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in Table N-9.

Table N-7: Direct N₂O Emissions from Managed Soils (Tg CO₂ Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Commercial Fertilizers*	55	56	57	59	61	59	61	61	61	62	60	59
Livestock Manure	13	13	13	14	14	14	14	14	14	14	14	14
Sewage Sludge	+	+	+	1	1	1	1	1	1	1	1	1
Nitrogen Fixation	58	60	61	57	66	62	64	68	69	68	69	71
Crop Residue	23	22	26	21	28	23	27	29	29	28	29	29
Histosol Cultivation	3	3	3	3	3	3	3	3	3	3	3	3
Total	153	155	161	154	172	162	169	176	178	176	176	177

+ Less than 0.5 Tg CO₂ Eq.

Note: Totals may not sum due to independent rounding.

* These data do not include sewage sludge and livestock manure used as commercial fertilizers, to avoid double counting.

Table N-8: Direct N₂O Emissions from Pasture, Range, and Paddock Livestock Manure (Tg CO₂ Eq.)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	35	35	36	37	38	39	39	38	37	37	36	36
Dairy Cows	2	2	2	2	2	1	1	1	1	1	1	1
Swine	+	1	1	+	+	+	+	+	+	+	+	+
Sheep	+	+	+	+	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+	+	+	+	+
Poultry	+	+	+	+	+	+	+	+	+	+	+	+
Horses	2	2	2	2	2	2	2	2	2	2	2	2
Total	40	41	41	42	43	44	44	42	41	41	40	40

+ Less than 0.5 Tg CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table N-9: Indirect N₂O Emissions (Tg CO₂ Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Volatil. & Atm. Deposition	12	12	12	12	13	12	13	13	13	13	12	12
Comm. Fertilizers	5	5	5	5	5	5	5	5	5	5	5	5
Livestock Manure	7	7	7	7	7	7	7	7	7	7	7	7
Sewage Sludge	+	+	+	+	+	+	+	+	+	+	+	+
Surface Leaching & Runoff	62	63	64	66	68	66	68	68	68	68	66	65
Comm. Fertilizers	37	38	38	39	41	39	41	41	41	41	40	39
Livestock Manure	25	25	26	26	26	27	27	26	26	26	26	26

Sewage Sludge	+	+	+	+	+	+	+	+	1	1	1	1
Total	74	75	76	78	80	79	81	80	80	80	79	78

+ Less than 0.5 Tg CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Step 5: Estimate Total N₂O Emissions

In this step, total emissions are calculated by summing direct emissions from managed soils, direct emissions from pasture, range, and paddock livestock manure, and indirect emissions (Table N-10).

Table N-10: Total N₂O Emissions (Tg CO₂ Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Direct Emissions from Managed Soils	153	155	161	154	172	162	169	176	178	176	176	177
Direct Emissions from Pasture, Range, and Paddock Livestock	40	41	42	42	43	44	44	42	41	41	40	40
Indirect Emissions	74	75	76	78	80	79	81	80	80	80	79	78
Total	268	271	278	274	296	284	293	298	299	297	295	294

Note: Totals may not sum due to independent rounding.

ANNEX O

Methodology for Estimating Net Changes in Forest Carbon Stocks

This annex presents a discussion of the methodology used to calculate net changes in carbon stocks in trees, understory, forest floor, down dead wood, forest soils, wood products and landfilled wood. More detailed discussions of selected topics may be found in the references cited in this annex.

The details of carbon conversion factors and procedures for calculating net CO₂ flux for forests are given in three steps. In addition, the USDA Forest Service forest sector modeling projection system is described briefly.

Step 1: Estimate Forest Carbon Stocks and Net Changes in Forest Carbon Stocks

Step 1a: Obtain Forest Inventory Data

Forest survey data in the United States by broad forest type and region for 1987 and 1997 were obtained from USDA Forest Service, Forest Inventory and Analysis estimates of forest resources, published in Waddell et al. (1989) and Smith et al. (2001). The Forest Inventory and Analysis data include: (1) growing stock volume per acre by forest type (referred to hereinafter as “growing stock volumes”); and (2) area by timberland and other forest land, for general forest types by region (referred to hereinafter as “forest areas”). For 2001, the same variables were obtained from model results as described in Haynes (2002). (See Forest Sector Modeling Projection System below). This information was combined with separate estimates of carbon density (carbon mass per unit area) to estimate carbon stocks.

Step 1b: Estimate Carbon in Living and Standing Dead Trees

To estimate live tree biomass, equations that convert forest tree volumes to total live tree dry biomass (Smith et al. in press) were applied to the growing stock volumes by forest type and region (obtained in Step 1a). Tree biomass includes aboveground biomass and belowground biomass of coarse roots. The minimum sized tree is one-inch diameter at diameter breast height (1.3 meter). Trees less than one-inch diameter are counted as carbon in understory vegetation. Biomass estimates were divided by two to obtain estimates of carbon in living trees (i.e., it was assumed that dry biomass is 50 percent carbon). Standing dead tree biomass was calculated by applying equations that estimate biomass for standing dead trees (Smith et al., in press) from growing stock volumes. Again, standing dead tree biomass was divided by two to estimate carbon in standing dead trees. Table O-1 lists the average living and standing dead tree carbon densities by forest type, as calculated by applying the equations to the 1997 data.

Table O-1: Average U.S. Carbon Densities of Forest Components* (Metric Tons C/ha)

Region ^a /Forest Type	Live and Standing Dead Tree Carbon	Forest Floor Carbon	Soil Organic Carbon ^b
Eastern			
White-red-jack pine	77.1	13.8	196.1
Spruce-fir	59.8	40.2	192.9
Longleaf-slash pine	42.4	9.2	136.3
Loblolly-shortleaf pine	49.3	9.1	91.7
Oak-pine	57.3	11.6	82.3
Oak-hickory	76.3	6.6	85.0
Oak-gum-cypress	86.0	6.0	152.2
Elm-ash-cottonwood	67.6	23.0	118.1
Maple-beech-birch	82.5	28.0	139.5
Aspen-birch	56.0	7.6	237.0
Other forest types	1.8	2.1	99.6
Nonstocked	3.7	3.5	99.6

Western

Douglas-fir	110.8	30.7	89.6
Ponderosa pine	66.3	20.3	70.4
Western white pine	69.2	25.8	68.3
Fir-spruce	113.0	37.4	137.5
Hemlock-Sitka spruce	152.4	34.1	157.1
Larch	97.0	30.2	65.6
Lodgepole pine	67.8	23.9	62.7
Redwood	186.6	26.9	85.8
Hardwoods	89.0	9.9	79.5
Other forest types	55.4	28.2	90.1
Pinyon-juniper	20.8	21.1	56.3
Chaparral	17.5	25.7	58.7
Nonstocked	18.1	24.4	90.1

* Based on 1997 data for major forest types of the conterminous United States.

^aEastern United States is defined as states east of, and including, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. Western United States includes the remaining conterminous states.

^bSoil includes both mineral soils and organic soils (i.e., histosols); carbon densities are to a depth of 1 meter.

Step 1c: Estimate Carbon in Understory Vegetation

To estimate carbon in understory vegetation, equations based on Birdsey (1992) were applied to the database that was used to produce the compiled forest statistics in Smith et al. (2001). Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch diameter, measured at breast height. A ratio of understory carbon to live tree carbon was calculated, and multiplied by 100 to calculate the percentage of carbon in the understory relative to that in live trees. These percentages were then averaged for each forest type in each region. This percentage was multiplied by the live tree carbon data in 1987 and 1997 to calculate understory carbon. These percentages are given in Table O-2. This procedure was used instead of applying the Birdsey equations directly, because detailed databases are not available for inventory years prior to 1987. Using estimated average values results in consistent historical carbon estimates for all survey years.

Table O-2: Ratios of Understory and Down Dead Wood Carbon to Live Tree Carbon* (Percent)

Region/Forest Type	Ratio of Understory Carbon to Live Tree Carbon	Ratio of Down Dead Wood Carbon to Live Tree Carbon
Northeast		
White-red-jack pine	2.5	10.8
Spruce-fir	2.6	13.3
Longleaf-Slash pine	2.5	10.8
Loblolly-shortleaf pine	2.5	10.8
Oak-pine	2.8	12.9
Oak-hickory	2.4	10.9
Oak-gum-cypress	2.6	11.1
Elm-ash-cottonwood	2.6	11.1
Maple-beech-birch	1.9	11.1
Aspen-birch	2.7	13.6
Other Forest Types	8.9	3.8
Nonstocked	8.9	3.8
North Central		
White-red-jack pine	1.8	9.8
Spruce-fir	2.2	17.4
Longleaf-Slash pine	2.4	7.4
Loblolly-shortleaf pine	2.4	7.4
Oak-pine	1.9	7.2
Oak-hickory	2.3	9.6
Oak-gum-cypress	2.3	9.6
Elm-ash-cottonwood	2.2	10.8
Maple-beech-birch	2.2	10.8
Aspen-birch	2.8	13.3
Other Forest Types	5.5	4.1
Nonstocked	5.5	4.1

Southeast

White-red-jack pine	6.8	23.9
Spruce-fir	6.8	23.9
Longleaf-Slash pine	6.8	23.9
Loblolly-shortleaf pine	6.8	23.9
Oak-pine	5.2	28.0
Oak-hickory	4.4	24.2
Oak-gum-cypress	2.2	21.8
Elm-ash-cottonwood	2.2	21.8
Maple-beech-birch	4.4	24.2
Aspen-birch	2.2	21.8
Other Forest Types	11.9	2.0
Nonstocked	11.9	2.0

South Central

White-red-jack pine	5.9	18.6
Spruce-fir	5.9	18.6
Longleaf-Slash pine	5.9	18.6
Loblolly-shortleaf pine	5.9	18.6
Oak-pine	4.4	17.3
Oak-hickory	3.7	15.0
Oak-gum-cypress	2.2	15.7
Elm-ash-cottonwood	2.2	15.7
Maple-beech-birch	3.7	15.0
Aspen-birch	2.2	15.7
Other Forest Types	16.9	1.7
Nonstocked	16.9	1.7

Pacific Northwest Eastside of Cascades

Douglas-fir	1.6	10.0
Ponderosa Pine	2.5	12.6
Western White Pine	1.6	10.0
Fir-Spruce	1.1	15.7
Hemlock-Sitka spruce	1.6	10.0
Larch	1.6	10.0
Lodgepole pine	2.6	21.3
Redwood	1.9	25.8
Other hardwoods	1.4	8.9
Unclassified & other	2.5	12.6
Pinyon-Juniper	10.7	3.7
Chaparral	9.7	2.1
Nonstocked	9.7	2.1

Pacific Northwest Westside of Cascades

Douglas-fir	2.0	11.9
Ponderosa Pine	2.5	18.1
Western White Pine	2.5	18.1
Fir-Spruce	1.0	13.7
Hemlock-Sitka spruce	1.0	13.7
Larch	2.0	11.9
Lodgepole pine	1.7	16.4
Redwood	2.0	11.9
Other hardwoods	4.5	3.9
Unclassified & other	1.7	16.4
Pinyon-Juniper	20.2	3.7
Chaparral	14.2	3.0
Nonstocked	14.2	3.0

Rocky Mountain, Northern

Douglas-fir	2.6	19.2
Ponderosa Pine	2.4	19.6
Western White Pine	2.2	9.7
Fir-Spruce	1.7	14.8
Hemlock-Sitka spruce	2.0	18.7
Larch	2.2	9.7
Lodgepole pine	2.4	19.6

Redwood	2.2	9.7
Other hardwoods	1.9	14.2
Unclassified & other	2.2	9.7
Pinyon-Juniper	16.1	3.2
Chaparral	16.1	3.2
Nonstocked	16.1	3.2
Rocky Mountain, Southern		
Douglas-fir	2.8	19.4
Ponderosa Pine	4.1	21.6
Western White Pine	2.8	19.4
Fir-Spruce	2.2	17.4
Hemlock-Sitka spruce	2.8	19.4
Larch	2.8	19.4
Lodgepole pine	3.1	12.8
Redwood	2.8	19.4
Other hardwoods	9.2	26.7
Unclassified & other	10.7	3.3
Pinyon-Juniper	9.8	3.9
Chaparral	9.8	3.9
Nonstocked	2.6	15.2
Pacific Southwest		
Douglas-fir	2.3	15.5
Ponderosa Pine	2.6	15.2
Western White Pine	2.2	11.5
Fir-Spruce	2.6	15.2
Hemlock-Sitka spruce	2.6	15.2
Larch	4.6	10.8
Lodgepole pine	2.6	15.2
Redwood	4.4	9.7
Other hardwoods	2.8	11.5
Unclassified & other	9.9	3.1
Pinyon-Juniper	15.3	3.5
Chaparral	15.3	3.5
Nonstocked	2.5	10.8

* Based on data from 1997. Regions are defined in Figure 6-2 of the Land-Use Change and Forestry Chapter.

Step 1d: Estimate Carbon in Forest Floor

Forest floor carbon is the pool of organic carbon (litter, duff, humus, and small woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. To estimate carbon in the forest floor, equations developed by Smith and Heath (in press) were applied to the dataset described in Step 1a. Table O-1 shows the average forest floor carbon densities by forest type, as calculated based on the 1997 data.

Step 1e: Estimate Carbon in Down Dead Wood

Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter that are not attached to trees. Down dead wood includes stumps and roots of harvested trees. To estimate carbon in down dead wood, a procedure similar to estimating carbon in understory vegetation was used. Down dead wood was estimated in the projections by using decay rates applied to logging residue, along with equations that estimate the amount of down dead wood from causes other than harvesting. The percentage of down dead wood carbon relative to that in live trees was calculated. As for the understory carbon, average values of down dead wood were derived for each forest type in each region. This percentage was multiplied by the live tree carbon data from the dataset described in step 1a to calculate the total amount of carbon in down dead wood. These percentages are given in Table O-2. This procedure was used because detailed databases are not available for older data. By using this procedure, carbon estimates from historical data are consistent with carbon estimates from current Forest Inventory and Analysis data.

Step 1f: Estimate Forest Soil Carbon

To estimate the amount of carbon in forest soils, data for soils from the surface down to a depth of 1 meter were obtained from the STATSGO spatial database (USDA 1991). Then a spatial data set delineating forest types throughout the conterminous United States (Powell et al. 1993) was overlaid onto the soil carbon data from STATSGO. An estimate of the average amount of carbon in the soil was then calculated for each forest type. Estimates included both mineral soils and organic soils.¹ Coarse roots were included with tree carbon estimates rather than with soils. The soil carbon estimates are given in Table O-1. These estimates were multiplied by the area of forest land in each forest type for all years. Thus, any change in soil carbon is a reflection of changes in the area of forest land or changes in forest type.

Step 1g: Calculate Net Carbon Stock Changes

After calculation of all forest carbon stocks, the final step was to calculate the average annual net carbon stock change for each forest carbon pool for the years from 1990 through 2001. The net annual stock change for each pool for 1987 through 1997 was derived by subtracting the 1987 stock from the 1997 stock, and dividing by the number of years between estimates (10 years). The stocks, by definition, correspond to the stock as of January 1 of the given year. The net annual stock changes for 1997 through 2001 were derived in the same way using the 1997 and 2002 stocks. The procedure for estimating carbon stocks in 2002 is described below under the heading “Forest Sector Modeling Projection System.”

Step 2: Estimate Harvested Wood Carbon Fluxes

The first step in estimating stocks and fluxes of harvested wood (i.e., wood products and landfilled wood) was to compile historical data on: the production of lumber, plywood and veneer, pulp and other products; product and log imports and exports; and fuelwood (in terms of million cubic feet of roundwood equivalent beginning in the year 1900, as described in Skog and Nicholson 1998). Data were obtained from USDA (1964), Ulrich (1989), and Howard (2001). Projected values for wood products and roundwood use were obtained from the models used for the USDA Forest Service 2000 Resource Planning Act Assessment (Haynes 2002, Ince 1994, see “Forest Sector Modeling Projection System” below). Roundwood products include logs, bolts, and other round timber generated from harvesting trees for industrial or consumer use. The harvested wood-to-carbon conversion factors presented by Skog and Nicholson (1998) were applied to annual estimates and projections to estimate the amount of carbon in roundwood and wood products. The amount of roundwood consumed was categorized according to product such as lumber, railroad ties, and paper, because the length of time that carbon remains in these products differs substantially. The dynamics of carbon loss through decay or through disposal of the product is summarized as the half-life of each product (Skog and Nicholson 1998). The resulting estimates were applied to products to derive the net carbon change in wood products and landfills. Note that, unlike forest carbon stock estimates, carbon in harvested wood products estimates are derived as a carbon stock change. In other words, the annual roundwood production is a change variable already before it is converted to carbon.

Step 3: Sum the Results from Step 1 and Step 2 for the Total Net Flux from U.S. Forests

In the final step, net changes in forest carbon stocks are added to net changes in harvested wood carbon stocks, to obtain estimates of total net forest flux (see Table O-3).

Table O-3: Net CO₂ Flux from U.S. Forest Carbon Stocks (Tg CO₂ Eq.)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Forests	(773.7)	(773.7)	(773.7)	(773.7)	(773.7)	(773.7)	(773.7)	(546.3)	(546.3)	(546.3)	(546.3)	(546.3)
Trees	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(447.3)	(447.3)	(447.3)	(447.3)	(447.3)
Understory	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(14.7)	(14.7)	(14.7)	(14.7)	(14.7)
Forest Floor	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	29.3	29.3	29.3	29.3	29.3
Down Dead Wood	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Forest Soils	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)

¹ Organic soils, otherwise known as histosols, are soils that develop in wetland areas and have greater than 20 to 30 percent organic matter by weight depending on clay content.

Harvested Wood	(209.0)	(198.0)	(202.8)	(203.9)	(210.5)	(205.3)	(205.3)	(212.7)	(205.3)	(216.3)	(209.0)	(212.7)
Wood Products	(47.7)	(40.7)	(46.6)	(54.6)	(60.9)	(55.0)	(55.0)	(58.7)	(51.3)	(62.3)	(58.7)	(58.7)
Landfilled Wood	(161.3)	(157.3)	(156.2)	(149.2)	(149.6)	(150.3)	(150.3)	(154.0)	(154.0)	(154.0)	(150.3)	(154)
Total	(982.7)	(971.7)	(976.4)	(977.5)	(984.1)	(979.0)	(979.0)	(759.0)	(751.7)	(762.7)	(755.3)	(759.0)

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total net flux) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

Forest Sector Modeling Projection System

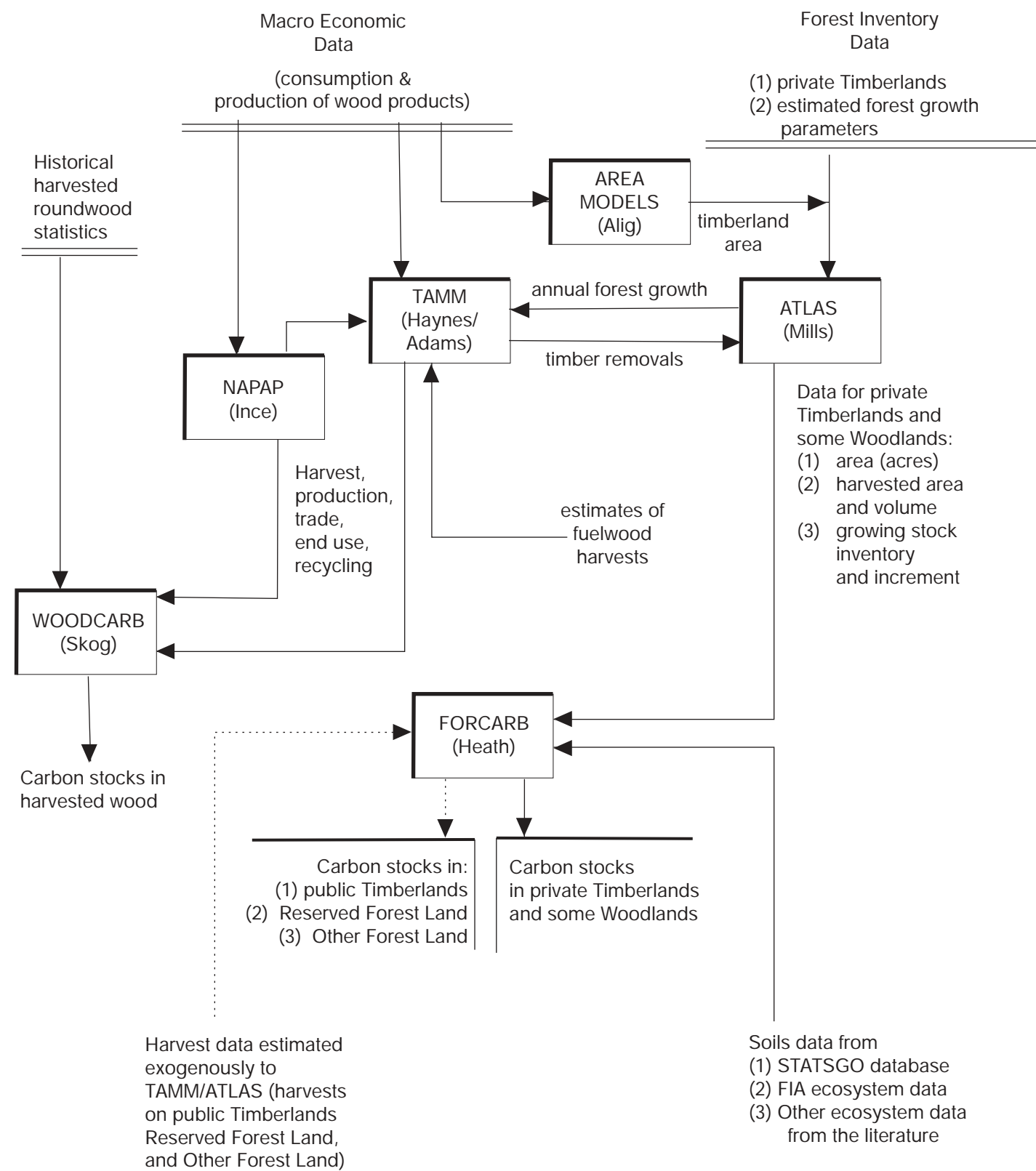
The modeling projection system is a set of models that has been used for the USDA Forest Service, Resource Planning Act Assessment since the late 1980s (Figure O-1). The models include an area change model (Alig 1985), a timber market model (TAMM; Adams and Haynes 1980), a pulp and paper model (NAPAP; Ince 1994) and an inventory model (ATLAS; Mills and Kincaid 1992). Many of these models are econometric models, designed to project the demand and supply and prices in the forest sector. Results of the projection include timber volume, forest areas, harvests, and primary product production. For a description of the assumptions and results of the modeling system, see Haynes (2002).

The FORCARB model (Plantinga and Birdsey 1993, Heath and Birdsey 1993, and Heath et al. 1996) uses data on timber volume, forest areas, and harvests from the modeling system to estimate carbon in trees using biometrical relationships between carbon and live tree volume. FORCARB estimates carbon in all other forest ecosystem components, producing carbon density estimates similar to those in Table O-1 and Table O-2. The model WOODCARB (Skog and Nicholson 1998) uses harvested roundwood product statistics, along with end-use, decay rate, and duration information to estimate carbon in harvested wood.

Figure O-1 illustrates the connections between the various models, data inputs, and data outputs that comprise the forest sector modeling projection system. Names of model authors are in parentheses in each model box to facilitate identification of model citations. Data that are external to the models are marked with double lines.

Figure O-1: Forest Sector Modeling Projection System

Figure 0-1: Forest Sector Modeling Projection System



ANNEX P

Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils

This annex presents a discussion of the methodology used to calculate annual carbon flux from mineral and organic soils under agricultural management, based on changes in soil organic carbon storage. The methodology uses a modified version of the IPCC method and a Monte Carlo uncertainty analysis, with the most detailed data available for the United States. As part of this analysis, U.S.-specific reference carbon stocks and management factor values were derived, along with their uncertainty as represented in probability density functions. These were used to estimate soil organic carbon stocks for 1982, 1992, and 1997, which coincide with the years of the *1997 National Resources Inventory* (NRCS 2000). More detailed discussions of selected topics may be found in the references cited in this annex. The details of carbon conversion factors and step-by-step details of calculating net CO₂ flux for mineral and organic soils are given in four steps.

Step 1: Obtain Data on Climate, Soil Types, Land-Use and Land Management Activity Over Time, and Estimate Management Factors Quantifying the Effect of Management Change on Soil Organic Carbon Storage

Step 1a: Climate and Soils

The IPCC inventory methodology for agricultural soils divides climate into eight distinct zones based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC/UNEP/OECD/IEA 1997) (see Table P-1). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table P-1: Characteristics of the IPCC Climate Zones that Occur in the United States

Climate Zone	Annual Average Temperature (°C)	Average Annual Precipitation (mm)	Length of Dry Season (months)
Cold Temperate, Dry	< 10	< Potential Evapotranspiration	NA
Cold Temperate, Moist	< 10	≥ Potential Evapotranspiration	NA
Warm Temperate, Dry	10 – 20	< 600	NA
Warm Temperate, Moist	10 – 20	≥ Potential Evapotranspiration	NA
Sub-Tropical, Dry*	> 20	< 1,000	Usually long
Sub-Tropical, Moist (w/short dry season)*	> 20	1,000 – 2,000	< 5

* The climate characteristics listed in the table for these zones are those that correspond to the tropical dry and tropical moist zones of the IPCC. They have been renamed “sub-tropical” here.

Climate in the United States is monitored through an extensive network of National Weather Service cooperative weather stations. Other national agencies also maintain specific climate databases such as the USDA-NRCS Snotel network and the National Climatic Data Center Global Gridded Upper Air Statistics database. The Parameter-elevation Regressions on Independent Slopes Model has combined the 1961 through 1990 averages from each of these sources with topographic information derived from digital elevation models, generating a grid (4 km x 4 km grid cells) of temperature and precipitation estimates for the United States (Daly et al. 1994, Daly et al. 1998). Average annual precipitation and average annual temperature were derived for the 180 Major Land Resource Areas in the United States from Parameter-elevation Regressions on Independent Slopes Model outputs, and an IPCC climate zone was assigned to each Major Land Resource Area (see Figure P-1). Each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).

Figure P-1. Major Land Resource Areas by IPCC Climate Zone

Soils were classified into one of seven classes based upon texture, morphology, and ability to store organic matter (IPCC/UNEP/OECD/IEA 1997). Six of the categories are mineral types and one is organic (i.e., histosol). Reference carbon stocks, representing estimates from conventionally managed cropland, were computed for each of the mineral soil types across the various climate zones, based on pedon data from the National Soil Survey Characterization Database (NRCS 1997) (see Table P-2). These stocks are used in conjunction with management factors to compute the modified carbon stocks that result from management and land-use change. Probability density functions, which represent the variability in the stock estimates, were constructed as normal densities based on the mean and variance from the pedon data. Pedon locations were clumped in various parts of the country, which reduces the statistical independence of individual pedon estimates. To account for this lack of independence, samples from each climate by soil zone were tested for spatial autocorrelation using the Moran's I test, and variance terms were inflated by 10 percent for all zones with significant p-values.

Table P-2: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

IPCC Inventory Soil Categories	USDA Taxonomic Soil Orders	Climate Regions					
		Cold Temperate, Dry	Cold Temperate, Moist	Warm Temperate, Dry	Warm Temperate, Moist	Sub- Tropical, Dry	Sub- Tropical, Moist
High Clay Activity Mineral Soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols	42 (n = 133)	65 (n = 526)	37 (n = 203)	51 (n = 424)	42 (n = 26)	57 (n = 12)
Low Clay Activity Mineral Soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (n = 37)	52 (n = 113)	25 (n = 86)	40 (n = 300)	39 (n = 13)	47 (n = 7)
Sandy Soils	Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols)	24 (n = 5)	40 (n = 43)	16 (n = 19)	30 (n = 102)	33 (n = 186)	50 (n = 18)
Volcanic Soils	Andisols	124 (n = 12)	114 (n = 2)	124 (n = 12)	124 (n = 12)	124 (n = 12)	128 (n = 9)
Spodic Soils	Spodosols	86 (n=20)	74 (n = 13)	86 (n=20)	107 (n = 7)	86 (n=20)	86 (n=20)
Aquic Soils	Soils with Aquic suborder	86 (n = 4)	89 (n = 161)	48 (n = 26)	51 (n = 300)	63 (n = 503)	48 (n = 12)
Organic Soils*	Histosols	NA	NA	NA	NA	NA	NA

* Carbon stocks are not needed for organic soils.

Notes: Carbon stocks are for the top 30 cm of the soil profile, and were estimated from pedon data available in the National Soil Survey Characterization database (NRCS 1997); sample size provided in parentheses.

Step1b: Land Use and Management Activity Data

Land use and management data for 1982, 1992, and 1997 were obtained from the *1997 National Resources Inventory* (NRCS 2000). The *1997 National Resources Inventory* is a stratified multi-stage design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel 1997). An extensive amount of soils, land use, and land management data are collected during each survey, which occurs every five years (Nusser et al. 1998). Primary sources for data include aerial photography and remote sensing materials as well as field visits and county office records.

Land use information in the *1997 National Resources Inventory* was merged into a set of land use and management systems relevant for the soil organic carbon calculations based on the IPCC method (see Table P-3). Each National Resources Inventory point was assigned to a system based upon the land use data collected in 1982, 1992, and 1997 (NRCS 2000). Each National Resources Inventory point contains information on land use from the inventory year as well as three previous years. The four years of land use data were used to assign National Resources Inventory points to an agricultural system. Inventory data for the years 1979 through 1982 were used to define the 1982 land use, 1989 through 1992 for the 1992 land use, and 1994 through 1997 for the 1997 land use. National Resources Inventory points were assigned an IPCC soil type using soil taxonomy and texture information in the soils database that accompanies the *1997 National Resources Inventory* data (NRCS 2000). In addition, points were assigned to an IPCC climate zone based on location within Major Land Resource Areas. More than 400,000 National Resources Inventory points were included in the inventory calculations that had been identified as

cropland or grazing land in 1992 or 1997. Each point represents a specific land area based upon the weighted expansion factors.

Table P-3. Land Use and Management Categories

General Land Use		IPCC Category	
Categories	Specific Management Related Sub-Categories	Mineral Soils	Organic Soils
Agricultural (Cropland and Grazing Land)			
	Irrigated Crops	High Input Cultivation	Cultivated Crops
	Continuous Row Crops	Medium Input Cultivation	Cultivated Crops
	Continuous Small Grains	Medium Input Cultivation	Cultivated Crops
	Continuous Row Crops and Small Grains	Medium Input Cultivation	Cultivated Crops
	Row Crops in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Small Grains in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Row Crops and Small Grains in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Vegetable Crops	Low Input Cultivation	Cultivated Crops
	Low Residue Annual Crops (e.g., Tobacco or Cotton)	Low Input Cultivation	Cultivated Crops
	Small Grains with Fallow	Low Input Cultivation	Cultivated Crops
	Row Crops and Small Grains with Fallow	Low Input Cultivation	Cultivated Crops
	Row Crops with Fallow	Low Input Cultivation	Cultivated Crops
	Miscellaneous Crop Rotations	Medium Input Cultivation	Cultivated Crops
	Continuous Rice	Improved Land ¹	Undrained
	Rice in Rotation with other crops	Improved Land ¹	Undrained
	Continuous Perennial or Horticultural Crops	Improved Land ¹	Pasture/Forest
	Continuous Hay	Uncultivated Land (General)	Pasture/Forest
	Continuous Hay with Legumes or Irrigation	Improved Land ¹	Pasture/Forest
	Conservation Reserve Program	Uncultivated Land (Set-aside)	Undrained
	Rangeland	Uncultivated Land (General)	Undrained
	Continuous Pasture	Uncultivated Land (General)	Pasture/Forest
	Continuous Pasture with Legumes or Irrigation	Improved Land ¹	Pasture/Forest
	Aquaculture ²	Not Estimated	Not Estimated
Non-Agricultural³			
	Forest	Uncultivated Land (General)	Pasture/Forest
	Federal	Uncultivated Land (General)	Undrained
	Water ²	Not Estimated	Not Estimated
	Urban Land ²	Not Estimated	Not Estimated
	Miscellaneous ^{2,4}	Not Estimated	Not Estimated

Note: These land use and management categories were derived through analysis of the 1997 *National Resources Inventory* data (NRCS 2000).

¹ Improved land increases soil organic carbon storage above the levels found in general land-use changes.

² Assume no change in carbon stocks when converting to or from these land uses because of a lack of information about the effect of these practices on soil organic carbon storage.

³ Some non-agricultural land is included in the inventory because it was an agricultural land use in 1992 or 1997.

⁴ Includes a variety of land uses from roads, beaches, and marshes to mining and gravel pits.

Probability density functions for the 1997 *National Resources Inventory* land use data were assumed to be multivariate normal, and they were constructed to have a mean vector equal to the vector of total areas in different land use categories for different years of inventory, and to have a covariance matrix equal to the sampling covariance matrix computed from the 1997 *National Resources Inventory* data. Through this approach, interdependencies in land use were taken into account resulting from the likelihood that current use is correlated with past use.

Data on tillage practices are not reported in the 1997 *National Resources Inventory*, but have been collected by the Conservation Technology Information Center (CTIC 1998). Each year the Conservation Technology Information Center conducts a Crop Residue Management survey to estimate the portion of cropland managed under the various tillage systems. Probability density functions were constructed for the Conservation Technology Information Center data as bivariate normal on a log-ratio scale, to reflect negative dependence among tillage classes and to ensure that simulated tillage percentages were non-negative and summed to 100 percent. Conservation Technology Information Center data do not differentiate between continuous and intermittent use of no-tillage, which is important for estimating soil organic carbon storage. Thus regional-based estimates for continuous no-tillage (defined as 5 or more years of continuous use) were modified based on consultation with

Conservation Technology Information Center experts (downward adjustment of total no-tillage acres reported, Towery 2001).

Wetlands enrolled in the Conservation Reserve Program have been restored in the Northern Prairie Pothole Region through the Partners for Wildlife Program funded by the U.S. Fish and Wildlife Service. The amount of restored wetlands was estimated from contract agreements (Euliss and Gleason 2002). While the contracts provide reasonable estimates of the amount of land restored in the region, they do not provide the information necessary to estimate uncertainty. Consequently, a nominal ± 50 percent range was used to construct the probability density functions for the uncertainty analysis.

Probability density functions for manure and sludge application on cropland and grazing land have not been developed because minimal data exist on where and how much manure and sludge has been applied. Consequently, the impact of manure management on soil organic carbon was not part of the base inventory calculation (i.e., uncertainty analysis). Rather, a separate estimation was made for the contribution of manure and sludge management to soil C stocks, and the resulting changes were combined with the uncertainty calculation during post processing.

The amount of manure nitrogen and sewage sludge nitrogen produced each year, including the amount of each that was available for application on agricultural lands, was provided in the Agricultural Soil Management section of the Agriculture chapter of this volume. Manure and sewage sludge nitrogen were assumed to be applied at the assimilative capacity for crops (Kellogg et al. 2000). Assimilative capacity is the amount of nutrients taken up by a crop and removed at harvest, and it may vary from year to year because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total manure nitrogen and sewage sludge nitrogen available for application was divided by the assimilative capacity to estimate the total land area over which the manure and sewage sludge had been applied. Supplemental data are available regarding the amount of cropland area receiving manure and sewage sludge for major crops in the United States (ERS 2000). The percentage of fields receiving manure and sewage sludge had been estimated between 1990 and 1997 for corn, soybeans, winter wheat, cotton, and potatoes. This information was used in conjunction with the USDA *National Agricultural Statistics Database* (NASS 2002), which provides information on the amount of land planted to each crop, for estimating the cropland area receiving manure and sewage sludge. The remaining area receiving manure and sewage sludge was assumed to occur in grazing lands (calculated as the difference between the total area receiving manure and sewage sludge and the cropland area receiving manure and sewage sludge).

Step 1c: Management Factors Quantifying the Effect of Land Use and Management Change on Soil Organic Carbon Storage

Management factors representative of U.S. conditions were estimated from published studies. The numerical factors quantify the impact on soil organic carbon storage resulting from changing land use and management on soil organic carbon storage, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program). Studies from the United States and Canada were used in this analysis under the assumption that they would best represent management impacts for this inventory. Also, studies had to report soil organic carbon stocks (or information to compute stocks), depth of sampling, and the number of years since a management change. The data were synthesized in linear mixed-effects models, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data were not aggregated for the carbon stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) was included as a separate point in the dataset. Similarly, time series data were not aggregated in these datasets. Consequently, random effects were needed to account for the interdependence in times series data and the interdependence among data points representing different depth increments from the same study. Factors were estimated for the effect of management practices at 20 years for the top 30 cm of the soil (see Table P-4). Variance was calculated for each of the U.S. factor values, and used to construct probability density functions with a normal density. In the IPCC method, specific factor values are given for improved pastures and for wetland rice, both of which yield carbon stocks higher than for nominal uncultivated systems. The higher stocks are associated with increased productivity and C inputs (relative to native grasslands) on improved pastures and reduced decomposition due to periodic flooding in rice cultivation. (Improved pastures are identified in the 1997 *National Resources Inventory* as pastures that were irrigated or seeded with legumes.). There

were insufficient field studies to re-estimate factor values for these systems and thus the IPCC defaults were used, along with a nominal ± 50 percent range to construct the probability density function for the uncertainty analysis.

Table P-4. Management Factors for the United States and the IPCC Default Values

	IPCC default	U.S. factor
Land-Use Change		
Cultivated ¹	1	1
General Uncultivated ^{1,2}	1.4	1.3 (± 0.04)
Set-Aside ¹	1.25	1.2 (± 0.03)
Improved Pasture Lands³	1.1	1.1
Wetland Rice Production³	1.1	1.1
Tillage		
Conventional Till	1	1
Reduced Till	1.05	1.02 (± 0.03)
No-till	1.1	1.13 (± 0.03)
Input		
Low	0.9	0.94 (± 0.01)
Medium	1	1
High	1.1	1.074 (± 0.03)

¹ Factors in the IPCC documentation (IPCC/UNEP/OECD/IEA 1997) were converted to represent changes in soil organic carbon storage from a cultivated condition rather than a native condition.

² Default factor was higher for aquatic soils at 1.7, but the U.S. analysis showed no significant differences between aquatic and non-aquatic soils and so a single U.S. factor was estimated for all soil types.

³ A U.S. specific factor was not estimated for land or management leading to additional carbon storage because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for pasture lands in the United States, or the impact of wetland rice production in the United States.

Wetland restoration management also influences soil organic carbon storage because restoration leads to higher water tables and inundation of the soil for at least part of the year (Olness et al. in press, Euliss et al. in prep). A management factor was estimated assessing the difference in soil organic carbon storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Olness et al. in press, Euliss et al. in prep, Euliss and Gleason 2002), which represents an initial increase of carbon in the restored soils over the first 10 years (see Table P-5). A probability density function with a normal density was constructed from these data based on results from a linear regression model. Following the initial increase of carbon, natural erosion and deposition leads to additional accretion of carbon in these wetlands. Mass accumulation rate of organic carbon was estimated using annual sedimentation rates (cm/yr) in combination with percent organic carbon, and soil bulk density (g/cm^3) (Euliss and Gleason 2002). Procedures for calculation of mass accumulation rate are described in Dean and Gorham (1998); the resulting rate and variance were used to construct a probability density function with a normal density (see Table P-5).

Table P-5. Factor Estimate for the Initial Increase in Carbon During the First 10 Years Following Wetland Restoration of Conservation Reserve Program; Mass Accumulation Rate Represents Additional Gains in Carbon After the First 10 Years

Factor (Initial Increase—First 10 Years)	1.22 \pm 0.18
Mass Accumulation (After Initial 10 Years)	0.79 \pm 0.05 Mg C/ha-yr

Note: Mass accumulation rate from Euliss and Gleason (2002).

In addition, carbon loss rates were estimated for cultivated organic soils based on subsidence studies in the United States and Canada (see Table P-6). Probability density functions were constructed as normal densities based on the mean carbon loss rates and associated variances.

Table P-6: Carbon Loss Rates from Organic Soils Under Agricultural Management in the United States, and the IPCC Default Rates (Metric Ton C/ha-yr)

Region	Cropland		Pasture / Forest	
	IPCC	U.S. Revised	IPCC	U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2 \pm 2.5	0.25	2.8 \pm 0.5 ¹

Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8 ¹
Sub-Tropical, Dry & Sub-Tropical, Moist	20	14.0±3.3	5	3.5±0.8 ¹

¹ There were not enough data available to estimate a U.S. value for C losses from managed pastures and forests. Consequently, estimates are 25 percent of the values for cropland, which was an assumption used for the IPCC default organic soil C losses on pasture/forest lands.

Step 2: Estimate Land-Use and Management Activity Trends

Each National Resources Inventory point contains land-use information for the inventory year and the three previous years, which were used to assign each agricultural National Resources Inventory point to a land use/management system (see Table P-3). National Resources Inventory points that were not designated agricultural management in 1992 or 1997 were eliminated from the land base. However, a limited number of points classified as non-agricultural land uses did remain in the analysis. For example, non-agricultural land uses were included if a National Resources Inventory point was cropland or grazing land in 1992 or 1997, but was a non-agricultural land use in 1982. In addition, non-agricultural uses appeared in the land base if a National Resources Inventory point became a non-agricultural use in 1997 after being cropland or grazing land in 1992.

Land areas were summed to evaluate trends in the activity data between 1982 and 1997 for the IPCC land use and management categories (see Table P-7). Between 1997 and 2001, no changes were assumed to have occurred in the relative areas of the agricultural systems with the exception of additional enrollment in the Conservation Reserve Program (discussed later in this document).

Table P-7: Areas for each Land-Use and Management System Used in IPCC Method for all U.S. Land Area Categorized as an Agricultural Use in 1992 or 1997 (Million Hectares)

IPCC Land Use/Management Categories	Land Areas		
	1982	1992	1997
Medium Input Cropping	87.49	77.17	78.27
High Input Cropping ¹	22.21	22.02	21.74
Low Input Cropping ²	30.96	28.92	25.13
Rice ³	2.71	2.13	2.22
Uncultivated Land ⁴	210.04	207.77	210.26
Improved Land ⁵	31.19	33.65	31.43
Conservation Reserve Program ⁶	0.00	13.78	13.23
Urban, Water, Miscellaneous Non-Cropland	1.78	0.96	4.11
Totals	386.39	386.39	386.39

Note: Based on analysis of the 1997 *National Resources Inventory* data (NRCS 2000).

1 Includes hay or legumes in rotation, winter cover crop, and irrigated cropland.

2 Includes fallow and low residue cropland.

3 The rice areas in this table do not match those in the Rice Cultivation section of the Agriculture chapter because here, rice areas include both fields under continuous rice production and fields under rice in rotation with other crops (e.g., a year of rice followed by a year of wheat production). Therefore, for any particular year, the rice area in this table, representing rice-dominated management systems, is greater than the area under rice production in that year. The rice areas in the Rice Cultivation section of the Agriculture chapter include only areas that are under rice production in each year.

4 Includes hayland, rangeland, pasture, forest, and federal land-use.

5 Includes pasture or hayland with legumes or irrigation and continuous perennial crops.

6 Includes set-aside land.

The trends showed a decline for the area in the high, low, and medium input cropping systems between 1982 and 1997. In addition, the rice-dominated area declined slightly over this time period. A portion of the loss in cultivated cropland was due to setting-aside areas from production in the Conservation Reserve Program, and the remaining decline can be attributed mostly to increases in urban areas, land covered in water (e.g., lakes), and miscellaneous non-cropland (e.g., barren areas and roads). The amount of area in other uncultivated land uses, including pastures and rangelands, remained relatively stable across this time period.

Almost no cropland was managed using no-till in 1982 (see Table P-8). Some land managers, however, had started using reduced tillage systems. For the most part, adoption of reduced tillage and no-till increased steadily in the late 1980s and early 1990s, and leveled off somewhat in the mid- to late- 1990s (CTIC 1998). Because adoption of these conservation tillage techniques has leveled off, adoption was assumed to remain constant between 1997 and 2001 for this analysis. Overall, conventional tillage is the dominant management practice used in U.S. croplands over the inventory period.

Table P-8: Tillage Percentages for each Management Category in the U.S. Climate Zones, with Adjustments for Long-term Adoption of No-till Agriculture (Percent)

System	1982			1992			1997		
	No Till ¹	Reduced Till ²	Conventional Till ³	No Till	Reduced Till	Conventional Till	No Till	Reduced Till	Conventional Till
Sub-Tropical, Dry									
Continuous Cropping Rotations ⁴	0	3	97	0	4	96	0	15	85
Rotations with Fallow ⁵	0	0	100	0	2	98	0	5	95
Low Residue Agriculture ⁶	0	3	97	0	4	96	0	10	90
Sub-Tropical, Moist									
Continuous Cropping Rotations	0	0	100	0	20	80	1	10	89
Rotations with Fallow	0	0	100	0	10	90	1	10	89
Low Residue Agriculture	0	3	97	0	4	96	0	5	95
Warm Temperate, Dry									
Continuous Cropping Rotations	0	0	100	0	10	90	1	15	84
Rotations with Fallow	0	3	97	0	15	85	2	20	78
Low Residue Agriculture	0	3	97	0	1	99	0	0	100
Warm Temperate, Moist									
Continuous Cropping Rotations	0	6	94	10	30	60	12	28	60
Rotations with Fallow	0	6	94	5	30	65	8	27	65
Low Residue Agriculture	0	9	91	1	10	89	2	13	85
Cold Temperate, Dry									
Continuous Cropping Rotations	0	3	97	2	25	73	8	12	80
Rotations with Fallow	0	6	94	4	25	71	12	13	75
Low Residue Agriculture	0	0	100	1	2	97	2	6	92
Cold Temperate, Moist									
Continuous Cropping Rotations	0	11	89	5	30	65	3	17	80
Rotations with Fallow	0	11	89	5	30	65	3	27	70
Low Residue Agriculture	0	0	100	1	2	97	1	7	92

¹ No-till includes CTIC survey data designated as no-tillage.

² Reduced-till includes CTIC survey data designated as ridge tillage, mulch tillage, and reduced tillage.

³ Conventional till includes CTIC survey data designated as intensive tillage and conventional tillage.

⁴ Medium and high input rotations (based on the IPCC categories) found in Table P-3. CTIC survey data for corn, soybeans, and sorghum were used in this category.

⁵ Rotations with fallow found in Table P-3. CTIC survey data on fallow and small grain cropland were used in this category.

⁶ Low input rotations found in Table P-3, with the exception of rotations with fallow. CTIC survey data on cotton were used in this category; tillage rates are assumed to be the same for low residue crops and vegetables in rotation.

Organic soils are categorized into land-use systems based on drainage for purposes of estimating carbon losses (IPCC/UNEP/OECD/IEA 1997). Undrained soils are treated as having no loss of organic C for purposes of the inventory. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and greater losses of carbon, and those used for managed pasture or agroforestry, which are assumed to have less drainage and smaller losses of carbon. Overall, organic soils cultivated for cropland production have remained relatively stable since 1982, but the area of organic soils managed as forest or pasture has increased slightly (see Table P-9).

Table P-9: Land Areas for Each Organic Land Use Category (For All U.S. Land Area Categorized as Agricultural in 1992 or 1997) Based on Analysis of 1997 National Resources Inventory Data. (Million Hectares)

IPCC Land Use Category for Organic Soils ¹	Land Areas		
	1982	1992	1997
Undrained	0.17	0.19	0.16
Managed Pasture and Forest (Low Drainage)	0.49	0.50	0.52
Cultivated Cropland (High Drainage)	0.63	0.62	0.63
Other Land Uses ²	0.05	0.02	0.03
Total	1.34	1.34	1.34

¹ Table P-4 provides information how the IPCC land use systems are classified in the land management categories for organic soils.

² Urban, water, and miscellaneous non-cropland, are not included in the inventory calculations because they are not agricultural uses and little is known about how they affect soil carbon storage relative to agricultural land management.

The annual areas of mineral soil agricultural lands on which manure and sewage sludge were applied were estimated to range from 23 to 25 million hectares between 1990 and 2001 (see Table P-11 for calculations). Of this total area, manure and sewage sludge applications were estimated to range from 7.5 to 9.5 million hectares of cropland and 14 to 17 million hectares of grazing land.

Step 3: Estimate Soil Carbon Stocks

The IPCC method is a carbon accounting approach that is used to estimate carbon stock changes and CO₂ fluxes between soils and the atmosphere based on land use and management (IPCC/UNEP/OECD/IEA 1997). For mineral soils (i.e., all soil orders from the USDA taxonomic classification except histosols), the IPCC inventory method uses reference carbon values to establish baseline carbon stocks that are modified through agricultural activities as quantified by land-use change, tillage, and input factors. For this inventory, the standard approach was modified to use agricultural soil organic carbon stocks as the reference condition, rather than uncultivated soils under native vegetation. This modification was needed because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997). Measurements of soils under native vegetation are uncommon in the major agricultural regions of the United States because most of the area has been converted into cropland.

Organic soils used for agricultural production are treated in a separate calculation. These soils are made up of deep (greater than 30 cm) layers of organic material that can decompose at a steady rate over several decades following drainage for cropland production (IPCC/UNEP/OECD/IEA 1997). The IPCC approach uses an emission factor to estimate annual losses of CO₂ from organic soils, rather than a stock change approach.

Mineral and organic soil calculations were made for each climate by soil zone across the United States. Mineral stock values were derived for 1982, 1992, and 1997 based on the land use and management activity data in conjunction with appropriate reference carbon stocks, land-use change, tillage, input and wetland restoration factors. Carbon losses from organic soils were computed based on 1992 and 1997 land use and management in conjunction with the appropriate carbon loss rate.

Each input to the inventory calculations had some level of uncertainty that was quantified in probability density functions, including the land use and management activity data, reference carbon stocks, and management factors. A Monte Carlo Analysis was used to quantify the uncertainty in carbon change for the inventory period based on uncertainty in the inputs. Input values were randomly selected from the probability density functions in an iterative process to estimate soil organic carbon change 50,000 times, and produce a 95 percent confidence interval for soil organic carbon change in agricultural lands.

Step 4: Estimate Average Annual Changes in Soil Carbon Stocks

In accordance with IPCC methodology, annual changes in mineral soil carbon were calculated by subtracting the beginning stock from the ending stock and dividing by 20. For this analysis, the base inventory estimate for 1990 through 1992 is the annual average of 1992 stock minus the 1982 stock. Annual average change between 1993 and 2001 is the difference between the 1997 and 1992 carbon stocks. Using the Monte Carlo Approach, soil organic carbon stock change for mineral soils was estimated 50,000 times between 1982 and 1992, and between 1992 and 1997. From the final distribution of 50,000 values, a 95 percent confidence interval was generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution. For organic soils, annual losses of CO₂ were estimated for 1992 and 1997 by applying the Monte Carlo approach to 1992 and 1997 land use data and the U.S. carbon loss rates (see Table P-6). The results for 1992 were applied to the years 1990 through 1992, and the results for 1997 were applied to the years 1993 through 2001. On average, mineral soils under agricultural management were sequestering about 35.8 to 35.4 Tg CO₂ Eq. annually and organic soils lost about 34.3 to 34.8 Tg CO₂ Eq. annually (see Table P-10). Overall, U.S. agricultural soils appear to be sequestering from 0.7 to 1.5 Tg CO₂ Eq. annually, although the uncertainties are rather large, ranging from emissions of about 24.2 Tg CO₂ Eq. annually to sequestration of about 19.5 Tg CO₂ Eq. annually.

Table P-10: Annual Change in Soil Organic Carbon for U.S. Agricultural Soils Based Upon the Monte Carlo Uncertainty Analysis with U.S. Factor Values, Reference Carbon Stocks, and Carbon Loss Rates (Tg CO₂ Eq.)

	1990-1992	1993-2001
Mineral Soils	(35.8)*	(35.4)*

	(13.9 to 58.7)	(20.9 to 50.3)
Organic Soils	34.3	34.8
	23.1 to 48.4	23.5 to 49.1
Total	(1.5)	(0.7)
	24.2 to (27.2)	19.5 to (19.5)

*Does not include the change in storage resulting from the annual application of manure or the additional Conservation Reserve Program enrollment after 1997.

Note: The ranges are a 95 percent confidence interval from 50,000 simulations (Ogle et al. in review).

There are two additional land use and management activities in U.S. agriculture lands that were not accounted for in the base inventory (i.e., uncertainty analysis). The first activity involved the application of manure and sewage sludge to agricultural lands. Minimal data exist on where and how much manure and sewage sludge is applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving manure and sewage sludge are available by combining information from the USDA *National Agricultural Statistics Database* (NASS 2002), manure and sewage sludge nitrogen applications (from the Agricultural Soil Management Section of the Agriculture chapter of this Inventory), and USDA Economic Research Service reports on percentage of fields receiving manure for major crops in the United States (ERS 2000). The impact of manure and sewage sludge additions on soil organic carbon was calculated as 0.1 metric ton C/ha-yr for croplands, and 0.33 metric ton C/ha-yr for grazing lands. These rates are based on IPCC calculations that represent the effect of converting medium input cropping systems to high input systems and on converting nominal pastures to improved lands, respectively (assuming a reference carbon stock of 50 metric ton C/ha-yr, which represents a mid-range value for the dominant agricultural soils in the United States). From 1990 through 2001, manure and sewage sludge applications in agricultural lands increased soil organic carbon storage in mineral soils by about 5.79 to 6.26 Tg C annually (21.3 to 23.0 Tg CO₂ Eq.) (see Table P-11).

Table P-11: Assumptions and Calculations to Estimate the Contribution to Agricultural Soil Organic Carbon from Application of Animal Manure and Sewage Sludge to Mineral Soils

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Total N (Tg)¹	2.76	2.84	2.83	2.90	2.92	2.90	2.94	3.00	3.04	3.04	3.09	3.11
Manure N ¹	2.71	2.78	2.77	2.83	2.85	2.82	2.85	2.91	2.95	2.94	3.00	3.01
Sewage Sludge N ¹	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10
Assimilative Capacity (metric ton / ha)²	0.120	0.120	0.120	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122
Area covered by Available N (ha x 10⁶)^{3,4}	22.98	23.64	23.61	23.75	23.97	23.78	24.08	24.59	24.89	24.90	25.36	25.47
Cropland Receiving Manure	7.78	8.58	8.04	8.42	8.51	6.69	8.66	9.27	9.30	9.17	9.34	9.34
Grazing Land Receiving Manure	15.20	15.06	15.57	15.32	15.46	17.09	15.42	15.32	15.59	15.73	16.02	16.13
Contribution to Agricultural Land Soil C (Tg C)⁵	5.79	5.83	5.94	5.90	5.95	6.31	5.95	5.98	6.07	6.11	6.22	6.26
Contribution to Cropland Soil C	0.78	0.86	0.80	0.84	0.85	0.67	0.87	0.93	0.93	0.92	0.93	0.93
Contribution to Grazing Land Soil C ⁵	5.01	4.97	5.14	5.06	5.10	5.64	5.09	5.06	5.14	5.19	5.29	5.32

¹ Total N available to be applied to soils (this volume).

² Assimilative Capacity is the national average amount of sewage sludge and manure-derived N that can be applied on cropland without buildup of nutrients in the soil (Kellogg et al. 2000).

³ Area which received manure or sewage sludge amendments was calculated based on the available N for application divided by the assimilative capacity. The 1992 assimilative capacity rate was applied to 1990 - 1992 and the 1997 rate was applied to 1993-2000.

⁴ Some small, undetermined fraction of this applied N is probably not applied to agricultural soils, but instead is applied to forests, home gardens, and other lands

⁵ Soil C stock is calculated as the area covered by available N multiplied by a national average annual rate of soil C change per ha (0.1 metric ton/ha-yr for croplands and 0.33 metric ton/ha-yr for grazing lands).

The second activity, which is not included as part of the baseline inventory, is the change in enrollment for the Conservation Reserve Program after 1997. Relative to the enrollment in 1997, the total area in the Conservation Reserve Program declined in 1998 through 2000, and then increased in 2001, leading to an additional enrollment of 362,377 ha over the four year period (Barbarika 2002). An average annual change in soil organic carbon of 0.5 metric ton C/ha-yr was used to estimate the effect of the enrollment changes. This estimate was based on an IPCC calculation for how much soil organic carbon increases by setting aside a medium input cropping system in the Conservation Reserve Program (assuming a reference carbon stock of 50 metric ton C/yr, which represents a mid-range value for the dominant agricultural soils in the United States). The change in enrollment generated emissions

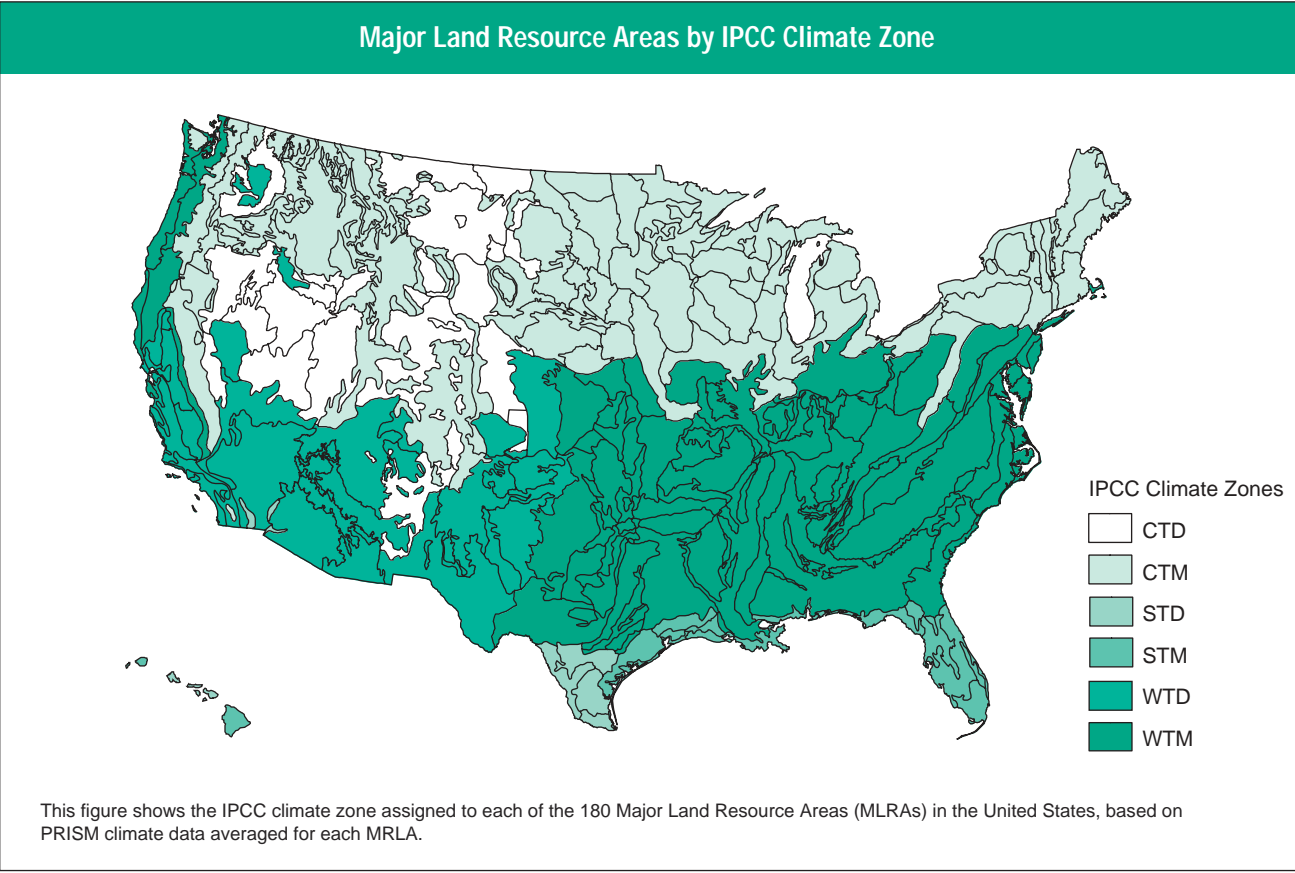
in 1998 through 2000, but with increased enrollment by 2001, agricultural lands sequestered an additional 0.7 Tg CO₂ Eq. in 2001 relative to the baseline inventory (see Table P-12).

The sum total of the base inventory and the additional land use and management considerations (i.e., manure and sewage sludge additions, and Conservation Reserve Program enrollment in 1998 through 2001) are presented in Table P-12. Agricultural soils were estimated to sequester from 21.0 to 24.3 Tg CO₂ Eq. annually between 1990 and 2001, based on the change in soil organic carbon storage.

Table P-12: Annual Net Flux of CO₂ from U.S. Agricultural Soils for the Baseline Inventory (Uncertainty Analysis) Plus the Additional Land Use/Management Considerations (Tg)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Net emissions based on uncertainty analysis	(1.5)	(1.5)	(1.5)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soils	(35.8)	(35.8)	(35.8)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)
Organic Soils	34.3	34.3	34.3	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Additional changes in net emissions from mineral soils	(21.3)	(21.4)	(21.8)	(21.7)	(21.9)	(23.2)	(21.9)	(22.0)	(20.4)	(20.3)	(21.9)	(23.6)
Application of manure and sewage sludge N to crop and grazing lands	(21.3)	(21.4)	(21.8)	(21.7)	(21.9)	(23.2)	(21.9)	(22.0)	(22.3)	(22.4)	(22.8)	(23.0)
Changes in Conservation Reserve Program enrollment relative to 1997	NA	NA	NA	NA	NA	NA	NA	NA	1.9	2.1	0.9	(0.7)
Total net emissions	(22.8)	(22.9)	(23.3)	(22.3)	(22.5)	(23.8)	(22.5)	(22.6)	(21.1)	(21.0)	(22.6)	(24.3)

Figure P-1



ANNEX Q

Methodology for Estimating CH₄ Emissions from Landfills

Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in municipal solid waste (MSW). By volume, MSW landfill gas is about half methane and half carbon dioxide.¹ The amount and rate of methane generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment.

Not all methane generated within a landfill is emitted to the atmosphere. If no measures are taken to extract the methane, a portion of it will oxidize as it travels through the top layer of the landfill cover. The portion of the methane that oxidizes turns primarily to carbon dioxide (CO₂). If the methane is extracted and either flared or utilized for energy, then that portion of the methane generated will also be oxidized to CO₂ during combustion. In general, landfill-related CO₂ emissions are of biogenic origin and primarily result from the decomposition, either aerobic or anaerobic, of organic matter such as food or yard wastes.²

To estimate the amount of methane produced in a landfill in a given year, information is needed on the type and quantity of waste in the landfill, as well as the landfill characteristics (e.g., size, aridity, waste density). However, this information is not available for all landfills in the United States. Consequently, a methodology to estimate methane emissions based on available landfill-specific data on waste in place (WIP) was developed.

From an analysis of the population of MSW landfills, the quantity of waste disposed in U.S. landfills was simulated in a landfill population model, which also modeled changes in landfill size over time. An EPA study of the methane generation properties of landfilled waste was then used in an emissions model to estimate methane generation. Based on organic content in industrial landfills, methane emissions from industrial landfills were assumed to be seven percent of the total methane generated from MSW at landfills. Total methane emissions were estimated by adding the methane from MSW and industrial landfills, subtracting the amount recovered and used for energy or flared, and subtracting the amount oxidized in the soil. The steps taken to estimate emissions from U.S. landfills for the years 1990 through 2001 are discussed in greater detail below.

Figure Q-1 presents the methane emissions process—from waste generation to emissions—in graphical format.

Step 1: Estimate Municipal Solid Waste Landfilled by Individual Landfill

First, a landfill survey was used to estimate the amount and distribution of landfilled waste in the United States (EPA 1988). The survey consisted of approximately 1,100 landfills representative of approximately 6,000 landfills that were active in the United States in 1986, and included information on annual waste acceptance, size, design capacity, open year, and closure year. The landfills selected in the survey varied by age, depth, regional distribution, and other factors.

Based on the results of this survey, a population model was developed to simulate the flow of landfilled waste from 1960 through the current year. For 1960 to 1990, the data from the landfill survey were extrapolated to other years using annual waste acceptance, design capacity, open year, and closure year. For 1991 to 2001, the model distributed estimates of total waste landfilled from BioCycle's *State of Garbage in America* report across the U.S. landfill population based on the same variables.³ If landfills reached their design capacity, they were simulated to close. New landfills were simulated to open when a significant shortfall in disposal capacity was predicted. Simulated new landfills were assumed to be larger, on average, reflecting the trend toward fewer and more

¹ Landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

² See Box 7-1 in the Waste chapter for additional background on how biogenic emissions of landfill CO₂ are addressed in the U.S. Inventory.

³ Since the BioCycle survey does not include U.S. territories, waste generation from U.S. territories was estimated using population data for the U.S. territories (U.S. Census Bureau 2000) and U.S. per capita waste generation (EPA 2002b).

centralized facilities. The analysis updated the landfill characteristics each year, calculating the profile of waste disposal over time.

Table Q-1 shows the BioCycle estimates of total waste landfilled each year from 1990 through 2000, adjusted for U.S. territories. Regression analysis was used to develop an estimate of waste landfilled in 2001, since BioCycle data were not yet available at the time this report was published.

Step 2: Estimate 30-Year Waste In Place by Landfill for Municipal Solid Waste Landfills

Methane is generated for approximately 30 years after waste is landfilled (EPA 1993). Consequently, each landfill's 30-year WIP was estimated in order to estimate methane generation in 2001.⁴ For each landfill, this estimate was calculated as the sum of the MSW landfilled over the previous 30 years, as shown in the following equation:

$$\text{waste in place (tons)} = \sum_{t=1972}^{2001} \text{waste landfilled (tons)}$$

Closed landfills were included in this analysis, since they continue to generate methane after closure.

Step 3: Estimate Methane Generation at Municipal Solid Waste Landfills

Each landfill's WIP estimate was then converted to methane generation using the following emissions equations:

Small landfills (< 2 MMT WIP): $\text{CH}_4 \text{ (m}^3\text{/min)} = 7.43 \text{ WIP (10}^6 \text{ MT)}$

Large landfills (> 2 MMT WIP): $\text{CH}_4 \text{ (m}^3\text{/min)} = 8.22 + 5.27 \text{ WIP (10}^6 \text{ MT)}$

These equations are the result of a regression analysis performed by EPA of 85 large landfills in the United States (EPA 1993). Equations for small landfills were estimated by averaging the estimates of methane generation per megagram of WIP for each of the 85 large landfills. The study resulted in four emissions equations for each of the following landfill size and aridity combinations: small/arid, small non-arid, large/arid, and large/non-arid. Data on the percentage of U.S. landfills in arid versus non-arid locations were then used to develop the two weighted equations shown above.

These equations were incorporated into an emissions model that converted WIP for each landfill to methane generation. Total methane generation was then calculated as the sum of methane generation from all landfills, open and closed.

Step 4: Estimate Methane Generation at Industrial Landfills

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Because no data were available on methane generation at industrial landfills, emissions from industrial landfills were assumed to equal seven percent of the total methane emitted from MSW landfills (EPA 1993). This estimate was based on the relative quantities and organic content of industrial waste compared to municipal waste at the time of the EPA study, as shown in the equations below (EPA 1993):

$$\frac{8.6 \text{ MMT organic waste in industrial landfills}}{65\% \text{ organic content of MSW}} = 13.2 \text{ MMT of equivalent total MSW}$$

$$13.2 \text{ MMT} \div 190 \text{ MMT total MSW in MSW landfills} = 7\%$$

⁴ Other methods exist for estimating landfill methane emissions, such as the first order decay method. However, these methods require data that are not readily available for the U.S. landfill population. In particular, landfill-specific data on the waste composition and rate of methane generation are not available for the over 2,000 U.S. landfills. EPA believes that using landfill specific data on the waste-in-place provides a better approximation of methane generation than the use of national average coefficients for model parameters that are necessary to use other methods. Consequently, EPA uses the regression equations rather than other methods that are typically applied to evaluate methane generation.

Estimates of methane generation from industrial landfills are shown in Table Q-2.

Step 5: Estimate Methane Emissions Avoided

The estimate of methane emissions avoided (e.g., combusted) was based on landfill-specific data on flares and landfill gas-to-energy (LFGTE) projects.

Step 5a: Estimate Methane Emissions Avoided Through Flaring

The quantity of methane flared was based on data collected from flaring equipment vendors, including information on the quantity of flares, landfill gas flow rates, and year of installation (ICF 2002). To avoid double counting, flares associated with landfills that had an LFGTE project were excluded from the flaring analysis. The median landfill gas flow rate provided by vendors was used to estimate methane recovered from each remaining flare. However, several vendors provided information on the size of the flare rather than the landfill gas flow rate. To estimate a median flare rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Total methane recovered through flaring was estimated by summing the estimates of methane recovered by each flare for each year.

Step 5b: Estimate Methane Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects

The quantity of methane avoided due to LFGTE systems was estimated based on information in a database compiled by EPA's Landfill Methane Outreach Program (EPA 2002a). Using data on landfill gas flow and energy generation (i.e. MW capacity), the total direct methane emissions avoided due to the recovery and use of methane were estimated.

Step 5c: Reduce Methane Emissions Avoided Through Flaring

As mentioned in Step 5a, flares associated with LFGTE projects were excluded from the flare analysis. If EPA had comprehensive data on flares, each LFGTE project would have an identified flare because most LFGTE projects have flares. However, given that the flare data only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGTE projects. These LFGTE projects likely have flares, however EPA was unable to identify a flare due to one of two reasons: 1) inadequate identifier information in the flare data; or 2) the lack of the flare in the database. For those projects for which a flare was not identified due to inadequate information, EPA would be overestimating methane avoided as both the methane avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, EPA determined the methane avoided from LFGTE projects for which no flare was identified and reduced the flaring estimate by this quantity. This step likely results in an underestimate of methane avoided due to flaring. EPA took this approach to be conservative in the estimates of methane avoided.

Step 6: Estimate Methane Oxidation

A portion of the methane escaping from a landfill oxidizes to carbon dioxide in the top layer of the soil. The amount of oxidation depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that ten percent of the methane produced, minus the amount of gas recovered for flaring or LFGTE projects, was oxidized in the soil (Liptay et al. 1998). This oxidation factor was applied to the methane generation estimates for both MSW and industrial landfills.

Step 7: Estimate Total Methane Emissions

Total methane emissions were calculated by adding emissions from MSW and industrial waste, and subtracting methane recovered and oxidized, as shown in Table Q-2.

Table Q-1: Municipal Solid Waste (MSW) Contributing to Methane Emissions (Tg unless otherwise noted)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Total MSW Generated ^a	269	258	268	281	296	299	300	312	343	350	374	370
Percent of MSW Landfilled ^a	77%	76%	72%	71%	67%	63%	62%	61%	61%	60%	61%	61%
Total MSW Landfilled	207	196	193	200	198	189	186	190	209	210	228	228
MSW Contributing to Emissions ^b	4,926	5,027	5,164	5,296	5,434	5,568	5,686	5,802	5,920	6,051	6,165	6,280

^a Source: *BioCycle* (2001), adjusted for missing U.S. territories using U.S. Census Bureau (2000), and EPA (2002b). The data, originally reported in short tons, are converted to metric tons. Data shown for 1990 are not used in EPA analysis (see "step 1" above). Data shown for 2001 based on regression analysis using historical waste generation and population, as *BioCycle* data were not available at the time this report was published.

^b The emissions model (EPA 1993) defines all waste that has been in place for less than 30 years as contributing to methane emissions.

Table Q-2: Methane Emissions from Landfills (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
MSW Generation	11,599	11,837	12,175	12,510	12,863	13,238	13,520	13,802	14,047	14,385	14,659	14,954
Large Landfills	4,534	4,625	4,771	4,927	5,127	5,314	5,488	5,663	5,836	6,055	6,231	6,439
Medium Landfills	5,791	5,912	6,071	6,223	6,349	6,515	6,607	6,699	6,755	6,857	6,941	7,016
Small Landfills	1,273	1,300	1,332	1,360	1,387	1,409	1,425	1,440	1,456	1,474	1,487	1,499
Industrial Generation	812	829	852	876	900	927	946	966	983	1,007	1,026	1,047
Potential Emissions	12,411	12,665	13,027	13,385	13,764	14,165	14,466	14,768	15,030	15,392	15,685	16,001
Emissions Avoided	(1,190)	(1,460)	(1,667)	(1,916)	(2,283)	(2,732)	(3,244)	(3,790)	(4,320)	(4,613)	(4,798)	(5,263)
Landfill Gas-to-Energy	(732)	(772)	(826)	(892)	(1,028)	(1,064)	(1,220)	(1,452)	(1,752)	(2,002)	(2,187)	(2,396)
Flare	(458)	(687)	(841)	(1,023)	(1,255)	(1,668)	(2,024)	(2,338)	(2,568)	(2,611)	(2,611)	(2,867)
Oxidation at MSW Landfills	(1,041)	(1,038)	(1,051)	(1,059)	(1,058)	(1,051)	(1,028)	(1,001)	(973)	(977)	(986)	(969)
Oxidation at Industrial Landfills	(81)	(83)	(85)	(88)	(90)	(93)	(95)	(97)	(98)	(101)	(103)	(105)
Net Emissions	10,099	10,085	10,224	10,323	10,333	10,290	10,100	9,880	9,639	9,701	9,798	9,663

Note: Totals may not sum due to independent rounding.

Note: MSW generation in Table Q-2 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.

() denotes a negative value

Figure Q-1: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste

*Seven percent represents the relative methane generation at MSW landfills versus industrial landfills, and is based on a comparative analysis of MSW and industrial waste (see "step 4" above). Consequently, the value for methane generated at industrial landfills is not subtracted from the value for methane generation at MSW landfills.

^a *BioCycle*

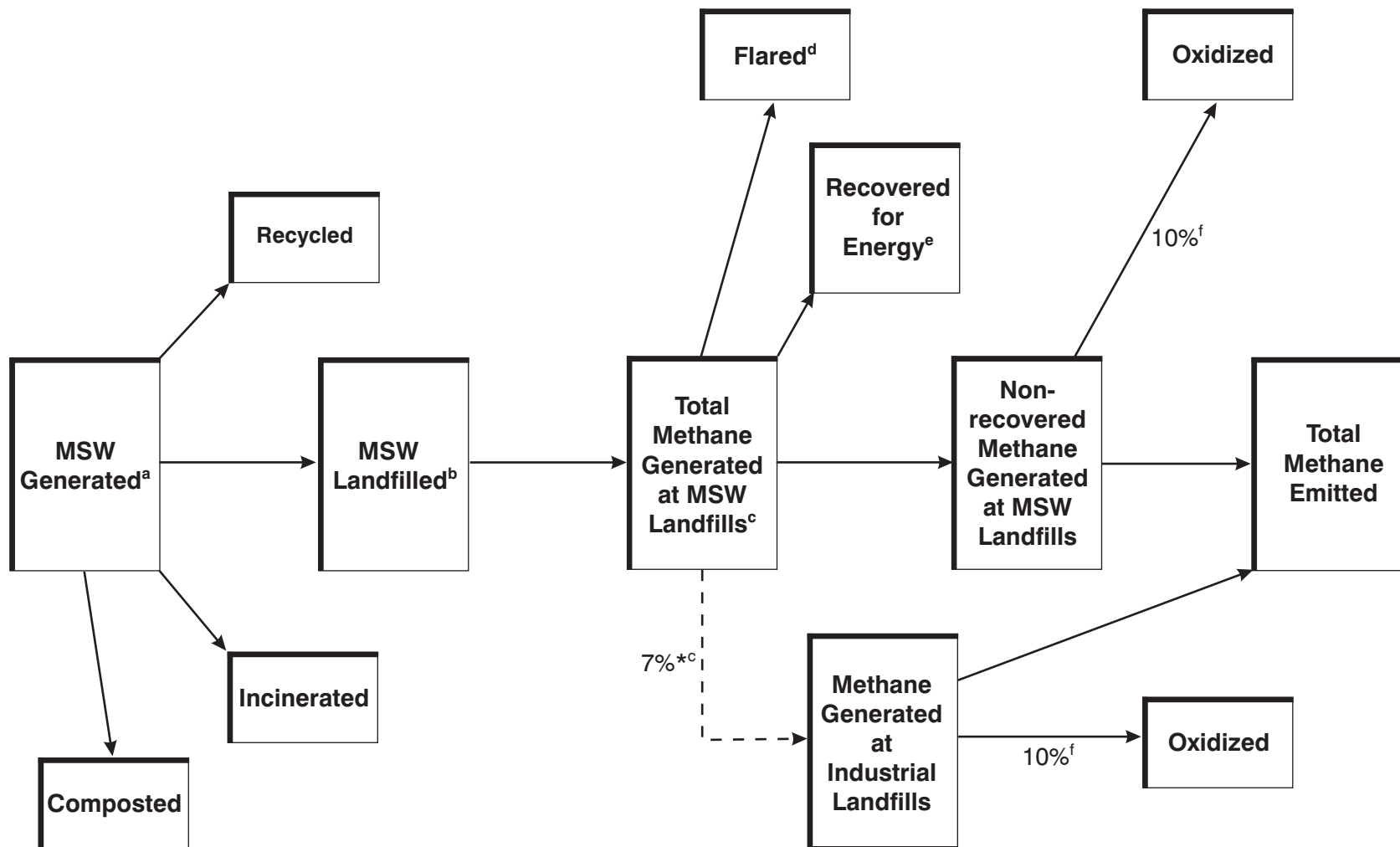
^b 1961 through 1990 based on EPA 1988; 1991 through 2001 based on *BioCycle*

^c EPA 1993

^d ICF Consulting 2002

^e EPA 2002a

^f Liptay et al. 1998



ANNEX R

Key Source Analysis

This Annex provides an analysis of key sources of emissions found in this report in order to ensure accuracy and reliability of inventory estimates. The IPCC's *Good Practice Guidance* (IPCC 2000) defines a key source category as a "[source category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."¹ By definition, key source categories are sources that have the greatest contribution to the absolute overall level of national emissions. In addition, when an entire time series of emission estimates is prepared, a thorough investigation of key source categories must also include accounting for the influence of trends of individual source categories. Therefore, a trend assessment is also conducted based on an attempt to identify source categories for which significant uncertainty in the estimate would have considerable effects on overall emission trends. This analysis culls out source categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key source categories should be performed, in order to capture any key source categories that were not identified in either of the quantitative analyses.

The methodology for conducting a key source analysis, as defined by IPCC's *Good Practice Guidance* (IPCC 2000), includes:

- Tier 1 approach (including both level and trend assessments);
- Tier 2 approach (including both level and trend assessments, and incorporating uncertainty analysis); and
- Qualitative approach.

Following this introduction, the Annex will present and analyze key source categories; discuss Tier 1, Tier 2, and qualitative approaches to identifying key sources; provide level and trend assessment equations; and provide a brief statistical evaluation of IPCC's quantitative methodologies for defining key sources.

Table R-1 presents the key source categories for the United States using emissions data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2001. The table also identifies the criteria used in identifying these source categories (i.e., level, trend, and/or qualitative assessments).

Table R-1: Key Source Categories for the United States (1990-2001) Based on Tier 1 Approach

IPCC Source Categories	Gas	Level	Trend	2001 Emissions (Tg CO ₂ Eq.)
Energy				
CO ₂ Emissions from Stationary Combustion – Coal	CO ₂	✓	✓	1,993.8
Mobile Combustion: Road & Other	CO ₂	✓	✓	1,538.7
CO ₂ Emissions from Stationary Combustion – Gas	CO ₂	✓	✓	1,168.2
CO ₂ Emissions from Stationary Combustion – Oil	CO ₂	✓	✓	671.6
Mobile Combustion: Aviation	CO ₂	✓	✓	183.9
Fugitive Emissions from Natural Gas Operations	CH ₄	✓	✓	117.3
Fugitive Emissions from Coal Mining & Handling	CH ₄	✓	✓	60.7
Mobile Combustion: Marine	CO ₂	✓		58.3
Mobile Combustion: Road & Other	N ₂ O	✓		52.6
Fugitive Emissions from Oil Operations	CH ₄		✓	21.2
Industrial Processes				
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓	63.7
CO ₂ Emissions from Iron and Steel Production	CO ₂	✓	✓	59.1
CO ₂ Emissions from Cement Production	CO ₂	✓	✓	41.4
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	✓	✓	19.8
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂		✓	16.6
SF ₆ Emissions from Electrical Equipment	SF ₆	✓	✓	15.3

¹ See chapter 7 "Methodological Choice and Recalculation" in IPCC (2000).
< <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>>

N ₂ O Emissions from Adipic Acid Production	N ₂ O	✓	4.9
PFC Emissions from Aluminum Production	PFCs	✓	4.1
Agriculture			
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	✓	216.6
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	✓	114.8
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	✓	77.7
CH ₄ Emissions from Manure Management	CH ₄	✓	38.9
Waste			
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	✓	202.9
CO ₂ Emissions from Waste Incineration	CO ₂	✓	26.9
Subtotal			6,769.2
Total Emissions			6,936.2
Percent of Total			97.6%

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

Table R-2 provides a complete listing of source categories by IPCC sector and with additional comments on the criteria used in identifying key source categories. Specifically, the level assessment was performed for each year that inventory data was available (i.e., 1990 to 2001). As the emissions change over time, categories may fall under or over the threshold for being key. The following points should be noted regarding the key sources identified.

Due to the relative quantity of CO₂ emissions from fossil fuel combustion—particularly from mobile source and stationary combustion of coal, gas, and oil—these sources contributed most to each year’s level assessment. Additionally, the following sources were the largest contributors to the level assessments for each year (listed in descending order):

- N₂O from agricultural soils;
- CH₄ from solid waste disposal sites;
- CO₂ emissions from mobile combustion in the aviation sector;
- Fugitive emissions from natural gas operations;
- CH₄ from enteric fermentation in domestic livestock;
- CO₂ emissions from iron and steel production;
- Indirect N₂O emissions from nitrogen used in agriculture;
- Fugitive emissions from coal mining;
- N₂O emissions from mobile road source emissions; and
- CO₂ emissions from cement production.

The remaining key sources identified under the level assessment varied by year. The following five source categories were determined to be key using the level assessment for only part of the complete times series:

- CO₂ emissions from mobile combustion in the marine sector (1990-1997, 1999-2001);
- HFC and PFC emissions from substitutes for ozone depleting substances (1997 to 2001);
- HFC-23 emissions from HCFC-22 manufacture (1990, 1992, 1996, 1998);
- SF₆ Emissions from electrical equipment (1990-1991, 1993-1995); and
- CH₄ Emissions from manure management (1991-1999).

Although other sources have fluctuated by greater percentages since 1990, by virtue of their size, CO₂ emissions from mobile combustion from road vehicles, and stationary combustion of oil, coal, and gas are the greatest contributors to the overall trend for 2001.

Another large contributor to the overall trend is emissions from substitutes for ozone depleting substances (ODSs), which are growing quickly with the Montreal Protocol phase-out of ODSs.

Fugitive emissions from coal mining and PFC emissions from aluminum manufacturing have decreased by approximately 30 and 77 percent, respectively from 1990 through 2001. Reductions in emissions from coal mining are primarily due to EPA's voluntary coalbed methane capture program and the mining of less gassy coal than in previous years. PFC emissions have decreased primarily as a result of emission reduction activities by the aluminum industry.

Two other source categories were determined to be key using the qualitative criteria. A brief discussion of the reasoning for the qualitative designation is given below:

- International bunker fuels are fuels consumed for aviation or marine international transport activities, and emissions from these fuels are reported separately from totals in accordance with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key source according to the Tier 1 approach. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key.
- Non-energy uses of fossil fuels represent a significant percentage of the total carbon inventory, and the idea that small changes in storage factors for these non-energy uses may result in large changes in storage and emissions qualifies this source category as key.

Following the text of this Annex, Table R-3 through Table R-14 contain each individual year's level assessment and contain further detail on where each source falls within the analysis. Table R-15 details the trend assessment for 1990-2001.

Table R-2: U.S Greenhouse Gas Inventory Source Categories Based on Tier 1 Approach

IPCC Source Categories	Direct GHG	2001 Emissions (Tg CO ₂ Eq.)	Key Source Category Flag?	ID Criteria ¹	Comments
Energy					
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,993.8	✓	L, T	All years
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	671.6	✓	L, T	All years
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	1,168.2	✓	L, T	All years
CO ₂ Emissions from Stationary Combustion - Geothermal	CO ₂	0.4			
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.2			
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	7.4			
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	14.2			
Mobile Combustion: Road & Other	CO ₂	1,538.7	✓	L, T	All years
Mobile Combustion: Road & Other	CH ₄	4.1			
Mobile Combustion: Road & Other	N ₂ O	52.6	✓	L	All years
Mobile Combustion: Aviation	CO ₂	183.9	✓	L, T	All years
Mobile Combustion: Aviation	CH ₄	0.1			
Mobile Combustion: Aviation	N ₂ O	1.8			
Mobile Combustion: Marine	CO ₂	58.3	✓	L	Level in 1990 - 1997, 1999 - 2001
Mobile Combustion: Marine	CH ₄	0.1			
Mobile Combustion: Marine	N ₂ O	0.3			
Fugitive Emissions from Coal Mining & Handling	CH ₄	60.7	✓	L, T	All years
Fugitive Emissions from Natural Gas Operations	CH ₄	117.3	✓	L, T	All years
Fugitive Emissions from Oil Operations	CH ₄	21.2	✓	T	
Industrial Processes					
CO ₂ Emissions from Cement Production	CO ₂	41.4	✓	L, T	All years
CO ₂ Emissions from Iron and Steel Production	CO ₂	59.1	✓	L, T	All years
CO ₂ Emissions from Lime Production	CO ₂	12.9			
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.3			
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	16.6	✓	T	
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.9			
CO ₂ Emissions from Ferrolloys	CO ₂	1.3			
CO ₂ Emissions from CO ₂ Consumption	CO ₂	1.3			

CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.1			
CO ₂ Emissions from Aluminum Production	CO ₂	4.1			
CH ₄ Emissions from Silicon Carbide Production	CH ₄	+			
CH ₄ Emissions from Petrochemical Production	CH ₄	1.5			
N ₂ O Emissions from Adipic Acid Production	N ₂ O	4.9	✓	T	
N ₂ O Emissions from Nitric Acid Production		17.6			
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.8			
PFC Emissions from Aluminum Production	PFCs	4.1	✓	T	
SF ₆ Emissions from Magnesium Production	SF ₆	2.5			
SF ₆ Emissions from Electrical Equipment	SF ₆	15.3	✓	L, T	Level in 1990 - 1991, 1993 - 1995
HFC, PFC, and SF ₆ Emissions from Semiconductor Manufacturing	Several	5.5			
Emissions from Substitutes for Ozone Depleting Substances	Several	63.7	✓	L, T	Level from 1997 - 2001
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	19.8	✓	L, T	Level in 1990, 1992, 1996, 1998
Agriculture					
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	114.8	✓	L, T	All years
CH ₄ Emissions from Manure Management	CH ₄	38.9	✓	L	Level in 1991 - 1999
N ₂ O Emissions from Manure Management	N ₂ O	18.0			
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	216.6	✓	L	All years
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	77.7	✓	L, T	All years
CH ₄ Emissions from Rice Production	CH ₄	7.6			
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.8			
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.5			
Waste					
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	202.9	✓	L, T	All years
CH ₄ Emissions from Wastewater Handling	CH ₄	28.3			
N ₂ O Emissions from Wastewater Handling	N ₂ O	15.3			
CO ₂ Emissions from Waste Incineration	CO ₂	26.9	✓	T	
N ₂ O Emissions from Waste Incineration	N ₂ O	0.2			

¹ Qualitative criteria.

+ Does not exceed 0.05 Tg CO₂ Eq.

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

Tier 1 Approach

The Tier 1 method for identifying key source categories assesses the impacts of all IPCC-defined source categories on the level and trend of the national emission inventory for the 1990 through 2001 time-series, but works independently of any formal uncertainty analysis. However, it is important to mention that although conducting a key source analysis can be very valuable in improving the U.S. inventory, it would be ideal to undertake a full uncertainty analysis in order to be able to take into account the level of uncertainty associated with each estimate.

When using a Tier 1 approach for the *level*, a predetermined cumulative emissions threshold is used to identify key source categories. When source categories are sorted in order of decreasing emissions, those that fall at the top of the list and cumulatively account for 95 percent of emissions are considered key source categories. The 95 percent threshold was established based on an evaluation of several inventories, and was designed to establish a general level where the key source category analysis covers 90 percent of inventory uncertainty. The Tier 1 approach for the *trend* uses a 95 percent contribution threshold of the cumulative contribution to the trend assessment metric, which was also designed to establish a general level where the key source category analysis covers 90 percent of inventory uncertainty. The Tier 1 method is completed using a simple spreadsheet analysis based on equations for both level and trend assessments that are described in detail below. It is the current approach that the United States is taking to identify key source categories of greenhouse gas emissions until a rigorous uncertainty analysis is completed.

Tier 2 Approach

IPCC recommends that inventory agencies use the Tier 2 method for identifying key source categories if nationally derived source-level uncertainties are measured. The Tier 2 approach is a more detailed analysis that

builds on the Tier 1 approach by multiplying the results of the Tier 1 analysis by the relative uncertainty of each source category. This method is likely to reduce the number of key source categories under consideration. Using the Tier 2 approach, key source categories represent 90 percent of the quantified uncertainty contribution, as opposed to those that sum to the pre-determined cumulative emissions or trend threshold. A simple spreadsheet version accounts for the uncertainty contribution by applying the source category percentage uncertainty estimates to the Tier 1 level and trend assessments.

The U.S. EPA is in the process of developing a robust plan to support data gathering for both a Tier 1 and a Monte Carlo level analysis. In the Monte Carlo approach to uncertainty analysis, uncertainty estimates for each source category are developed based on (a) source category-specific input variables, such as activity data and emission factors, (b) the statistical properties underlying the input variables (i.e., the characteristics of the probability distributions of the input variables, such as mean and standard deviation in the case of a normal distribution), and (c) mathematical relationship between the input variables used to estimate the emissions for each source category (e.g., emissions = activity data * emission factor). Initial work on select sources has provided some insight into the data requirements and resources necessary to conduct a Monte Carlo Analysis. Over time, the United States seeks to conduct a Monte Carlo analysis on key sources.

Qualitative Approach

In addition to conducting a quantitative assessment like the ones described above, a variety of qualitative criteria could be applied to identify additional key source categories. The following qualitative criteria for identifying key source categories have been outlined in the *Good Practice Guidance* (IPCC 2000). A source category should be identified as a key source if:

- Mitigation techniques and technologies are being implemented to reduce emissions from the source category that are expected to be reflected in the inventory estimates;
- Significant changes in emissions (i.e., growth or decline) from the source category is expected in the future;
- High uncertainty is evident for the source category;
- Unexpectedly low or high emissions, or other order of magnitude discrepancies, are apparent for the source category; and
- Major changes in estimation methodology or data have occurred.

In many cases, the results of this qualitative approach to identifying key source categories will overlap with source categories already defined as key source categories through the quantitative analysis. However, the qualitative method may illuminate a few additional key source categories, which should then be included in the final list of key source categories. However, the application of such qualitative criteria are primarily intended to identify any additional source categories that were “just under” the threshold criteria for the level assessment and not for extremely minor source categories. Among those that are considered key from a qualitative standpoint are emissions from international bunker fuels and non-fuel use of fossil fuels. International bunker fuel emissions are not included in national totals, and are not considered in the level or trend analyses mentioned above, but are considered key from a qualitative standpoint due to their unique position within the emissions accounting framework. Additionally, non-fuel use of fossil fuels is also not included in the level or trend analyses. However, due to the significant quantity of fossil fuels consumed in the United States that are not used to produce energy (generically referred to as feedstocks), it is imperative to understand their fate and to determine how much of the consumption results in emissions, versus in stored carbon.

Level and Trend Assessments of Key Source Categories

Level Assessment

A level assessment was performed for years 1990 to 2001. Key sources were identified as any source category which, when summed in descending order of magnitude for a given year, cumulatively add up to 95 percent of the total level assessment for that year. Level estimates are based upon the following equation:

$$\text{Source Category Level Assessment} = \text{Source Category} / \text{Total Estimate}$$

$$L_{x,t} = E_{x,t} / E_t$$

Where:

$L_{x,t}$ = level assessment for source x in year t

$E_{x,t}$ = emissions estimate for source x in year t

E_t = total emissions estimate for year t

Trend Assessment

A trend assessment was then conducted to evaluate how significantly the difference between the source category's trend and the overall inventory trend affect the overall trend. This assessment was done by multiplying the difference between the source category trend and the total inventory trend by the source category level assessment. Trend assessments were based upon the following equation:

$$\text{Source Category Trend Assessment} = (\text{Source Category Level Assessment}) \times \left| \frac{(\text{Source Category Trend} - \text{Total Trend})}{\text{Trend}} \right|$$

$$T_{x,t} = L_{x,t} \times \left| \left[\frac{(E_{x,t} - E_{x,0})}{E_{x,t}} - \frac{(E_t - E_0)}{E_t} \right] \right|$$

Where:

$T_{x,t}$ = trend assessment for source x in year t

$L_{x,t}$ = level assessment for source x in year t

$E_{x,t}$ and $E_{x,0}$ = emissions estimates for source x in year t and year 0, respectively

E_t and E_0 = total emissions estimate for year t and year 0, respectively

0 = base year (e.g., 1990)

The following section of this annex evaluates these key source category analyses. The remainder of the annex summarizes the key source categories identified by these analyses, and quantifies their contribution to total level and trend assessments.

Evaluation of Key Source Identification Methodologies

Level Assessment

The Tier 1 approach for level assessment defines the source category contribution as the percentage of total inventory emissions from that source category. Only emission source categories are considered.² To determine key source categories, the level assessments are sorted in decreasing order, so that the source categories with the highest level assessments appear first. The level assessments are summed until the threshold of 95 percent is reached; all source categories that fall within that cumulative 95 percent are considered key source categories.

Since the Tier 1 approach does not explicitly incorporate uncertainties, the level assessment key source categories will be the largest contributors to total emissions but will not necessarily have large contributions to the total uncertainty. Focusing resources on improving the methodologies for estimating emissions from the source categories with the largest emissions is undesirable if those emissions are estimated relatively precisely using the current methodologies. Nevertheless, the analysis (reported in IPCC 2000) of several inventories that have source category uncertainties showed that about 90 percent of the total uncertainty could be covered by the source categories in the top 95 percent of emissions.

It is important to note that this key source category analysis can be very sensitive to the definitions of the source categories. If a large source category is split into many subcategories, then the subcategories may have contributions to the total inventory that are too small for those source categories to be considered key. Similarly, a collection of small, non-key source categories adding up to less than 5 percent of total emissions could become key source categories if those source categories were aggregated into a single source category. A consistent approach to addressing this issue is available in the *Good Practice Guidance*. Table 7.1 in IPCC (2000) provides guidance and a

² The level assessment is intended to be applied to sources and to exclude sinks. Although the assessment would still be valid if sinks were included (as unsigned values), the 95 percent threshold by which sources are deemed "key" would lose significance because it is based on an analysis (Flusgrud et al. 1999) of selected inventories where sinks were excluded.

suggested list of source categories for analysis, although countries are given some discretion based upon their national circumstances.

Some important components of other source categories were not included in the list of IPCC source categories in the key source category chapter of IPCC's *Good Practice Guidance* (IPCC 2000). These source categories include fossil fuel feedstocks, international bunkers, and emissions from U.S. territories. They are potentially large source categories that often are derived from unique data sources, have a significant impact on the uncertainty of the estimates.

Trend Assessment

The Tier 1 approach for trend assessment is defined as the product of the source category level assessment (i.e., source category emissions as a fraction, or percentage, of total emissions) and the absolute difference between the source category trend and the total trend. In turn, the source category trend is defined as the change in source category emissions from the base year to the current year, as a percentage of current year emissions from that source category. The total trend is the percentage change in total inventory emissions from the base year to the current year. Thus, the *source category trend assessment* will be large if the source category represents a large percentage of emissions and/or has a trend that is quite different from the overall inventory trend. Only emissions source categories are considered.³ To determine key source categories, the trend assessments are sorted in decreasing order, so that the source categories with the highest trend assessments appear first. The trend assessments are summed until the threshold of 95 percent is reached; all source categories that fall within that cumulative 95 percent are considered key source categories.

It is important to note that the trend assessment calculation assumes that the base and current year source category emission uncertainties are the same. Therefore, the trend assessment is a useful measure in cases where the percentage uncertainties of the base and current year source category emission levels are thought to be the same. However, its usefulness diminishes when individual source category uncertainties are different between the base year and the current year. Such time series inconsistencies could result from changes in data quality or availability over time. As more rigorous methods to determine uncertainties in emission estimates are applied, it may be necessary to revisit the results of the trend assessments.

Another important caveat to the identification of key source categories through the trend assessment is that, while each individual source category's trend assessment provides a measure of how sensitive the overall trend in the inventory is to the trend of a particular source category, the sum of a number of trend assessments does not yield the total sensitivity of the overall trend to changes in all of those source categories. In other words, the cumulative percentages should not be considered a measure of the percentage contributions to the trend from those source categories.

The trend assessment key source categories are also sensitive to the level of aggregation of the source categories; and the IPCC list of source categories may exclude some important, potentially key source category components.

³ The trend assessment is intended to be applied to sources and to exclude sinks. Although the assessment would still be valid if sinks were included (as unsigned values), the 95 percent threshold by which sources are deemed "key" would lose significance because it is based on an analysis (Flusgrud et al. 1999) of selected inventories where sinks were excluded.

Table R-3: 1990 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,697.29	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,244.98	0.20	0.48
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	976.63	0.16	0.64
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	669.99	0.11	0.75
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	212.07	0.03	0.78
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	193.71	0.03	0.81
Mobile Combustion: Aviation	CO ₂	176.88	176.88	0.03	0.84
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	122.01	0.02	0.86
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	117.85	0.02	0.88
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	87.12	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	85.41	0.01	0.91
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	73.83	0.01	0.92
Mobile Combustion: Marine	CO ₂	48.60	48.60	0.01	0.93
Mobile Combustion: Road & Other	N ₂ O	48.56	48.56	0.01	0.94
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	34.98	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	33.28	0.01	0.95
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	32.10	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	31.28	0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	27.49	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	24.08	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	19.31	<0.01	0.97
PFC Emissions from Aluminum Production	PFCs	18.11	18.11	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	17.85	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.18	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	15.20	<0.01	0.98
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	14.07	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	12.71	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	12.52	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	11.24	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.14	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.12	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	6.31	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.51	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	5.47	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.37	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.73	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.30	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.14	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	2.86	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.98	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.71	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.31	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.17	<0.01	1.00
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	0.94	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	0.90	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.68	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.40	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.37	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.36	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.29	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.16	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.07	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.03	<0.01	1.00
TOTAL		6,139.64	6,139.64	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-4: 1991 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,697.20	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,221.80	0.20	0.48
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,002.27	0.16	0.64
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	649.46	0.11	0.75
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	211.78	0.03	0.78
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	195.54	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	169.34	0.03	0.84
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	123.80	0.02	0.86
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	117.10	0.02	0.88
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	83.93	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	76.24	0.01	0.91
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	75.01	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	50.94	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	45.91	0.01	0.94
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	33.36	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	33.20	0.01	0.95
CO ₂ Emissions from Cement Production	CO ₂	33.28	32.54	0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	30.77	0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	27.72	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	24.42	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	19.17	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	17.83	<0.01	0.97
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.69	<0.01	0.98
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	15.73	<0.01	0.98
PFC Emissions from Aluminum Production	PFCs	18.11	15.68	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	14.84	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	13.05	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	12.30	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	11.01	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.25	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.00	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	6.43	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.59	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.11	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	4.79	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.69	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.18	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.04	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	2.86	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.98	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.64	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.33	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.19	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	0.93	<0.01	1.00
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	0.84	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.64	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.41	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.38	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.36	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.24	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.07	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,101.77	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-5: 1992 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,714.88	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,248.66	0.20	0.48
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,039.63	0.17	0.64
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	655.50	0.11	0.75
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	214.71	0.03	0.78
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	202.57	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	167.01	0.03	0.84
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	123.98	0.02	0.86
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	119.39	0.02	0.88
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	81.81	0.01	0.90
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	75.73	0.01	0.91
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	75.01	0.01	0.92
Mobile Combustion: Marine	CO ₂	48.60	56.18	0.01	0.93
Mobile Combustion: Road & Other	N ₂ O	48.56	54.19	0.01	0.94
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	34.87	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	32.79	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	32.14	0.01	0.95
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	31.14	0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	26.60	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	25.04	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	19.99	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	18.30	<0.01	0.97
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.46	<0.01	0.98
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	16.25	<0.01	0.98
PFC Emissions from Aluminum Production	PFCs	18.11	14.55	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	13.31	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	13.05	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	12.69	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	11.39	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.66	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.87	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	6.31	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.40	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.06	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	4.79	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.73	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.07	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	3.94	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	2.86	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.98	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.62	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.52	<0.01	1.00
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	1.52	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.26	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	0.94	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.75	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.43	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.43	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.41	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.27	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.08	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,212.93	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-6: 1993 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,777.91	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,284.81	0.20	0.48
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,065.16	0.17	0.65
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	655.08	0.10	0.76
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	216.78	0.03	0.79
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	195.84	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	168.04	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	127.36	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	118.82	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	77.78	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	69.86	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	69.68	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	56.59	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	48.51	0.01	0.94
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	35.14	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	34.62	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	32.93	0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	31.82	0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	25.45	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	25.34	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	20.41	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	18.57	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	17.10	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.89	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	13.98	<0.01	0.98
PFC Emissions from Aluminum Production	PFCs	18.11	13.86	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	13.52	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	12.93	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	11.64	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.14	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.02	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	6.55	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.76	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.51	<0.01	0.99
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	5.24	<0.01	1.00
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	4.89	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.72	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.48	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.02	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	3.58	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.98	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.63	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.55	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.38	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	0.99	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.60	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.43	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.40	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.34	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.26	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.14	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.08	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,326.15	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-7: 1994 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,787.57	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,325.10	0.21	0.48
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,084.55	0.17	0.65
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	663.32	0.10	0.75
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	216.99	0.03	0.79
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	215.47	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	175.85	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	128.07	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	120.40	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	80.26	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	73.61	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	70.32	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	58.27	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	48.89	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	36.09	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	35.46	0.01	0.95
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	32.43	0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	31.59	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	26.00	<0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	24.61	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	21.10	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	19.60	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	17.77	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.90	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	15.03	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	14.02	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.10	<0.01	0.98
PFC Emissions from Aluminum Production	PFCs	18.11	12.17	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	12.05	<0.01	0.99
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	8.38	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	8.21	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.12	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	6.62	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	5.56	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.38	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.15	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.70	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.48	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.02	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	3.93	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.85	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.71	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.67	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.48	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.04	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.81	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.45	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.41	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.34	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.27	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.08	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,451.41	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-8: 1995 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,805.85	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,354.70	0.21	0.49
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,134.43	0.17	0.66
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	623.10	0.10	0.75
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	216.09	0.03	0.79
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	205.09	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	171.45	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	127.24	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	122.96	0.02	0.88
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	78.97	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	74.36	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	73.54	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	58.80	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	51.66	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	36.85	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	36.19	0.01	0.95
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	27.48	<0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	27.03	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	26.60	<0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	24.21	<0.01	0.96
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	21.69	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	20.45	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	19.89	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	18.47	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	17.21	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.55	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	13.94	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.22	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	12.80	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	11.81	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	8.73	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.53	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.62	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	7.04	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	5.90	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.57	<0.01	1.00
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.27	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.64	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.48	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.30	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.87	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.67	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.67	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.51	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.09	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.66	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.46	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.38	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.37	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.28	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.09	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,514.90	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-9: 1996 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,893.35	0.28	0.28
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,389.11	0.21	0.49
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,155.05	0.17	0.66
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	659.64	0.10	0.76
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	212.59	0.03	0.79
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	212.09	0.03	0.82
Mobile Combustion: Aviation	CO ₂	176.88	180.16	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	127.45	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	120.47	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	80.60	0.01	0.90
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	68.36	0.01	0.91
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	68.32	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	58.53	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	48.11	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	37.08	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	34.89	0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	31.12	<0.01	0.95
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	30.42	<0.01	0.96
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	27.68	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	26.84	<0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	23.90	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	20.71	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	20.28	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	19.42	<0.01	0.98
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	17.04	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	16.97	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	14.13	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.80	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	13.49	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	12.47	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	8.72	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	8.23	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	7.61	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	6.97	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	6.53	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.58	<0.01	1.00
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	5.44	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.54	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.48	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.24	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.95	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.76	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.66	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.58	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.14	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.75	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.42	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.42	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.38	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.28	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.08	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,706.99	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-10: 1997 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,939.12	0.29	0.29
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,414.34	0.21	0.49
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,159.13	0.17	0.67
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	674.46	0.10	0.76
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	217.83	0.03	0.80
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	207.49	0.03	0.83
Mobile Combustion: Aviation	CO ₂	176.88	178.96	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	126.02	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	118.33	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	80.33	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	71.86	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	68.13	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	58.28	0.01	0.93
CO ₂ Emissions from Cement Production	CO ₂	33.28	38.32	0.01	0.94
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	37.72	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	36.56	0.01	0.95
Mobile Combustion: Marine	CO ₂	48.60	33.64	<0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	29.99	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	27.33	<0.01	0.96
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	25.24	<0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	23.58	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	21.22	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	21.17	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	20.65	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	17.28	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	14.40	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.71	<0.01	0.98
CO ₂ Emissions from Lime Production	CO ₂	11.24	13.69	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	10.99	<0.01	0.99
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	10.31	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	7.57	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.52	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.48	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	7.05	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	6.55	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	6.34	<0.01	1.00
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.62	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.47	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.35	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	2.04	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.84	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.74	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.61	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.16	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.76	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.45	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.38	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.30	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.26	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.06	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,782.59	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-11: 1998 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,957.32	0.29	0.29
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,443.49	0.21	0.50
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,142.14	0.17	0.67
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	666.77	0.10	0.77
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	218.97	0.03	0.80
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	202.42	0.03	0.83
Mobile Combustion: Aviation	CO ₂	176.88	183.02	0.03	0.85
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	123.97	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	116.70	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	80.18	0.01	0.90
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	67.94	0.01	0.91
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	67.43	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	57.61	0.01	0.93
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	44.53	0.01	0.94
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	40.15	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	39.22	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	39.02	0.01	0.95
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	27.67	<0.01	0.96
Mobile Combustion: Marine	CO ₂	48.60	27.40	<0.01	0.96
Fugitive Emissions from Oil Operations	CH ₄	27.49	22.90	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	22.45	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	21.93	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	20.89	<0.01	0.98
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	20.86	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	17.33	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	14.63	<0.01	0.98
CO ₂ Emissions from Lime Production	CO ₂	11.24	13.91	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.69	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	9.04	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.90	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	7.33	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	7.26	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.17	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	6.25	<0.01	0.99
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	5.99	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.79	<0.01	1.00
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	5.79	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.36	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.32	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	2.03	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.82	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.78	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.64	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.19	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.78	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.45	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.38	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.26	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.24	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.05	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,801.35	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-12: 1999 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,961.09	0.29	0.29
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,487.68	0.22	0.50
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,148.19	0.17	0.67
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	666.10	0.10	0.77
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	216.84	0.03	0.80
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	203.73	0.03	0.83
Mobile Combustion: Aviation	CO ₂	176.88	186.77	0.03	0.86
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	120.28	0.02	0.87
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	116.58	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	80.16	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	64.38	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	63.69	0.01	0.92
Mobile Combustion: Road & Other	N ₂ O	48.56	56.50	0.01	0.93
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	50.86	0.01	0.94
CO ₂ Emissions from Cement Production	CO ₂	33.28	39.99	0.01	0.94
CH ₄ Emissions from Manure Management	CH ₄	31.28	38.89	0.01	0.95
Mobile Combustion: Marine	CO ₂	48.60	38.58	0.01	0.95
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	30.41	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	28.16	<0.01	0.96
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	23.90	<0.01	0.97
Fugitive Emissions from Oil Operations	CH ₄	27.49	21.60	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	20.61	<0.01	0.97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	20.12	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	17.35	<0.01	0.98
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	16.40	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	15.11	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	13.72	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	13.47	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	8.94	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	8.29	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	7.73	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	7.67	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.38	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	6.68	<0.01	0.99
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	6.01	<0.01	0.99
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.90	<0.01	1.00
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	5.48	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.26	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.22	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	2.00	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.85	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.82	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.67	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.21	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.76	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.44	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.44	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.38	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.23	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.08	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.02	<0.01	1.00
TOTAL		6,139.64	6,849.54	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-13: 2000 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	2,051.53	0.29	0.29
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,507.74	0.21	0.51
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,204.81	0.17	0.68
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	672.73	0.10	0.77
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	215.85	0.03	0.80
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	205.76	0.03	0.83
Mobile Combustion: Aviation	CO ₂	176.88	195.32	0.03	0.86
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	121.20	0.02	0.88
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	115.68	0.02	0.89
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	78.72	0.01	0.90
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	65.76	0.01	0.91
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	60.95	0.01	0.92
Mobile Combustion: Marine	CO ₂	48.60	59.67	0.01	0.93
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	57.29	0.01	0.94
Mobile Combustion: Road & Other	N ₂ O	48.56	55.04	0.01	0.95
CO ₂ Emissions from Cement Production	CO ₂	33.28	41.19	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	38.22	0.01	0.96
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	29.79	<0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	28.31	<0.01	0.97
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	25.35	<0.01	0.97
Fugitive Emissions from Oil Operations	CH ₄	27.49	21.21	<0.01	0.97
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	19.59	<0.01	0.98
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	19.08	<0.01	0.98
N ₂ O Emissions from Manure Management	N ₂ O	16.18	17.90	<0.01	0.98
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	15.42	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	15.14	<0.01	0.98
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	14.25	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	13.31	<0.01	0.99
PFC Emissions from Aluminum Production	PFCs	18.11	7.92	<0.01	0.99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.63	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.49	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	7.37	<0.01	0.99
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	6.04	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	5.76	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.53	<0.01	1.00
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	5.41	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.18	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.17	<0.01	1.00
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	3.17	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.92	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.90	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.72	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.67	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.23	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.78	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.52	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.46	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.36	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.24	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.16	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.10	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.01	<0.01	1.00
TOTAL		6,139.64	7,047.36	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-14: 2001 Key Source Tier 1 Analysis - Level Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Level Assessment	Cumulative Total
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,993.78	0.29	0.29
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,538.66	0.22	0.51
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,168.23	0.17	0.68
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	671.62	0.10	0.77
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	216.59	0.03	0.81
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	202.93	0.03	0.84
Mobile Combustion: Aviation	CO ₂	176.88	183.93	0.03	0.86
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	117.35	0.02	0.88
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	114.82	0.02	0.90
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	77.73	0.01	0.91
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	63.65	0.01	0.92
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	60.75	0.01	0.92
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	59.07	0.01	0.93
Mobile Combustion: Marine	CO ₂	48.60	58.28	0.01	0.94
Mobile Combustion: Road & Other	N ₂ O	48.56	52.65	0.01	0.95
CO ₂ Emissions from Cement Production	CO ₂	33.28	41.36	0.01	0.95
CH ₄ Emissions from Manure Management	CH ₄	31.28	38.85	0.01	0.96
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	28.35	<0.01	0.96
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	26.91	<0.01	0.97
Fugitive Emissions from Oil Operations	CH ₄	27.49	21.23	<0.01	0.97
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	19.82	<0.01	0.97
N ₂ O Emissions from Manure Management	N ₂ O	16.18	18.00	<0.01	0.98
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	17.60	<0.01	0.98
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	16.59	<0.01	0.98
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	15.32	<0.01	0.98
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	15.30	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	14.18	<0.01	0.99
CO ₂ Emissions from Lime Production	CO ₂	11.24	12.86	<0.01	0.99
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.64	<0.01	0.99
Non- CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.41	<0.01	0.99
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	5.51	<0.01	0.99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	5.28	<0.01	0.99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.18	<0.01	0.99
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	4.92	<0.01	1.00
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	1.00
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.15	<0.01	1.00
PFC Emissions from Aluminum Production	PFCs	18.11	4.13	<0.01	1.00
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	4.11	<0.01	1.00
Mobile Combustion: Road & Other	CH ₄	4.73	4.08	<0.01	1.00
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	2.53	<0.01	1.00
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.86	<0.01	1.00
Mobile Combustion: Aviation	N ₂ O	1.71	1.79	<0.01	1.00
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.49	<0.01	1.00
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.33	<0.01	1.00
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.26	<0.01	1.00
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.76	<0.01	1.00
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.46	<0.01	1.00
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.35	<0.01	1.00
Mobile Combustion: Marine	N ₂ O	0.36	0.31	<0.01	1.00
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.24	<0.01	1.00
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	1.00
Mobile Combustion: Marine	CH ₄	0.07	0.06	<0.01	1.00
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.01	<0.01	1.00
TOTAL		6,139.64	6,936.21	1.00	

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

Table R-15: 1990-2001 Key Source Tier 1 Analysis - Trend Assessment

IPCC Source Categories	Direct Greenhouse Gas	Base Year Estimate (Tg CO ₂ Eq.)	Current Year Estimate (Tg CO ₂ Eq.)	Trend Assessment	Percent Contribution to Trend	Cumulative Total
Mobile Combustion: Road & Other	CO ₂	1,244.98	1,538.66	0.02	18	18
CO ₂ Emissions from Stationary Combustion - Oil	CO ₂	669.99	671.62	0.01	12	30
CO ₂ Emissions from Stationary Combustion - Coal	CO ₂	1,697.29	1,993.78	0.01	11	40
CO ₂ Emissions from Stationary Combustion - Gas	CO ₂	976.63	1,168.23	0.01	9	49
Emissions from Substitutes for Ozone Depleting Substances	Several	0.94	63.65	0.01	9	58
Fugitive Emissions from Coal Mining and Handling	CH ₄	87.12	60.75	<0.01	5	63
CO ₂ Emissions from Iron and Steel Production	CO ₂	85.41	59.07	<0.01	5	68
CH ₄ Emissions from Solid Waste Disposal Sites	CH ₄	212.07	202.93	<0.01	5	73
SF ₆ Emissions from Electrical Equipment	SF ₆	32.10	15.32	<0.01	3	76
Fugitive Emissions from Natural Gas Operations	CH ₄	122.01	117.35	<0.01	3	79
HFC-23 Emissions from HCFC-22 Manufacture	HFCs	34.98	19.82	<0.01	3	82
CH ₄ Emissions from Enteric Fermentation in Domestic Livestock	CH ₄	117.85	114.82	<0.01	3	84
PFC Emissions from Aluminum Production	PFCs	18.11	4.13	<0.01	2	87
Mobile Combustion: Aviation	CO ₂	176.88	183.93	<0.01	2	89
N ₂ O Emissions from Adipic Acid Production	N ₂ O	15.20	4.92	<0.01	2	90
CO ₂ Emissions from Waste Incineration	CO ₂	14.07	26.91	<0.01	2	92
Fugitive Emissions from Oil Operations	CH ₄	27.49	21.23	<0.01	1	93
Indirect N ₂ O Emissions from Nitrogen Used in Agriculture	N ₂ O	73.83	77.73	<0.01	1	94
CO ₂ Emissions from Ammonia Production and Urea Application	CO ₂	19.31	16.59	<0.01	1	95
CO ₂ Emissions from Cement Production	CO ₂	33.28	41.36	<0.01	1	95
SF ₆ Emissions from Magnesium Production	SF ₆	5.37	2.53	<0.01	0	96
CH ₄ Emissions from Manure Management	CH ₄	31.28	38.85	<0.01	0	96
Mobile Combustion: Marine	CO ₂	48.60	58.28	<0.01	0	97
CO ₂ Emissions from Aluminum Production	CO ₂	6.31	4.11	<0.01	0	97
N ₂ O Emissions from Nitric Acid Production	N ₂ O	17.85	17.60	<0.01	0	98
PFC, HFC, and SF ₆ Emissions from Semiconductor Manufacture	SF ₆	2.86	5.51	<0.01	0	98
Direct N ₂ O Emissions from Agricultural Soils	N ₂ O	193.71	216.59	<0.01	0	98
Mobile Combustion: Road & Other	N ₂ O	48.56	52.65	<0.01	0	99
Non-CO ₂ Emissions from Stationary Combustion	CH ₄	8.14	7.41	<0.01	0	99
Mobile Combustion: Road & Other	CH ₄	4.73	4.08	<0.01	0	99
CH ₄ Emissions from Wastewater Handling	CH ₄	24.08	28.35	<0.01	0	99
CO ₂ Emissions from Natural Gas Flaring	CO ₂	5.51	5.18	<0.01	0	99
N ₂ O Emissions from Wastewater Handling	N ₂ O	12.71	15.30	<0.01	0	99
CO ₂ Emissions from Ferroalloys	CO ₂	1.98	1.33	<0.01	0	99
CO ₂ Emissions from Limestone and Dolomite Use	CO ₂	5.47	5.28	<0.01	0	100
CO ₂ Emissions from Soda Ash Manufacture and Consumption	CO ₂	4.14	4.15	<0.01	0	100
CH ₄ Emissions from Rice Production	CH ₄	7.12	7.64	<0.01	0	100
CO ₂ Emissions from Titanium Dioxide Production	CO ₂	1.31	1.86	<0.01	0	100
N ₂ O Emissions from Manure Management	N ₂ O	16.18	18.00	<0.01	0	100
CO ₂ Emissions from CO ₂ Consumption	CO ₂	0.90	1.26	<0.01	0	100
CH ₄ Emissions from Petrochemical Production	CH ₄	1.17	1.49	<0.01	0	100
CO ₂ Emissions from Lime Production	CO ₂	11.24	12.86	<0.01	0	100
Mobile Combustion: Aviation	N ₂ O	1.71	1.79	<0.01	0	100
CO ₂ Emissions from Stationary Combustion - Geothermal Energy	CO ₂	0.40	0.35	<0.01	0	100
Mobile Combustion: Marine	N ₂ O	0.36	0.31	<0.01	0	100
N ₂ O Emissions from Waste Incineration	N ₂ O	0.29	0.24	<0.01	0	100
N ₂ O Emissions from N ₂ O Product Usage	N ₂ O	4.30	4.79	<0.01	0	100
N ₂ O Emissions from Agricultural Residue Burning	N ₂ O	0.37	0.46	<0.01	0	100
Non-CO ₂ Emissions from Stationary Combustion	N ₂ O	12.52	14.18	<0.01	0	100
Mobile Combustion: Aviation	CH ₄	0.16	0.15	<0.01	0	100
CH ₄ Emissions from Silicon Carbide Production	CH ₄	0.03	0.01	<0.01	0	100
Mobile Combustion: Marine	CH ₄	0.07	0.06	<0.01	0	100
CH ₄ Emissions from Agricultural Residue Burning	CH ₄	0.68	0.76	<0.01	0	100

TOTAL	6,139.64	6,936.21	0.09	100.00
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Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

References

Flugsrud, K., W. Irving, and K. Rypdal (1999) *Methodological Choice in Inventory Preparation. Suggestions for Good Practice Guidance*. Statistics Norway Department of Economic Statistics. 1999/19.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

ANNEX S

Global Warming Potential Values

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide (CO₂) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The relationship between gigagrams (Gg) of a gas and Tg CO₂ Eq. can be expressed as follows:

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

Where:

Tg CO₂ Eq. = Teragrams of Carbon Dioxide Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ± 35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table S-1).

In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.¹

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO₂ products and black carbon), however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table S-1: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) of Gases Used in this Report

Gas	Atmospheric Lifetime	100-year GWP ^a	20-year GWP	500-year GWP
Carbon dioxide (CO ₂)	50-200	1	1	1
Methane (CH ₄) ^b	12 \pm 3	21	56	6.5
Nitrous oxide (N ₂ O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800

¹ Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18. FCCC (1996)

HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF ₄	50,000	6,500	4,400	10,000
C ₂ F ₆	10,000	9,200	6,200	14,000
C ₄ F ₁₀	2,600	7,000	4,800	10,100
C ₆ F ₁₄	3,200	7,400	5,000	10,700
SF ₆	3,200	23,900	16,300	34,900

Source: IPCC (1996)

^a GWPs used in this report are calculated over 100 year time horizon

^b The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO₂ is not included.

Table S-2 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

Table S-2: Net 100-year Global Warming Potentials for Select Ozone Depleting Substances*

Gas	Direct	Net _{min}	Net _{max}
CFC-11	4,600	(600)	3,600
CFC-12	10,600	7,300	9,900
CFC-113	6,000	2,200	5,200
HCFC-22	1,700	1,400	1,700
HCFC-123	120	20	100
HCFC-124	620	480	590
HCFC-141b	700	(5)	570
HCFC-142b	2,400	1,900	2,300
CHCl ₃	140	(560)	0
CCl ₄	1,800	(3,900)	660
CH ₃ Br	5	(2,600)	(500)
Halon-1211	1,300	(24,000)	(3,600)
Halon-1301	6,900	(76,000)	(9,300)

Source: IPCC (2001)

* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The effects of these compounds on radiative forcing are not addressed in this report.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within this report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO₂ radiative forcing and an improved CO₂ response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO₂ is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO₂ tend to be larger, taking into account revisions in lifetimes. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated

for a variety of halocarbons, which were not presented in the SAR. The changes are described in the TAR as follows:

New categories of gases include fluorinated organic molecules, many of which are ethers that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to CO₂ using an improved calculation of the CO₂ radiative forcing, the SAR response function for a CO₂ pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.

Table S-3 compares the lifetimes and GWPs for the SAR and TAR. As can be seen in Table S-3, GWPs changed anywhere from a decrease of 35 percent to an increase of 49 percent.

Table S-3: Comparison of GWPs and lifetimes used in the SAR and the TAR

Gas	Lifetime (years)		GWP (100 year)			
	SAR	TAR	SAR	TAR	Difference	
Carbon dioxide (CO₂)	50-200	5-200 ^a	1	1	NC	NC
Methane (CH₄)^b	12±3	8.4/12 ^c	21	23	2	10%
Nitrous oxide (N₂O)	120	120/114 ^c	310	296	(14)	-5%
Hydrofluorocarbons						
HFC-23	264	260	11,700	12,000	300	3%
HFC-32	5.6	5.0	650	550	(100)	-15%
HFC-41	3.7	2.6	150	97	(53)	-35%
HFC-125	32.6	29	2,800	3,400	600	21%
HFC-134	10.6	9.6	1,000	1,100	100	10%
HFC-134a	14.6	13.8	1,300	1,300	NC	NC
HFC-143	3.8	3.4	300	330	30	10%
HFC-143a	48.3	52	3,800	4,300	500	13%
HFC-152	NA	0.5	NA	43	NA	NA
HFC-152a	1.5	1.4	140	120	(20)	-14%
HFC-161	NA	0.3	NA	12	NA	NA
HFC-227ea	36.5	33.0	2,900	3,500	600	21%
HFC-236cb	NA	13.2	NA	1,300	NA	NA
HFC-236ea	NA	10	NA	1,200	NA	NA
HFC-236fa	209	220	6,300	9,400	3,100	49%
HFC-245ca	6.6	5.9	560	640	80	14%
HFC-245fa	NA	7.2	NA	950	NA	NA
HFC-365mfc	NA	9.9	NA	890	NA	NA
HFC-4310mee	17.1	15	1,300	1,500	200	15%
Iodocarbons						
FIC-1311	<0.005	0.005	<1	1	NC	NC
Fully Fluorinated Species						
SF ₆	3,200	3,200	23,900	22,200	(1,900)	-7%
CF ₄	50,000	50,000	6,500	5,700	(800)	-12%
C ₂ F ₆	10,000	10,000	9,200	11,900	2,700	29%
C ₃ F ₈	2,600	2,600	7,000	8,600	1,600	23%
C ₄ F ₁₀	2,600	2,600	7,000	8,600	1,600	23%
c-C ₄ F ₈	3,200	3,200	8,700	10,000	1,300	15%
C ₅ F ₁₂	4,100	4,100	7,500	8,900	1,400	19%
C ₆ F ₁₄	3,200	3,200	7,400	9,000	1,600	22%
Ethers and Halogenated Ethers						
CH ₃ OCH ₃	NA	0.015	NA	1	NA	NA
(CF ₃) ₂ CFOCH ₃	NA	3.4	NA	330	NA	NA
(CF ₃)CH ₂ OH	NA	0.5	NA	57	NA	NA
CF ₃ CF ₂ CH ₂ OH	NA	0.4	NA	40	NA	NA
(CF ₃) ₂ CHOH	NA	1.8	NA	190	NA	NA
HFE-125	NA	150	NA	14,900	NA	NA
HFE-134	NA	26.2	NA	6,100	NA	NA
HFE-143a	NA	4.4	NA	750	NA	NA
HCFE-235da2	NA	2.6	NA	340	NA	NA
HFE-245cb2	NA	4.3	NA	580	NA	NA

HFE-245fa2	NA	4.4	NA	570	NA	NA
HFE-254cb2	NA	0.22	NA	30	NA	NA
HFE-347mcc3	NA	4.5	NA	480	NA	NA
HFE-356pcf3	NA	3.2	NA	430	NA	NA
HFE-374pcf2	NA	5.0	NA	540	NA	NA
HFE-7100	NA	5.0	NA	390	NA	NA
HFE-7200	NA	0.77	NA	55	NA	NA
H-Galden 1040x	NA	6.3	NA	1,800	NA	NA
HG-10	NA	12.1	NA	2,700	NA	NA
HG-01	NA	6.2	NA	1,500	NA	NA
Others^d						
NF ₃	NA	740	NA	10,800	NA	NA
SF ₆ CF ₃	NA	>1,000	NA	>17,500	NA	NA
c-C ₃ F ₆	NA	>1,000	NA	>16,800	NA	NA
HFE-227ea	NA	11	NA	1,500	NA	NA
HFE-236ea2	NA	5.8	NA	960	NA	NA
HFE-236fa	NA	3.7	NA	470	NA	NA
HFE-245fa1	NA	2.2	NA	280	NA	NA
HFE-263fb2	NA	0.1	NA	11	NA	NA
HFE-329mcc2	NA	6.8	NA	890	NA	NA
HFE-338mcf2	NA	4.3	NA	540	NA	NA
HFE-347-mcf2	NA	2.8	NA	360	NA	NA
HFE-356mec3	NA	0.94	NA	98	NA	NA
HFE-356pcc3	NA	0.93	NA	110	NA	NA
HFE-356pcf2	NA	2.0	NA	260	NA	NA
HFE-365mcf3	NA	0.11	NA	11	NA	NA
(CF ₃) ₂ CHOCHF ₂	NA	3.1	NA	370	NA	NA
(CF ₃) ₂ CHOCH ₃	NA	0.25	NA	26	NA	NA
-(CF ₂) ₄ CH(OH)-	NA	0.85	NA	70	NA	NA

^a No single lifetime can be determined for carbon dioxide. (See IPCC 2001)

^b The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO₂ is not included.

^c Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

^d Gases whose lifetime has been determined only via indirect means or for whom there is uncertainty over the loss process.

Source: IPCC (2001)

NC (No Change)

NA (Not Applicable)

When the GWPs from the TAR are applied to the emission estimates presented in this report, total emissions for the year 2001 are 6,965.5 Tg CO₂ Eq., as compared to 6936.2 Tg CO₂ Eq. when the GWPs from the SAR are used (a 0.4 percent difference). Table S-4 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2001, using the GWPs from the TAR. The adjusted greenhouse gas emissions are shown for each gas in units of Tg CO₂ Eq. in Table S-5. The correlating percent change in emissions of each gas is shown in Table S-6. The percent change in emissions is equal to the percent change in the GWP, however, in cases where multiple gases are emitted in varying amounts the percent change is variable over the years, such as with substitutes for ozone depleting substances. Table S-7 summarizes the emissions and resulting change in emissions using GWPs from the SAR or the TAR for 1990 and 2001.

Table S-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the TAR GWPs (Tg CO₂ Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO ₂	5,003.7	5,334.4	5,514.8	5,595.4	5,614.2	5,680.7	5,883.1	5,794.8
Fossil Fuel Combustion	4,814.8	5,141.5	5,325.8	5,400.0	5,420.5	5,488.8	5,692.2	5,614.9
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9
Limestone and Dolomite Use	5.5	7.0	7.6	7.1	7.3	7.7	5.8	5.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3
Waste Combustion	14.1	18.5	19.4	21.2	22.5	23.9	25.4	26.9

S-4 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001

Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4	4.1
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3
Ammonia Production and Urea Application	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6
Land-Use Change and Forestry (Sink) ^a	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
International Bunker Fuels ^b	113.9	101.0	102.3	109.9	112.9	105.3	99.3	97.3
CH₄	705.3	711.9	697.5	689.5	682.0	674.2	671.8	663.6
Stationary Sources	8.9	9.3	9.6	8.2	7.9	8.1	8.4	8.1
Mobile Sources	5.4	5.3	5.2	5.1	5.0	4.9	4.9	4.7
Coal Mining	95.4	80.5	74.9	74.6	74.4	69.8	66.8	66.5
Natural Gas Systems	133.6	139.4	139.6	138.0	135.8	131.7	132.7	128.5
Petroleum Systems	30.1	26.5	26.2	25.8	25.1	23.7	23.2	23.3
Petrochemical Production	1.3	1.7	1.7	1.8	1.8	1.8	1.8	1.6
Silicon Carbide Production	+	+	+	+	+	+	+	+
Enteric Fermentation	129.1	134.7	131.9	129.6	127.8	127.7	126.7	125.8
Manure Management	34.3	39.6	38.2	40.0	42.7	42.6	41.9	42.6
Rice Cultivation	7.8	8.3	7.6	8.2	8.7	9.1	8.2	8.4
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.9	0.8	0.9	0.8
Landfills	232.3	236.7	232.3	227.2	221.7	223.1	225.4	222.3
Wastewater Treatment	26.4	29.1	29.4	29.9	30.3	30.8	31.0	31.0
International Bunker Fuels ^b	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1
N₂O	379.6	411.5	421.8	421.0	417.1	413.4	410.5	405.4
Stationary Source	12.0	12.6	13.2	13.1	13.1	13.1	13.6	13.5
Mobile Sources	48.3	58.2	58.0	57.6	57.0	56.1	54.9	52.3
Adipic Acid	14.5	16.4	16.3	9.8	5.7	5.2	5.8	4.7
Nitric Acid	17.0	19.0	19.8	20.3	19.9	19.2	18.2	16.8
Manure Management	15.4	15.8	16.2	16.5	16.5	16.6	17.1	17.2
Agricultural Soil Management	255.5	271.2	279.9	284.7	285.6	283.6	281.3	281.0
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Human Sewage	12.1	13.3	13.5	13.8	14.0	14.4	14.5	14.6
N ₂ O Product Usage	4.1	4.3	4.3	4.6	4.6	4.6	4.6	4.6
Waste Combustion	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels ^b	0.9	0.8	0.9	0.9	0.9	0.9	0.8	0.8
HFCs, PFCs, and SF₆	91.7	95.2	106.6	109.8	120.5	112.3	112.5	101.7
Substitution of Ozone Depleting Substances	0.9	19.0	25.1	32.0	37.8	43.1	48.8	54.5
Aluminum Production	16.8	10.9	11.5	10.1	8.3	8.2	7.3	3.9
HCFC-22 Production ^c	35.9	27.7	31.9	30.8	41.2	31.2	30.6	20.3
Semiconductor Manufacture ^d	3.3	6.8	6.3	7.6	8.4	9.0	8.5	6.5
Electrical Transmission and Distribution ^e	29.8	25.5	25.7	23.4	19.4	15.2	14.3	14.2
Magnesium Production and Processing ^e	5.0	5.2	6.1	5.9	5.4	5.6	2.9	2.3
Total	6,180.4	6,553.1	6,740.6	6,815.6	6,833.7	6,880.6	7,077.9	6,965.5

+ Does not exceed 0.05 Tg CO₂ Eq.

^a Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

^c HFC-23 emitted

^d Emissions from HFC-23, CF₄, C₂F₆, C₃F₈, SF₆, and the addition of NF₃

^e SF₆ emitted

Note: Totals may not sum due to independent rounding.

Table S-5: Change in U.S. Greenhouse Gas Emissions and Sinks Using TAR vs SAR GWPs (Tg CO₂ Eq.)

Gas	1990	1995	1996	1997	1998	1999	2000	2001
CO ₂	NC	NC	NC	NC	NC	NC	NC	NC
CH ₄	61.3	61.9	60.6	60.0	59.3	58.6	58.4	57.7
N ₂ O	(18.0)	(19.5)	(19.9)	(19.9)	(19.7)	(19.6)	(19.4)	(19.2)
HFCs, PFCs, and SF ₆ *	(2.6)	(4.3)	(7.1)	(7.1)	(7.2)	(8.0)	(8.5)	(9.2)
Total	40.8	38.2	33.6	33.0	32.4	31.1	30.5	29.3

NC (No change)

*Includes NF₃

Note: Totals may not sum due to independent rounding.

Table S-6: Change in U.S. Greenhouse Gas Emissions Using TAR vs. SAR GWPs (Percent)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO ₂	NC	NC	NC	NC	NC	NC	NC	NC
CH ₄	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
N ₂ O	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)
HFCs, PFCs, and SF ₆	(2.8)	(4.3)	(6.2)	(6.0)	(5.6)	(6.7)	(7.0)	(8.3)
Substitution of Ozone Depleting Substances	(3.2)	(12.2)	(17.5)	(15.3)	(15.2)	(15.2)	(14.8)	(14.4)
Aluminum Production ^a	(7.0)	(7.7)	(7.8)	(7.9)	(7.9)	(7.9)	(8.0)	(6.8)
HCFC-22 Production ^b	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Semiconductor Manufacture ^c	15.9	15.9	15.9	15.9	15.9	15.9	15.9	17.2
Electrical Transmission and Distribution ^d	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)
Magnesium Production and Processing ^d	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)
Total	0.7	0.6	0.5	0.5	0.5	0.5	0.4	0.4

NC (No change)

^a PFC emissions from CF₄ and C₂F₆^b HFC-23 emitted^c Emissions from HFC-23, CF₄, C₂F₆, C₃F₈, SF₆, and the addition of NF₃^d SF₆ emitted

Note: Excludes Sinks.

Table S-7: Effects on U.S. Greenhouse Gas Emissions Using TAR vs. SAR GWPs (Tg CO₂ Eq.)

Gas	Trend from 1990 to 2001		Revisions to Annual Estimates	
	SAR	TAR	1990	2001
CO ₂	791.1	791.1	NC	NC
CH ₄	(38.12)	(41.75)	61.3	57.7
N ₂ O	27.0	25.8	(18.0)	(19.2)
HFCs, PFCs, and SF ₆ *	16.6	10.0	(2.6)	(9.2)
Total	796.6	785.1	40.8	29.3
Percent Change	13.0%	12.7%	0.7%	0.4%

NC (No Change)

*Includes NF₃

Note: Totals may not sum due to independent rounding. Excludes Sinks.

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table S-5 and Table S-6. Table S-8 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (8.7 percent), due the predominance of CH₄ emissions in this sector. Emissions from all other sectors were comprised of mainly CO₂ or a mix of gases, which moderated the effect of the changes.

Table S-8: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg CO₂ Eq.)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Energy								
SAR GWP (Used in Inventory)	5,147.5	5,481.6	5,661.4	5,733.0	5,749.4	5,809.5	6,010.4	5,927.1
TAR GWP	5,168.4	5,500.9	5,680.3	5,751.5	5,767.6	5,826.9	6,027.7	5,944.1
Difference (%)	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Industrial Processes								
SAR GWP (Used in Inventory)	302.2	308.3	318.8	321.4	325.9	313.7	312.6	287.6
TAR GWP	298.1	302.3	310.0	312.8	317.5	304.5	302.9	277.3
Difference (%)	-1.4%	-1.9%	-2.8%	-2.7%	-2.6%	-2.9%	-3.1%	-3.6%
Agriculture								
SAR GWP (Used in Inventory)	441.0	468.4	473.7	479.0	481.3	479.3	475.1	474.9
TAR GWP	443.1	470.8	475.2	480.3	482.7	480.8	476.4	476.2
Difference (%)	0.5%	0.5%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Land-Use Change and Forestry								
SAR GWP (Used in Inventory)	(1,072.81)	(1,064.17)	(1,061.02)	(840.62)	(830.48)	(841.05)	(834.64)	(838.14)
TAR GWP	(1,072.81)	(1,064.17)	(1,061.02)	(840.62)	(830.48)	(841.05)	(834.64)	(838.14)

Difference (%)	NC		NC	NC	NC	NC	NC	NC	NC
Waste									
SAR GWP (Used in Inventory)	248.9		256.6	253.1	249.2	244.7	247.0	249.2	246.6
TAR GWP	270.8		279.1	275.2	270.9	266.0	268.4	270.8	267.9
Difference (%)	8.8%		8.8%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%
Net Emissions (Sources and Sinks)									
SAR GWP (Used in Inventory)	5,066.8		5,450.7	5,646.0	5,942.0	5,970.9	6,008.5	6,212.7	6,098.1
TAR GWP	5,107.6		5,488.9	5,679.6	5,974.9	6,003.3	6,039.6	6,243.2	6,127.4
Difference (%)	0.8%		0.7%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%

NC (No change)

Note: Totals may not sum due to independent rounding.

ANNEX T

Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,¹ where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,² where it is the main component of anthropogenic photochemical “smog.” Chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), along with certain other chlorine and bromine containing compounds, have been found to deplete the ozone levels in the stratosphere. These compounds are commonly referred to as ozone depleting substances (ODSs). If left unchecked, stratospheric ozone depletion could result in a dangerous increase of ultraviolet radiation reaching the earth’s surface. In 1987, nations around the world signed the *Montreal Protocol on Substances that Deplete the Ozone Layer*. This landmark agreement created an international framework for limiting, and ultimately eliminating, the production of most ozone depleting substances. ODSs have historically been used in a variety of industrial applications, including refrigeration and air conditioning, foam blowing, fire extinguishing, as an aerosol propellant, sterilization, and solvent cleaning.

In the United States, the Clean Air Act Amendments of 1990 provide the legal instrument for implementation of the *Montreal Protocol* controls. The Clean Air Act classifies ozone depleting substances as either Class I or Class II, depending upon the ozone depletion potential (ODP) of the compound.³ The production of CFCs, halons, carbon tetrachloride, and methyl chloroform—all Class I substances—has already ended in the United States. However, large amounts of these chemicals remain in existing equipment,⁴ and stockpiles of the ODSs are used for maintaining the equipment. In addition, U.S. regulations require the recovery of ODSs in order to minimize “venting” to the atmosphere. As a result, emissions of Class I compounds will continue, albeit in ever decreasing amounts, for many more years. Class II designated substances, all of which are hydrochlorofluorocarbons (HCFCs), are being phased out at later dates because they have lower ozone depletion potentials. These compounds serve as interim replacements for Class I compounds in many industrial applications. The use and emissions of HCFCs in the United States is anticipated to increase over the next several years as equipment that use Class I substances are retired from use. Under current controls, however, the production for domestic use of all HCFCs in the United States will end by the year 2030.

In addition to contributing to ozone depletion, CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFCs are also potent greenhouse gases. However, the depletion of the ozone layer has a cooling effect on the climate that counteracts the direct warming from tropospheric emissions of ODSs. Stratospheric ozone influences the earth’s radiative balance by absorption and emission of longwave radiation from the troposphere as well as absorption of shortwave radiation from the sun, overall, stratospheric ozone has a warming effect.

The IPCC has prepared both direct GWPs and net (combined direct warming and indirect cooling) GWP ranges for some of the most common ozone depleting substances (IPCC 1996). See Annex S for a listing of the net GWP values for ODS.

Although the IPCC emission inventory guidelines do not require the reporting of emissions of ozone depleting substances, the United States believes that no inventory is complete without the inclusion of these compounds. Emission estimates for several ozone depleting substances are provided in Table T-1.

¹ The stratosphere is the layer from the top of the troposphere up to about 50 kilometers. Approximately 90 percent of atmospheric ozone is within the stratosphere. The greatest concentration of ozone occurs in the middle of the stratosphere, in a region commonly called the ozone layer.

² The troposphere is the layer from the ground up to about 11 kilometers near the poles and 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere, where humans live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for weather processes including most of the water vapor and clouds.

³ Substances with an ozone depletion potential of 0.2 or greater are designated as Class I. All other substances that may deplete stratospheric ozone but which have an ODP of less than 0.2 are Class II.

⁴ Older refrigeration and air-conditioning equipment, fire extinguishing systems, meter-dose inhalers, and foam products blown with CFCs/HCFCs may still contain ODS.

Table T-1: Emissions of Ozone Depleting Substances (Gg)

Compound	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Class I												
CFC-11	53.5	48.3	45.1	45.4	36.6	36.2	26.6	25.1	24.9	24.0	22.8	22.8
CFC-12	112.6	103.5	80.5	79.3	57.6	51.8	35.5	23.1	21.0	14.0	17.2	21.3
CFC-113	52.7	41.1	34.2	34.2	17.1	17.1	+	+	+	+	+	+
CFC-114	4.7	3.6	3.0	3.0	1.6	1.6	0.3	0.1	0.1	+	+	+
CFC-115	4.2	4.0	3.8	3.6	3.3	3.0	3.2	2.9	2.7	2.6	2.3	1.5
Carbon Tetrachloride	32.3	27.0	21.7	18.6	15.5	4.7	+	+	+	+	+	+
Methyl Chloroform	316.6	309.4	216.6	185.7	154.7	92.8	+	+	+	+	+	+
Halon-1211	1.0	1.1	1.0	1.1	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Halon-1301	1.8	1.8	1.7	1.7	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2
Class II												
HCFC-22	34.0	35.4	35.2	35.3	37.7	39.3	41.0	42.4	43.8	74.1	79.1	80.5
HCFC-123	+	+	0.1	0.3	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
HCFC-124	+	+	0.2	2.7	5.3	5.6	5.9	6.2	6.4	6.5	6.5	6.5
HCFC-141b	1.3	1.7	1.7	2.9	6.2	9.9	9.9	8.8	9.7	10.9	10.9	10.7
HCFC-142b	0.8	1.4	1.9	2.6	3.3	3.6	4.0	4.3	4.7	5.0	5.4	5.8
HCFC-225ca/cb	+	+	+	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.05 Gg

Methodology and Data Sources

Emissions of ozone depleting substances were estimated using two simulation models: the Atmospheric and Health Effects Framework (AHEF) and the EPA's Vintaging Model. AHEF contains estimates of U.S. domestic use of each of the ozone depleting substances. These estimates were based upon data that industry reports to the EPA and other published material. The annual consumption of each compound was divided into various end-uses based upon historical trends and research into specific industrial applications. These end-uses include refrigerants, foam blowing agents, solvents, aerosol propellants, sterilants, and fire extinguishing agents.

With the exception of aerosols, solvents, and certain foam blowing agents, emissions of ozone depleting substances are not instantaneous, but instead occur gradually over time (i.e., emissions in a given year are the result of both ODS use in that year and 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. In refrigeration equipment, for example, the initial charge is released or leaked slowly over the lifetime of the equipment, which could be 20 or more years. In addition, not all of the refrigerant is ultimately emitted—some will be recovered when the equipment is retired from operation.

The AHEF model was used to estimate emissions of ODSs that were in use prior to the controls implemented under the *Montreal Protocol*. This included CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFC-22. Certain HCFCs, such as HCFC-123, HCFC-124, HCFC-141b, HCFC-142b, HCFC-225ca and HCFC-225cb, have also entered the market as interim substitutes for ODSs. Emissions estimates for these compounds were taken from the EPA's Vintaging Model.

The Vintaging Model was used to estimate the use and emissions of various ODS substitutes, including HCFCs. The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment, as in the AHEF. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical. Please see Annex K of this Inventory for a more detailed discussion of the Vintaging Model.

Uncertainties

Uncertainties exist with regard to the levels of chemical production, equipment sales, equipment characteristics, and end-use emissions profiles that are used by these models.

ANNEX U

Sulfur Dioxide Emissions

Sulfur dioxide (SO₂), emitted into the atmosphere through natural and anthropogenic processes, affects the Earth's radiative budget through photochemical transformation into sulfate aerosols that can (1) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., stratospheric ozone, by providing surfaces for heterogeneous chemical reactions). The overall effect of SO₂-derived aerosols on radiative forcing is believed to be negative (IPCC 1996). However, because SO₂ is short-lived and unevenly distributed through the atmosphere, its radiative forcing impacts are highly uncertain. Sulfur dioxide emissions have been provided below in Table U-1.

The major source of SO₂ emissions in the United States was the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also released significant quantities of SO₂. The largest group of contributors to U.S. emissions of SO₂ was the electric utilities, accounting for 69 percent in 2001 (see Table U-2). Coal combustion accounted for approximately 92 percent of SO₂ emissions from electric utilities in the same year. The second largest source was industrial fuel combustion, which produced 14 percent of 2001 SO₂ emissions. Overall, SO₂ emissions in the United States decreased by 32 percent from 1990 to 2001. The majority of this decline came from reductions from electric utilities, primarily due to increased consumption of low sulfur coal from surface mines in western states.

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 SO₂ can cause significant increases in acute and chronic respiratory diseases. In addition, once SO₂ 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, and to cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the United States has regulated the emissions of SO₂ under the Clean Air Act. The EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Standards program,¹ (2) New Source Performance Standards,² (3) the New Source Review/Prevention of Significant Deterioration Program,³ and (4) the sulfur dioxide allowance program.⁴

References

EPA (2003) Unpublished data provided by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Table U-1: SO₂ Emissions (Gg)

Sector/Source	1990	1995	1996	1997	1998	1999	2000	2001
Energy	19,629	15,773	15,727	16,104	16,196	15,079	13,823	13,314
Stationary Combustion	18,407	14,724	14,746	15,104	15,191	14,073	12,883	12,367
Mobile Combustion	793	673	649	659	665	701	632	636
Oil and Gas Activities	390	334	304	312	310	275	279	281
Waste Combustion	39	42	29	29	30	29	29	30
Industrial Processes	1,306	1,117	953	985	991	933	977	1,008
Chemical Manufacturing	269	260	231	235	237	284	295	298
Metals Processing	658	481	353	369	367	297	306	325
Storage and Transport	6	2	5	5	5	5	5	5
Other Industrial Processes	362	365	350	371	376	337	352	370
Miscellaneous*	11	9	14	5	5	11	19	9

¹ [42 U.S.C § 7409, CAA § 109]

² [42 U.S.C § 7411, CAA § 111]

³ [42 U.S.C § 7473, CAA § 163]

⁴ [42 U.S.C § 7651, CAA § 401]

Solvent Use	+		1	1	1	1	1	1	1
Degreasing	+		+	+	+	+	+	+	+
Graphic Arts	+		+	+	+	+	+	+	+
Dry Cleaning	NA		+	+	+	+	+	+	+
Surface Coating	+		+	+	+	+	+	+	+
Other Industrial	+		+	1	1	1	1	1	1
Non-industrial	NA		NA	NA	NA	NA	NA	NA	NA
Agriculture	NA		NA	NA	NA	NA	NA	NA	NA
Agricultural Burning	NA		NA	NA	NA	NA	NA	NA	NA
Waste	+		1	1	1	1	1	1	1
Landfills	+		+	1	1	1	1	1	1
Wastewater Treatment	+		1	+	+	+	+	+	+
Miscellaneous Waste	+		+	+	+	+	+	+	+
Total	20,936		16,892	16,682	17,091	17,189	16,013	14,802	14,324

Source: (EPA 2003)

* Miscellaneous includes other combustion and fugitive dust categories.

+ Does not exceed 0.5 Gg

NA (Not Available)

Note: Totals may not sum due to independent rounding.

Table U-2: SO₂ Emissions from Electric Utilities (Gg)

Fuel Type	1990		1995	1996	1997	1998	1999	2000	2001
Coal	13,807		10,526	11,105	11,443	11,312	10,594	9,614	9,031
Petroleum	580		375	418	466	691	525	428	476
Natural Gas	1		8	6	5	5	151	157	181
Misc. Internal Combustion	45		50	48	51	52	54	54	55
Other	NA		NA	4	4	110	44	78	73
Total	14,432		10,959	11,581	11,970	12,170	11,368	10,331	9,817

Source: (EPA 2003)

Note: Totals may not sum due to independent rounding.

ANNEX V

Complete List of Source Categories

Chapter/Source	Gas(es)
Energy	
Carbon Dioxide Emissions from Fossil Fuel Combustion	CO ₂
Carbon Stored in Products from Non-Energy Uses of Fossil Fuels	CO ₂
Stationary Combustion (excluding CO ₂)	CH ₄ , N ₂ O, CO, NO _x , NMVOC
Mobile Combustion (excluding CO ₂)	CH ₄ , N ₂ O, CO, NO _x , NMVOC
Coal Mining	CH ₄
Natural Gas Systems	CH ₄
Petroleum Systems	CH ₄
Municipal Solid Waste Combustion	CO ₂ , N ₂ O
Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities	CO ₂ , CO, NO _x , NMVOC
International Bunker Fuels	CO ₂ , CH ₄ , N ₂ O, CO, NO _x , NMVOC
Wood Biomass and Ethanol Consumption	CO ₂
Industrial Processes	
Iron and Steel Production	CO ₂
Cement Manufacture	CO ₂
Ammonia Manufacture and Urea Application	CO ₂
Lime Manufacture	CO ₂
Limestone and Dolomite Use	CO ₂
Soda Ash Manufacture and Consumption	CO ₂
Ferroalloy Production	CO ₂
Titanium Dioxide Production	CO ₂
Carbon Dioxide Consumption	CO ₂
Petrochemical Production	CH ₄
Silicon Carbide Production	CH ₄
Adipic Acid Production	N ₂ O
Nitric Acid Production	N ₂ O
N ₂ O Product Use	N ₂ O
Substitution of Ozone Depleting Substances	HFCs, PFCs ^a
Aluminum Production	CO ₂ , CF ₄ , C ₂ F ₆
HCFC-22 Production	HFC-23
Semiconductor Manufacture	HFCs, PFCs, SF ₆ ^b
Electrical Transmission and Distribution	SF ₆
Magnesium Production and Processing	SF ₆
Industrial Sources of Ambient Air Pollutants	CO, NO _x , NMVOC
Solvent Use	CO, NO _x , NMVOC
Agriculture	
Enteric Fermentation	CH ₄
Manure Management	CH ₄ , N ₂ O
Rice Cultivation	CH ₄
Agricultural Soil Management	N ₂ O
Agricultural Residue Burning	CH ₄ , N ₂ O, CO, NO _x
Land-Use Change and Forestry	
Changes in Forest Carbon Stocks	CO ₂ (sink)
Changes in Carbon Stocks in Urban Trees	CO ₂ (sink)
Changes in Agricultural Soil Carbon Stocks	CO ₂ (sink)
Changes in Yard Trimming Carbon Stocks in Landfills	CO ₂ (sink)
Waste	
Landfills	CH ₄
Wastewater Treatment	CH ₄
Human Sewage	N ₂ O
Waste Sources of Ambient Air Pollutants	CO, NO _x , NMVOC

^a In 1999, included HFC-23, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-4310mee, C₄F₁₀, C₆F₁₄, PFC/PFPEs

^b Included such gases as HFC-23, CF₄, C₂F₆, SF₆

ANNEX W

IPCC Reference Approach for Estimating CO₂ Emissions from Fossil Fuel Combustion

It is possible to estimate carbon dioxide (CO₂) emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in Annex A. For example, the UNFCCC reporting guidelines request that countries, in addition to their “bottom-up” sectoral methodology, to complete a “top-down” Reference Approach for estimating CO₂ emissions from fossil fuel combustion. Section 1.3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reporting Instructions* states, “If a detailed, Sectoral Approach for energy has been used for the estimation of CO₂ from fuel combustion you are still asked to complete...the Reference Approach...for verification purposes” (IPCC/UNEP/OECD/IEA 1997). This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required. The following discussion provides the detailed calculations for estimating CO₂ emissions from fossil fuel combustion from the United States using the IPCC-recommended Reference Approach.

Step 1: Collect and Assemble Data in Proper Format

To ensure the comparability of national inventories, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected in physical units from several EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes (EIA 2002a).

It was necessary to make a number of modifications to these data to generate more accurate apparent consumption estimates of these fuels. The first modification adjusts for consumption of fossil fuel feedstocks accounted for in the Industrial Processes chapter, which include unspecified coal for coal coke used in iron and steel production, natural gas used for ammonia production, and petroleum coke used in the production of aluminum, ferroalloys, and titanium dioxide. The second modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The third modification consists of the addition of U.S. territories data that are typically excluded from the national aggregate energy statistics. The territories include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, Wake Island, and U.S. Pacific Islands. These data, as well as the production, import, export, and stock change statistics, are presented in Table W-1.

The carbon content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of CO₂ emissions, fuel statistics were provided on an energy content basis (e.g., BTUs or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table W-1), they were converted to units of energy before CO₂ emissions were calculated. Fuel statistics were converted to their energy equivalents by using conversion factors provided by EIA. These factors and their data sources are displayed in Table W-2. The resulting fuel type-specific energy data are provided in Table W-3.

Step 2: Estimate Apparent Fuel Consumption

The next step of the IPCC Reference Approach 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, anthracite, bituminous, subbituminous and lignite coal, and natural gas) can be calculated as follows:

$$\text{Apparent Consumption} = \text{Production} + \text{Imports} - \text{Exports} - \text{Stock Change}$$

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:

$$\text{Secondary Consumption} = \text{Imports} - \text{Exports} - \text{Stock Change}$$

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

Next, the apparent consumption and secondary consumption need to be adjusted for feedstock uses of fuels accounted for in the Industrial Processes chapter, international bunker fuels, and U.S. territory fuel consumption. Bunker fuels and feedstocks accounted for in the Industrial Processes chapter are subtracted from these estimates, while fuel consumption in U.S. territories is added.

The IPCC Reference Approach calls for estimating apparent fuel consumption before converting to a common energy unit. However, certain primary fuels in the United States (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 has different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. Results are provided in Table W-3.

Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are virtually identical to those for the “bottom-up” Sectoral Approach (see Annex A). That is:

- Potential CO₂ emissions were estimated using fuel-specific carbon coefficients (see Table W-4).¹
- The carbon in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted (see Table W-5).
- Finally, to obtain actual CO₂ emissions, net emissions were adjusted for any carbon that remained unoxidized as a result of incomplete combustion (e.g., carbon contained in ash or soot).²

Step 4: Convert to CO₂ Emissions

Because the IPCC reporting guidelines recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating CO₂ emissions from fossil fuel consumption was converting from units of carbon to units of CO₂. Actual carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO₂ to carbon (44/12) to obtain total carbon dioxide emitted from fossil fuel combustion in teragrams (Tg). The results are reported in Table W-6.

Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. The major difference between methodologies employed by each approach lies in the energy data used to derive carbon emissions (i.e., the actual surveyed consumption for the Sectoral Approach versus apparent

¹ Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Annex A.

² 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 United States are more efficient, the United States inventory uses 1 percent in its calculations for petroleum and coal and 0.5 percent for natural gas.

consumption derived for the Reference Approach). In theory, both approaches should yield identical results. In practice, however, slight discrepancies occur. For the United States, these differences are discussed below.

Differences in Total Amount of Energy Consumed

Table W-7³ summarizes the differences between the Reference and Sectoral approaches in estimating total energy consumption in the United States. Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the Reference Approach provides an energy total that is 0.6 percent higher than the Sectoral Approach for 2001. The greatest difference lies primarily in the higher estimate of petroleum consumption using the Reference Approach (1.9 percent).

There are several potential sources for the discrepancies in consumption estimates:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum. For example, the Reference Approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly, but refined into other products. As a result, the United States does not focus on estimating the energy content of the various grades of crude oil, but rather estimating the energy content of the various products resulting from crude oil refining. The United States 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 United States to estimate its energy consumption. Other differences in product definitions include using sector-specific coal statistics in the Sectoral Approach (i.e., residential, commercial, industrial coking, industrial other, and transportation coal), while the Reference Approach characterizes coal by rank (i.e. anthracite, bituminous, etc.). Also, the liquefied petroleum gas (LPG) statistics used in the bottom-up calculations are actually a composite category composed of natural gas liquids (NGL) and LPG.
- *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 United States and abroad. For heat equivalents by coal rank, it was necessary to refer back to EIA's *State Energy Data Report 1992* (1994) because this information is no longer published.
- *Possible inconsistencies in U.S. Energy Data.* The United States has not focused its energy data collection efforts on obtaining the type of aggregated information used in the Reference Approach. Rather, the United States believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the United States to obtain reliable energy data. Therefore, top-down statistics used in the Reference Approach may not be as accurately collected as bottom-up statistics applied to the Sectoral Approach.
- *Balancing Item.* The Reference Approach uses *apparent* consumption estimates while the Sectoral Approach 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."

Differences in Estimated CO₂ Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of CO₂. Table W-8 summarizes the differences between the two methods in estimated CO₂ emissions.

While the use of the Reference Approach resulted in a 0.6 percent higher estimate of energy consumption in the United States than the Sectoral Approach, the resulting emissions estimated was 1.0 percent higher. Potential reasons for these differences may include:

- *Product Definitions.* Coal data is aggregated differently in each methodology, as noted above. The format used for the Sectoral Approach likely results in more accurate estimates than in the Reference Approach. Also, the Reference Approach relies on a "crude oil" category for determining petroleum-related emissions. Given the many sources of crude oil in the United States, it is not an easy matter to track potential

³ Although complete energy consumption data and calculations are not presented, comparison tables are also presented for 1990-2001.

differences in carbon content between many different sources of crude, particularly since information on the carbon content of crude oil is not regularly collected.

- *Carbon Coefficients.* The Reference Approach relies on several default carbon coefficients by rank provided by IPCC (IPCC/UNEP/OECD/IEA 1997), while the Sectoral Approach uses annually updated category-specific coefficients by sector that are likely to be more accurate. Also, as noted above, the carbon coefficient for crude oil is more uncertain than that for specific secondary petroleum products, given the many sources and grades of crude oil consumed in the United States.

Although the two approaches produce similar results, the United States believes that the “bottom-up” Sectoral Approach provides a more accurate assessment of CO₂ emissions at the fuel level. This improvement in accuracy is largely a result of the data collection techniques used in the United States, where there has been more emphasis on obtaining the detailed products-based information used in the Sectoral Approach than obtaining the aggregated energy flow data used in the Reference Approach. The United States believes that it is valuable to understand both methods.

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Table W-1: 2001 U.S. Energy Statistics (Physical Units)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories
Solid Fuels (Thousand Short Tons)	Anthracite Coal	3,857	a	a	a			
	Bituminous Coal	620,226	a	a	a			
	Sub-bituminous Coal	413,329	a	a	a			
	Lignite	83,915	a	a	a			
	Coke		2,340	625	(91)			
	Unspecified Coal		19,787	48,666	30,676	24,604		441
Gas Fuels (Million Cubic Feet)	Natural Gas	20,156,010	4,028,904	394,248	1,155,344	250,986		22,248
Liquid Fuels (Thousand Barrels)	Crude Oil	2,117,511	3,404,894	7,386	36,036			
	Nat Gas Liquids and LRGs	681,964	91,374	16,492	40,550			2,559
	Other Liquids	34,498	275,838	13,523	7,337			
	Motor Gasoline	105,673	165,878	48,485	8,455			33,140
	Aviation Gasoline		598	0	199			
	Kerosene		1,773	768	1,281			705
	Jet Fuel		54,065	10,728	(2,565)		147,766	
	Distillate Fuel		125,586	43,543	26,486		12,429	17,436
	Residual Fuel		107,688	69,779	4,847		67,765	20,570
	Naphtha for petrochemical feedstocks		32,989	0	(359)			
	Petroleum Coke		2,016	122,746	(179)	11,264		
	Other Oil for petrochemical feedstocks		51,749	0	(300)			
	Special Naphthas		4,926	8,410	(106)			
	Lubricants		2,841	9,331	1,686			245
	Waxes		918	1,313	(435)			
	Asphalt/Road Oil		9,638	1,829	(4,403)			
	Still Gas		0	0	0			
	Misc. Products		267	88	272			44,450

[a] Included in "Unspecified Coal".

Data Sources: Solid and gas fuels are from EIA (2002a); liquid fuels are from EIA (1995-2002).

Table W-2: Conversion Factors to Energy Units (Heat Equivalents)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories
Solid Fuels (Million Btu/Short Ton)	Anthracite Coal	22.57						
	Bituminous Coal	23.89						
	Sub-bituminous Coal	17.14						
	Lignite	12.87						
	Coke		24.80	24.80	24.80			
Natural Gas (BTU/Cubic Foot)	Unspecified		25.00	26.12	21.07	27.43		25.14
		1,025	1,023	1,006	1,025	1,025		
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.80	5.98	5.80	5.80		5.80	5.80
	Nat Gas Liquids and LRGs	3.74	3.74	3.74	3.74		3.74	3.74
	Other Liquids	5.83	5.83	5.83	5.83		5.83	5.83
	Motor Gasoline	5.25	5.25	5.25	5.25		5.25	5.25
	Aviation Gasoline		5.05	5.05	5.05		5.05	5.05
	Kerosene		5.67	5.67	5.67		5.67	5.67
	Jet Fuel		5.67	5.67	5.67		5.67	5.67
	Distillate Fuel		5.83	5.83	5.83		5.83	5.83
	Residual Oil		6.29	6.29	6.29		6.29	6.29
	Naphtha for petrochemical feedstocks		5.25	5.25	5.25		5.25	5.25
	Petroleum Coke		6.02	6.02	6.02	6.02	6.02	6.02
	Other Oil for petrochemical feedstocks		5.83	5.83	5.83		5.83	5.83
	Special Naphthas		5.25	5.25	5.25		5.25	5.25
	Lubricants		6.07	6.07	6.07		6.07	6.07
	Waxes		5.54	5.54	5.54		5.54	5.54
	Asphalt/Road Oil		6.64	6.64	6.64		6.64	6.64
	Still Gas		6.00	6.00	6.00		6.00	6.00
	Misc. Products		5.80	5.80	5.80		5.80	5.80

Data Sources: Coal and lignite production are from EIA (1994); unspecified solid fuels are from EIA (2002b); coke, natural gas and petroleum products are from EIA (2002b).

Table W-3: 2001 Apparent Consumption of Fossil Fuels (TBTu)

Fuel Category	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories	Apparent Consumption
Solid Fuels	Anthracite Coal	87.1							87.1
	Bituminous Coal	14,817.2							14,817.2
	Sub-bituminous Coal	7,084.5							7,084.5
	Lignite	1,079.6							1,079.6
	Coke		58.0	15.5	(2.3)				44.8
Gas Fuels	Unspecified		494.7	1,271.0	646.4	674.8		11.1	(2,086.4)
	Natural Gas	20,659.9	4,121.6	396.6	1,184.2	257.3			22,943.4
Liquid Fuels	Crude Oil	12,281.6	20,347.6	42.8	209.0				32,377.4
	Nat Gas Liquids and LRGs	2,547.1	341.3	61.6	151.5			9.6	2,684.9
	Other Liquids	201.0	1,606.8	78.8	42.7				1,686.2
	Motor Gasoline	555.1	871.4	254.7	44.4			174.1	1,301.4
	Aviation Gasoline		3.0	0.0	1.0				2.0
	Kerosene		10.1	4.4	7.3			4.0	2.4
	Jet Fuel		306.5	60.8	(14.5)		837.8		(577.6)
	Distillate Fuel		731.5	253.6	154.3		72.4	101.6	352.8
	Residual Oil		677.0	438.7	30.5		426.0	129.3	(88.9)
	Naphtha for petrochemical feedstocks		173.1	0.0	(1.9)				175.0
	Petroleum Coke		12.1	739.4	(1.1)	67.9			(794.1)
	Other Oil for petrochemical feedstocks		301.4	0.0	(1.7)				303.2
	Special Naphthas		25.9	44.1	(0.6)				(17.7)
	Lubricants		17.2	56.6	10.2			1.5	(48.1)
	Waxes		5.1	7.3	(2.4)				0.2
	Asphalt/Road Oil		64.0	12.1	(29.2)				81.0
	Still Gas		0.0	0.0	0.0				0.0
	Misc. Products		1.5	0.5	1.6			257.6	257.1
Total		59,313.0	30,169.9	3,738.6	2,429.4	999.9	1,336.3	688.7	81,667.5

Note: Totals may not sum due to independent rounding.

Table W-4: 2001 Potential Carbon Dioxide Emissions

Fuel Category	Fuel Type	Apparent Consumption (QBtu)	Carbon Coefficients (Tg Carbon/QBtu)	Potential Emissions (Tg CO₂ Eq.)
Solid Fuels	Anthracite Coal	0.087	26.86	8.6
	Bituminous Coal	14.817	25.86	1,405.0
	Sub-bituminous Coal	7.084	26.26	682.1
	Lignite	1.080	27.66	109.5
	Coke	0.045	25.63	4.2
	Unspecified	(2.086)	25.34	(193.8)
Gas Fuels	Natural Gas	22.943	14.47	1,217.3
Liquid Fuels	Crude Oil	32.377	20.29	2,408.8
	Nat Gas Liquids and LRGs	2.685	16.99	167.2
	Other Liquids	1.686	20.29	125.4
	Motor Gasoline	1.301	19.34	92.3
	Aviation Gasoline	0.002	18.87	0.1
	Kerosene	0.002	19.72	0.2
	Jet Fuel	(0.578)	19.33	(40.9)
	Distillate Fuel	0.353	19.95	25.8
	Residual Oil	(0.089)	21.49	(7.0)
	Naphtha for petrochemical feedstocks	0.175	18.14	11.6
	Petroleum Coke	(0.794)	27.85	(81.1)
	Other Oil for petrochemical feedstocks	0.303	19.95	22.2
	Special Naphthas	(0.018)	19.86	(1.3)
	Lubricants	(0.048)	20.24	(3.6)
	Waxes	0.000	19.81	0.0
	Asphalt/Road Oil	0.081	20.62	6.1
	Still Gas	0.000	17.51	0.0
	Misc. Products	0.257	20.29	19.1
Total				5,977.9

Data Sources for Carbon Coefficients: Coal and lignite are from IPCC (1997); unspecified solid fuels are from EIA (2002b); natural gas and liquid fuels are from EIA (2001).

Note: Totals may not sum due to independent rounding.

Table W-5: 2001 Non-Energy Carbon Stored in Products

Fuel Type	Consumption for Non-Energy Use (TBtu)	Carbon Coefficients (Tg Carbon/QBtu)	Carbon Content (Tg Carbon)	Fraction Sequestered	Carbon Stored (Tg CO ₂ Eq.)
Coal	24.9	25.63	0.6	0.75	1.8
Natural Gas	333.9	14.47	4.8	0.61	10.8
Asphalt & Road Oil	1,257.6	20.62	25.9	1.00	95.1
LPG	1,690.4	16.88	28.5	0.61	63.7
Lubricants	340.4	20.24	6.9	0.09	2.3
Pentanes Plus	239.2	18.24	4.4	0.61	9.7
Petrochemical Feedstocks	a	a	a	a	49.7
Petroleum Coke	113.2	27.85	3.2	0.50	5.8
Special Naphtha	78.5	19.86	1.6	0.00	0.0
Waxes/Misc.	a	a	a	a	14.6
Misc. U.S. Territories Petroleum	a	a	a	a	1.9
Total					255.3

[a] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.

Note: Totals may not sum due to independent rounding.

Table W-6: 2001 Reference Approach CO₂ Emissions from Fossil Fuel Consumption (Tg CO₂ Eq. unless otherwise noted)

Fuel Category	Potential Emissions	Carbon Sequestered	Net Emissions	Fraction Oxidized	Total Emissions
Coal	2,015.6	1.8	2,013.8	99.0%	1,993.7
Petroleum	2,745.1	242.8	2,502.3	99.0%	2,477.2
Natural Gas	1,217.3	10.8	1,206.5	99.5%	1,200.5
Total	5,977.9	255.3	5,722.6	-	5,671.4

Note: Totals may not sum due to independent rounding.

Table W-7: Energy Consumption in the United States by Estimating Approach (Tbtu)

Approach	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Sectoral	66,518.1	66,278.1	67,598.4	69,008.3	70,179.1	71,167.6	73,525.9	74,432.9	74,514.4	75,259.6	78,045.2	77,133.7
Coal	18,019.4	18,001.7	18,169.4	18,927.8	19,022.2	19,187.3	20,122.8	20,615.1	20,789.7	20,800.1	21,754.2	21,144.1
Natural Gas	19,045.7	19,475.1	20,190.9	20,700.6	21,101.5	22,066.4	22,469.8	22,575.4	22,113.9	22,267.2	23,335.7	22,633.3
Petroleum	29,453.0	28,801.3	29,238.0	29,379.9	30,055.4	29,913.9	30,933.3	31,242.4	31,610.9	32,192.3	32,955.3	33,356.3
Reference (Apparent)	66,692.3	65,181.9	66,668.6	68,320.8	69,702.1	70,553.9	72,929.3	74,407.5	74,403.3	75,222.8	77,851.4	77,589.5
Coal	18,387.5	17,480.5	17,777.7	18,310.6	18,763.1	18,571.4	19,551.4	20,263.8	20,093.2	20,201.2	20,938.9	21,001.9
Natural Gas	19,494.8	19,485.6	20,196.9	20,710.1	21,110.6	22,100.5	22,501.3	22,591.4	22,106.4	22,276.7	23,381.9	22,609.5
Petroleum	28,809.9	28,215.7	28,694.0	29,300.1	29,828.4	29,881.9	30,876.7	31,552.3	32,203.7	32,744.8	33,530.6	33,978.1
Difference	0.3%	-1.7%	-1.4%	-1.0%	-0.7%	-0.9%	-0.8%	+	-0.1%	+	-0.2%	0.6%
Coal	2.0%	-2.9%	-2.2%	-3.3%	-1.4%	-3.2%	-2.8%	-1.7%	-3.4%	-2.9%	-3.7%	-0.7%
Natural Gas	2.4%	0.1%	+	+	+	0.2%	0.1%	0.1%	+	+	0.2%	-0.1%
Petroleum	-2.2%	-2.0%	-1.9%	-0.3%	-0.8%	-0.1%	-0.2%	1.0%	1.9%	1.7%	1.7%	1.9%

* Includes U.S. territories

+ Does not exceed 0.05%

Note: Totals may not sum due to independent rounding.

Table W-8: CO₂ Emissions from Fossil Fuel Combustion by Estimating Approach (Tg CO₂ Eq.)

Approach	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Sectoral	4,814.4	4,786.0	4,881.9	4,999.5	5,085.3	5,141.2	5,325.4	5,399.7	5,420.1	5,488.4	5,691.8	5,614.5
Coal	1,697.3	1,697.2	1,714.9	1,777.9	1,787.6	1,805.8	1,893.4	1,939.1	1,957.3	1,961.1	2,051.5	1,993.8
Natural Gas	1,012.5	1,035.0	1,071.7	1,099.2	1,121.9	1,172.6	1,193.9	1,200.3	1,177.2	1,183.8	1,240.3	1,202.1
Petroleum	2,104.5	2,053.8	2,095.3	2,122.4	2,175.8	2,162.7	2,238.2	2,260.3	2,285.6	2,343.6	2,400.0	2,418.6
Reference (Apparent)	4,864.4	4,727.3	4,839.6	4,963.1	5,067.2	5,109.4	5,298.2	5,411.0	5,425.3	5,494.0	5,670.1	5,671.4
Coal	1,746.9	1,657.8	1,686.0	1,735.1	1,778.9	1,761.3	1,853.5	1,920.2	1,907.0	1,919.3	1,985.9	1,993.7
Natural Gas	1,035.6	1,034.9	1,071.6	1,099.1	1,121.8	1,173.7	1,194.9	1,200.1	1,175.8	1,183.5	1,242.0	1,200.5
Petroleum	2,081.9	2,034.6	2,081.9	2,128.9	2,166.5	2,174.3	2,249.8	2,290.6	2,342.6	2,391.2	2,442.2	2,477.2
Difference	1.0%	-1.2%	-0.9%	-0.7%	-0.4%	-0.6%	-0.5%	0.2%	0.1%	0.1%	-0.4%	1.0%
Coal	2.9%	-2.3%	-1.7%	-2.4%	-0.5%	-2.5%	-2.1%	-1.0%	-2.6%	-2.1%	-3.2%	+
Natural Gas	2.3%	+	+	+	+	0.1%	0.1%	+	-0.1%	+	0.1%	-0.1%
Petroleum	-1.1%	-0.9%	-0.6%	0.3%	-0.4%	0.5%	0.5%	1.3%	2.5%	2.0%	1.8%	2.4%

+ Does not exceed 0.05%

Note: Totals may not sum due to independent rounding. Includes U.S. territories.

ANNEX X

Sources of Greenhouse Gas Emissions Excluded

Although this report is intended to be a comprehensive assessment of anthropogenic¹ sources and sinks of greenhouse gas emissions for the United States, certain sources have been identified yet excluded from the estimates presented for various reasons. Before discussing these sources, however, it is important to note that processes or activities that are not *anthropogenic in origin* or do not result in a *net source or sink* of greenhouse gas emissions are intentionally excluded from a national inventory of anthropogenic greenhouse gas emissions. In general, processes or activities that are not anthropogenic are considered natural (i.e., not directly influenced by human activity) in origin and, as an example, would include the following:

- Volcanic eruptions
- Carbon dioxide (CO₂) exchange (i.e., uptake or release) by oceans
- Natural forest fires²
- Methane (CH₄) emissions from wetlands not affected by human induced land-use changes

Some processes or activities may be anthropogenic in origin but do not result in net emissions of greenhouse gases, such as the respiration of CO₂ by people or domesticated animals.³ Given a source category that is both anthropogenic and results in net greenhouse gas emissions, reasons for excluding a source related to an anthropogenic activity include one or more of the following:

- There is insufficient scientific understanding to develop a reliable method for estimating emissions at a national level.
- Although an estimating method has been developed, data were not adequately available to calculate emissions.
- Emissions were implicitly accounted for within another source category (e.g., CO₂ from Fossil Fuel Combustion).

It is also important to note that the United States believes the exclusion of the sources discussed below introduces only a minor bias in its overall estimate of U.S. greenhouse gas emissions.

Separate Cruise and LTO Emissions from the Combustion of Jet Fuel

The combustion of jet fuel by aircraft results in emissions of CH₄, N₂O, CO, NO_x, and NMVOCs. The emissions per mass of fuel combusted during landing/take-off (LTO) operations differ from those during aircraft cruising. Accurate estimation of these emissions requires a detailed accounting of LTO cycles and fuel consumption during cruising by aircraft model (e.g., Boeing 747-400) as well as appropriate emission factors. Sufficient data for separately calculating near ground-level emissions during landing and take-off and cruise altitude emissions by aircraft model were not available for this report. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 1.93 - 1.96)

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

² In some cases forest fires that are started either intentionally or unintentionally are viewed as mimicking natural burning processes that have been suppressed by other human forest management activities. The United States does not consider forest fires within its national boundaries to be a net source of greenhouse emissions.

³ Respiration of CO₂ by biological organisms is simply part of the broader global carbon cycle that also includes uptake of CO₂ by photosynthetic organisms.

CO₂ from Burning in Coal Deposits and Waste Piles

Coal is periodically burned in deposits and waste piles. It has been estimated that the burning of coal in deposits and waste piles would represent less than 1.3 percent of total U.S. coal consumption, averaged over ten-years. Because there is currently no known source of data on the quantity of coal burned in waste piles and there is uncertainty as to the fraction of coal oxidized during such burnings, these CO₂ emissions are not currently estimated. Further research would be required to develop accurate emission factors and activity data for these emissions to be estimated (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 1.112 - 1.113).

Fossil CO₂ from Petroleum and Natural Gas Wells, CO₂ Separated from Natural Gas, and CO₂ from Enhanced Oil Recovery (EOR)

Petroleum and natural gas well drilling, petroleum and natural gas production, and natural gas processing—including removal of CO₂—may result in emissions of CO₂ that was at one time stored in underground formations.

Carbon dioxide and other gases are naturally present in raw natural gas, in proportions that vary depending on the geochemical circumstances that caused the formation of the gas. After the heavier gases are removed during processing, small amounts of carbon dioxide may be allowed to remain in the natural gas. If the amount of CO₂ sufficiently lowers the heating value of the natural gas, it is typically extracted by amine scrubbing and, in most cases, released into the atmosphere. These emissions can be estimated by calculating the difference between the average carbon dioxide content of raw natural gas and the carbon dioxide content of pipeline gas. The Energy Information Administration (EIA) estimates that annual CO₂ emissions from scrubbing are about 15 Tg CO₂ Eq. Because of imprecision in the reporting of U.S. natural gas production and processing, emissions estimates from energy production sources may be double-counted or under-reported, and thus are uncertain.

Carbon dioxide is also injected into underground deposits to increase crude oil reservoir pressure in a field technique known as enhanced oil recovery (EOR). It is thought that much of the injected CO₂ may be effectively and permanently sequestered, but the fraction of injected CO₂ that is re-released remains uncertain. The fraction re-released varies from well to well depending upon the field geology and the gas capture/re-injection technology employed at the wellhead. Over time, carbon dioxide may also seep into the producing well and mix with the oil and natural gas present there. If the gas portion of this mixture has a sufficiently high energy content, it may be collected and sent to a natural gas plant; if not, it may be vented or flared. The EIA estimates that the amount of CO₂ used for EOR is on the order of 8 Tg CO₂ Eq. (EIA 2002), of which emissions would be some fraction yet to be defined. This figure is based on the difference between U.S. Department of Commerce (Census 2002) sales figures for industrial CO₂ (13 Tg CO₂ Eq.) minus the 5 Tg CO₂ Eq. reported by the Freedonia Group (2000) that is used for purposes other than EOR. Further research into EOR is required before the resulting CO₂ emissions can be adequately quantified. (See Carbon Dioxide Consumption in the Industrial Processes chapter).

Carbon Sequestration in Underground Injection Wells

Data for sequestration of carbon in underground injection wells is obtained from the EPA Toxic Release Inventory (EPA 2000). The carbon content of wastes reported in the EPA TRI as being injected into underground injection wells is estimated from the TRI data, and the carbon is assumed to be sequestered. The sequestration of underground injection carbon is one of the many elements in calculating the storage factor for petrochemical feedstock (see Annex C). The "base year" for this storage factor calculation is 1998 and only EPA TRI data for calendar year 1998 is used in the storage factor calculation. Further research is required if the entire time series for this potential sink is to be fully quantified.

CH₄ from Abandoned Coal Mines

Abandoned coal mines are a source of CH₄ emissions. In general, many of the same factors that affect emissions from operating coal mines will affect emissions from abandoned mines such as the permeability and gassiness of the coal, the mine's depth, geologic characteristics, and whether it has been flooded. A few gas developers have recovered methane from abandoned mine workings; therefore, emissions from this source may be

significant. Further research and methodological development is needed if these emissions are to be estimated. (See Coal Mining in the Energy chapter.)

CO₂ from “Unaccounted for” Natural Gas

There is a discrepancy between the amount of natural gas sold by producers and that reported as purchased by consumers. This discrepancy, known as “unaccounted for” or unmetered natural gas, was assumed to be the sum of leakage, measurement errors, data collection problems, undetected non-reporting, undetected over reporting, and undetected under reporting. Historically, the amount of gas sold by producers has always exceeded that reportedly purchased by consumers; therefore, some portion of unaccounted for natural gas was assumed to be a source of CO₂ emissions. In other words, it was assumed that consumers were underreporting their usage of natural gas. In DOE/EIA’s energy statistics for 1996, however, reported consumption of natural gas exceeded the amount sold by producers. Therefore, the historical explanation given for this discrepancy has lost credibility and unaccounted for natural gas is no longer used to calculate CO₂ emissions.

CO₂ from Shale Oil Production

Oil shale is shale saturated with kerogen.⁴ It can be thought of as the geological predecessor to crude oil. Carbon dioxide is released as a by-product of the process of producing petroleum products from shale oil. As of now, it is not cost-effective to mine and process shale oil into usable petroleum products. The only identified large-scale oil shale processing facility in the United States was operated by Unocal during the years 1985 to 1990. There have been no known emissions from shale oil processing in the United States since 1990 when the Unocal facility closed.

CH₄ from the Production of Carbides other than Silicon Carbide

Methane (CH₄) may be emitted from the production of carbides because the petroleum coke used in the process contains volatile organic compounds, which form CH₄ during thermal decomposition. Methane emissions from the production of silicon carbide were estimated and accounted for, but emissions from the production of calcium carbide and other carbides were not. Further research is needed to estimate CH₄ emissions from the production of calcium carbide and other carbides other than silicon carbide. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

CO₂ from Calcium Carbide and Silicon Carbide Production

Carbon dioxide is formed by the oxidation of petroleum coke in the production of both calcium carbide and silicon carbide. These CO₂ emissions are implicitly accounted for with emissions from the combustion of petroleum coke in the Energy chapter. There is currently not sufficient data on coke consumption to estimate emissions from these sources explicitly. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

CO₂ from Graphite Consumption in Ferroalloy and Steel Production

Emissions from "graphite" "wood" or "biomass" in calculating CO₂ emissions from ferroalloy production, iron and steel production or other "Industrial Processes" included in Chapter 3 of the inventory are not explicitly calculated. It is assumed that 100% of the carbon used in ferroalloy production is derived from petroleum coke and that all of the carbon used in iron and steel production is derived from coal coke or petroleum coke. It is possible that some non-coke carbon is used in the production of ferroalloys and iron and steel, but no data are available to conduct inventory calculations for sources of carbon other than petroleum coke and coal coke used in these processes.

⁴ Kerogen is fossilized insoluble organic material found in sedimentary rocks, usually shales, which can be converted to petroleum products by distillation.

Non-fuel uses of coal coke and petroleum coke are accounted for in the Industrial Process chapter, either directly for iron and steel, aluminum, ferroalloy, and titanium dioxide production, or indirectly by applying a storage factor to "uncharacterized" non-fuel uses of petroleum coke and coal coke.

Non-fuel uses of wood and biomass are not accounted for in the Energy or Industrial Process chapters, as all uses of wood and biomass are accounted for in the Land Use and Forestry chapter. It is assumed for the purposes of the CO₂ emission calculation that no wood or other biogenic carbon is used in any of these industrial processes. Some biogenic carbon may be used in these industrial processes but sufficient data to estimate emissions are not available.

Consumption of either natural or synthetic graphite is not explicitly accounted for in the Industrial Process chapter. It is assumed that all of the carbon used in manufacturing carbon anodes for production of aluminum, ferroalloys, and electric arc furnace (EAF) steel are derived directly from petroleum coke and coal tar pitch (a coal coke byproduct), not from natural graphite or synthetic graphite sources. Some amount of carbon used in these industrial processes may be derived from natural or synthetic graphite sources, but sufficient data to estimate emissions are not currently available.

CH₄ from Production of Iron and Steel

Iron and steel production is a source of CH₄ emissions. Coke and sinter are raw materials for the production of pig iron, and pig iron is a raw material for the production of steel. Coke is produced by heating coal in the absence of oxygen, which releases CH₄ as a byproduct. Coke, iron ore, and flux materials are then combined to form sinter. Coke is burned to produce heat, causing the sinter to agglomerate and releasing CH₄ as a byproduct. Coke and iron, in the form of ore, pellets, or sinter, are then added to flux materials in a blast furnace, and are reduced to pig iron and slag. Methane is a component of the exhaust gases from the blast furnace. The IPCC has published emission factors for methane emitted from the production of coke, sinter, and pig iron.

Methane emissions from iron and steel production are not included in this inventory. The Energy Information Administration estimates that CH₄ emissions from iron and steel production were 0.048 million metric tons of CH₄ in 2001.⁵ Methane emissions from iron and steel production will be investigated further to be incorporated in future inventories.

N₂O from Caprolactam Production

Caprolactam is a widely used chemical intermediate, primarily to produce nylon-6. All processes for producing caprolactam involve the catalytic oxidation of ammonia, with N₂O being produced as a by-product. Caprolactam production could be a significant source of N₂O—it has been identified as such in the Netherlands. More research is required to determine this source's significance because there is currently insufficient information available on caprolactam production to estimate emissions in the United States. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.22 - 2.23)

N₂O from Cracking of Certain Oil Fractions

In order to improve the gasoline yield in crude oil refining, certain oil fractions are processed in a catcracker. Because crude oil contains some nitrogen, N₂O emissions may result from this cracking process. There is currently insufficient data to develop a methodology for estimating these emissions. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

CH₄ from Coke Production

Coke production may result in CH₄ emissions. Detailed coke production statistics were not available for the purposes of estimating CH₄ emissions from this minor source. (See Petrochemical Production in the Industrial Processes chapter and the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

⁵ Energy Information Administration: Emissions of Greenhouse Gases in the United States, 2001, Page 43.

CO₂ from Metal Production

Coke is used as a reducing agent in the production of some metals from their ores, including magnesium, chromium, lead, nickel, silicon, tin, and zinc. Carbon dioxide may be emitted during the metal's production from the oxidization of this coke and, in some cases, from the carbonate ores themselves (e.g., some magnesium ores contain carbonate). The CO₂ emissions from the carbonate ores are not presently accounted for, but their quantities are thought to be minor. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.37 - 2.38)

N₂O from Acrylonitrile Production

Nitrous oxide may be emitted during acrylonitrile production. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.22)

SF₆ from Aluminum Fluxing and Degassing

Occasionally, sulfur hexafluoride (SF₆) is used by the aluminum industry as a fluxing and degassing agent in experimental and specialized casting operations. In these cases it is normally mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum; however, this practice is not used by primary aluminum production firms in the United States and is not believed to be extensively used by secondary casting firms. Where it does occur, the concentration of SF₆ in the mixture is small and a portion of the SF₆ is decomposed in the process (Waite and Bernard 1990, Corns 1990). It has been estimated that 230 Mg of SF₆ were used by the aluminum industry in the United States and Canada (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

SF₆ from Production/Leakage/Breakage of Soundproofed Double-glazed Windows

Sulfur hexafluoride (SF₆) may be emitted from the production, breakage, or leakage of soundproof double-glazed windows. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included.

SF₆ from Production/Leakage/Dismantling of Radar, Tracer and Night Vision Equipment

Sulfur hexafluoride (SF₆) may be emitted from the production, leakage, and dismantling of radar, tracer, and night vision equipment. Emissions from this source are believed to be minor, and no data were available for estimating the emissions.

SF₆ from Applications in Sports Shoes, Tires, and Tennis Balls

Sulfur hexafluoride (SF₆) may be emitted from application involving the production of sport shoes, tires, and tennis balls. These emissions are believed to be minor, and no data were available for estimating emissions.

SF₆ from Applications to Trace Leakage of Pressure Vessels and Used as a Tracer Gas in Open Air

Sulfur hexafluoride (SF₆) may be emitted from application involving tracer gasses to detect leakage from pressure vessels and as a tracer gas in the open air. Although emissions from this source are believed to be minor, emissions estimation data and methodologies were not available.

Miscellaneous SF₆ Uses

Sulfur hexafluoride may be used in foam insulation, for dry etching, in laser systems, for indoor air quality testing, for laboratory hood testing, for chromatography, in tandem accelerators, in loudspeakers, in shock absorbers, and for certain biomedical applications. Data need to be gathered and methodologies developed if these emissions are to be estimated. A preliminary global assessment of aggregate emissions from these applications can be found in Maiss, M. Brenninkmeijer, and C.A.M. Brenninkmeijer (1998).

CO₂ from Solvent Incineration

Carbon dioxide may be released during the incineration of solvents. Although emissions from this source are believed to be minor, data need to be gathered and methodologies developed if these emissions are to be estimated. Solvents are hazardous wastes, and emissions from solvent incineration were taken into account to estimate the carbon storage factor for hazardous waste incineration. However, sufficient data is not available to obtain a complete time series estimate for this source category. Further research is required for these potential emissions to be fully quantified.

N₂O from Domestic House Animal Waste Deposited on Soils

A substantial amount of liquid and solid waste is produced by domestic animals that are kept as pets. A preliminary methodology was developed to estimate nitrous oxide (N₂O) emissions from the deposition of domestic house animal (i.e., dogs and cats) waste on lawns, fields and parks. Estimates calculated with this methodology suggest that, in 1990, approximately 330 Gg of nitrogen originating as domestic house animal waste were deposited on soils resulting in approximately 2.9 Tg CO₂ Eq. of N₂O emissions from soils. To estimate the amount of nitrogen deposited by domestic house animals, only those excretions that remained on land surfaces—as opposed to wastes that were collected by owners and are managed as municipal solid waste—were included.

Annual dog and cat population numbers were obtained from the Pet Food Institute.⁶ Annual nitrogen excretion rates were estimated from protein intake. The recommended protein intake for an average size adult of each animal type⁷ was multiplied by the average amount of nitrogen per unit of protein (0.16 kg N/kg protein, from the *Revised 1996 IPCC Guidelines*) to estimate nitrogen consumption. It was then assumed that 95 percent of this nitrogen was excreted, either in solid or liquid form (i.e., it was assumed that 5 percent was retained for fur and milk production). Of the total nitrogen excretion, 90 percent was assumed to occur through liquid waste, with the balance from solid waste⁸. Both cat and dog populations were divided into urban and rural fractions, using the metropolitan and non-metropolitan human population categories, respectively, of the U.S. Census Bureau⁹. Both liquid and solid wastes from the urban cat population, and solid waste from the urban dog population were assumed to be collected (i.e., not deposited on soils). Nitrous oxide emission estimates from domestic house animal excretion were calculated in the same manner as performed for estimating emissions from livestock excretion. Producing these estimates involved making a number of simplifying assumptions regarding average animal size and protein consumption, as well as the proportions of animal populations residing in urban and rural areas and the proportions of wastes that are deposited on land. Further methodological development and data collection is required in order to reduce the uncertainty involved in the domestic house animal excretion estimates.

CO₂ from Food Scraps Disposed in Landfills

A certain amount of food scraps generated from food processing or as leftovers join the waste stream and are landfilled. Nationally, an estimated 0.4 Tg CO₂ Eq. per year are stored in the form of organic carbon contained in food scraps in landfills, acting as a carbon sink. A portion of the landfilled food scraps becomes a source of methane emissions, which offset the sink estimates to an extent. Further data collection on the amount and composition of food scraps generated and landfilled is required in order to reduce the uncertainty associated with this estimate.

CO₂ from Industrial Waste Combustion

Waste combustion is incorporated in two sections of the energy chapter of the inventory: in the section on CO₂ emissions from waste combustion, and in the calculation of emissions and storage from non-energy uses of

⁶ Pet Food Institute (1999) *Pet Incidence Trend Report*. Pet Food Institute, Washington DC.

⁷ Bright, S. (1999) Personal communication between Marco Alcaraz of ICF Consulting and Susan Bright of the Dupont Animal Clinic, Washington, DC, August 1999.

⁸ Swenson, M.J. and W.G. Reece, eds. (1993) *Duke's Physiology of Domestic Animals*. Cornell University Press. 11th Edition.

⁹ U.S. Census Bureau (1999) <<http://www.census.gov/population/estimates/metro-city/ma96-08.txt>>

fossil fuels. The former section addresses fossil-derived materials (such as plastics) that are discarded as part of the municipal wastestream and combusted (generally for energy recovery). The latter addresses two types of combustion: hazardous waste incineration of organic materials (assumed to be fossil-derived), in which regulated wastes are burned without energy recovery, and burning of fossil-derived materials for energy recovery. There is one potentially significant category of waste combustion that is not included in our calculus: industrial non-hazardous waste, burned for disposal (rather than energy recovery). Data are not readily available for this source; further research is needed to estimate the magnitude of CO₂ emissions.

CH₄ from Land-Use Changes Including Wetlands Creation or Destruction

Wetlands are a known source of methane (CH₄) emissions. When wetlands are destroyed, CH₄ emissions may be reduced. Conversely, when wetlands are created (e.g., during the construction of hydroelectric plants), CH₄ emissions may increase. Grasslands and forestlands may also be weak sinks for CH₄ due to the presence of methanotrophic bacteria that use CH₄ as an energy source (i.e., they oxidize CH₄ to CO₂). Currently, an adequate scientific basis for estimating these emissions and sinks does not exist, and therefore further research and methodological development is required.

N₂O from Wastewater Treatment and Biological Processes

As a result of nitrification and denitrification processes, nitrous oxide (N₂O) may be produced and emitted from large-scale composting, small scale composting (e.g. households), post-composting of anaerobic digested wastes, and both domestic and industrial wastewater treatment plants. Nitrogen-containing compounds are found in composted wastes and wastewater due to the presence of both human excrement and other nitrogen-containing constituents (e.g. garbage, industrial wastes, animal carcasses, etc.) The portion of emitted N₂O that originates from human excrement is currently estimated under the Human Sewage source category- based upon average dietary assumptions. The portion of emitted N₂O that originates from other nitrogen-containing constituents is not currently estimated. Further research and methodological development is needed if these emissions are to be accurately estimated.

CH₄ from Large and Small Scale Composting

Methane (CH₄) may be released through large and small scale (e.g. household) composting. Detailed composting data is necessary in order to estimate emissions but were not available.

CH₄ from Treatment of Dredging Sludge, Remediation of Groundwater, Intermediate Storage of Slaughter Waste, Production of Process Water from Groundwater, and Post Composting of Anaerobic Digested Wastes.

Methane (CH₄) may be released through the treatment of dredging sludge, remediation of groundwater, intermediate storage of slaughter waste, production of process water from groundwater, and post composting of anaerobic digested wastes. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included.

References

Census (2002) *Industrial Gases: 2001*. U.S. Census Bureau, Department of Commerce, Washington, DC. MQ325C(01)-5.

EIA (2002) *Emissions of Greenhouse Gases in the United States 2001*. Energy Information Administration, Office of Integrated Analysis and Forecasting. DOE-EIA-0573(2001).

EPA (2000) Toxics Release Inventory, 1998. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, DC. Available online at <<http://www.epa.gov/triexplorer/chemical.htm>>.

Freedonia Group, Inc. (2000) *Report 1091: Industrial Gases To 2003, Record 4, Carbon Dioxide Shipments and Production, 1989-2009*. Cleveland, OH.

ANNEX Y

Constants, Units, and Conversions

Metric Prefixes

Although most activity data for the United States is gathered in customary U.S. units, these units are converted into metric units per international reporting guidelines. The following table provides a guide for determining the magnitude of metric units.

Table Y-1: Guide to Metric Unit Prefixes

Prefix/Symbol	Factor
atto (a)	10^{-18}
femto (f)	10^{-15}
pico (p)	10^{-12}
nano (n)	10^{-9}
micro (μ)	10^{-6}
milli (m)	10^{-3}
centi (c)	10^{-2}
deci (d)	10^{-1}
deca (da)	10^0
hecto (h)	10^2
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9
tera (T)	10^{12}
peta (P)	10^{15}
exa (E)	10^{18}

Unit Conversions

1 kilogram = 2.205 pounds
1 pound = 0.454 kilograms
1 short ton = 2,000 pounds = 0.9072 metric tons
1 metric ton = 1,000 kilograms = 1.1023 short tons

1 cubic meter = 35.315 cubic feet
1 cubic foot = 0.02832 cubic meters
1 U.S. gallon = 3.785412 liters
1 barrel (bbl) = 0.159 cubic meters
1 barrel (bbl) = 42 U.S. gallons
1 liter = 0.1 cubic meters

1 foot = 0.3048 meters
1 meter = 3.28 feet
1 mile = 1.609 kilometers
1 kilometer = 0.622 miles

1 acre = 43,560 square feet = 0.4047 hectares = 4,047 square meters
1 square mile = 2.589988 square kilometers

To convert degrees Fahrenheit to degrees Celsius, subtract 32 and multiply by 5/9
To convert degrees Celsius to Kelvin, add 273.15 to the number of Celsius degrees

Density Conversions¹

Methane	1 cubic meter	=	0.67606 kilograms
Carbon dioxide	1 cubic meter	=	1.85387 kilograms

Natural gas liquids	1 metric ton	=	11.6 barrels	=	1,844.2 liters
Unfinished oils	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Alcohol	1 metric ton	=	7.94 barrels	=	1,262.36 liters
Liquefied petroleum gas	1 metric ton	=	11.6 barrels	=	1,844.2 liters
Aviation gasoline	1 metric ton	=	8.9 barrels	=	1,415.0 liters
Naphtha jet fuel	1 metric ton	=	8.27 barrels	=	1,314.82 liters
Kerosene jet fuel	1 metric ton	=	7.93 barrels	=	1,260.72 liters
Motor gasoline	1 metric ton	=	8.53 barrels	=	1,356.16 liters
Kerosene	1 metric ton	=	7.73 barrels	=	1,228.97 liters
Naphtha	1 metric ton	=	8.22 barrels	=	1,306.87 liters
Distillate	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Residual oil	1 metric ton	=	6.66 barrels	=	1,058.85 liters
Lubricants	1 metric ton	=	7.06 barrels	=	1,122.45 liters
Bitumen	1 metric ton	=	6.06 barrels	=	963.46 liters
Waxes	1 metric ton	=	7.87 barrels	=	1,251.23 liters
Petroleum coke	1 metric ton	=	5.51 barrels	=	876.02 liters
Petrochemical feedstocks	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Special naphtha	1 metric ton	=	8.53 barrels	=	1,356.16 liters
Miscellaneous products	1 metric ton	=	8.00 barrels	=	1,271.90 liters

Energy Conversions

Converting Various Energy Units to Joules

The common energy unit used in international reports of greenhouse gas emissions is the joule. A joule is the energy required to push with a force of one Newton for one meter. A terajoule (TJ) is one trillion (10^{12}) joules. A British thermal unit (Btu, the customary U.S. energy unit) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at or near 39.2 Fahrenheit.

	2.388×10 ¹¹ calories
1 TJ =	23.88 metric tons of crude oil equivalent
	947.8 million Btus
	277,800 kilowatt-hours

Converting Various Physical Units to Energy Units

Data on the production and consumption of fuels are first gathered in physical units. These units must be converted to their energy equivalents. The values in the following table of conversion factors can be used as default factors, if local data are not available. See Appendix A of EIA's *Annual Energy Review 1997* (EIA 1998) for more detailed information on the energy content of various fuels.

¹ Reference: EIA (1998a)

Table Y-2: Conversion Factors to Energy Units (Heat Equivalents)

Fuel Type (Units)	Factor
Solid Fuels (Million Btu/Short ton)	
Anthracite coal	22.573
Bituminous coal	23.89
Sub-bituminous coal	17.14
Lignite	12.866
Coke	24.8
Natural Gas (Btu/Cubic foot)	1,027
Liquid Fuels (Million Btu/Barrel)	
Crude oil	5.800
Natural gas liquids and LRGs	3.777
Other liquids	5.825
Motor gasoline	5.253
Aviation gasoline	5.048
Kerosene	5.670
Jet fuel, kerosene-type	5.670
Distillate fuel	5.825
Residual oil	6.287
Naphtha for petrochemicals	5.248
Petroleum coke	6.024
Other oil for petrochemicals	5.825
Special naphthas	5.248
Lubricants	6.065
Waxes	5.537
Asphalt	6.636
Still gas	6.000
Misc. products	5.796

Note: For petroleum and natural gas, *Annual Energy Review 1997* (EIA 1998b). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

References

EIA (1998a) *Emissions of Greenhouse Gases in the United States*, DOE/EIA-0573(97), Energy Information Administration, U.S. Department of Energy. Washington, DC. October.

EIA (1998b) *Annual Energy Review*, DOE/EIA-0384(97), Energy Information Administration, U.S. Department of Energy. Washington, DC. July.

EIA (1993) *State Energy Data Report 1992*, DOE/EIA-0214(93), Energy Information Administration, U.S. Department of Energy. Washington, DC. December.

ANNEX Z

Abbreviations

AAPFCO	American Association of Plant Food Control Officials
ABS	Acrylonitrile Butadiene Styrene
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFV	Alternative Fuel Vehicle
AGA	American Gas Association
AHEF	Atmospheric and Health Effect Framework
APC	American Plastics Council
API	American Petroleum Institute
ASAE	American Society of Agricultural Engineers
ASTM	American Society for Testing and Materials
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BoC	Bureau of Census
BOD ₅	Biochemical oxygen demand over a 5-day period
BRS	Biennial Reporting System
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAPP	Canadian Association of Petroleum Producers
CBI	Confidential Business Information
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CMA	Chemical Manufacturer's Association
CMOP	Coalbed Methane Outreach Program
CNG	Compressed Natural Gas
CRM	Crop Residue Management
CRP	Conservation Reserve Program
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
DE	Digestible Energy
DESC	Defense Energy Support Center-DoD's defense logistics agency
DFAMS	Defense Fuels Automated Management System
DIC	Dissolved inorganic carbon
DM	Dry Matter
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EAF	Electric Arc Furnace
EF	Emission Factor
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
GAA	Governmental Advisory Associates
GCV	Gross calorific value
GDP	Gross domestic product
Gg	Gigagram
GHG	Greenhouse gas

GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GWP	Global warming potential
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HFC	Hydrofluorocarbon
HFE	Hydrofluoroethers
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HTS	Harmonized Tariff Schedule
ICAO	International Civil Aviation Organization
IEA	International Energy Association
IFO	Intermediate Fuel Oil
IISRP	International Institute of Synthetic Rubber Products
ILENR	Illinois Department of Energy and Natural Resources
IMO	International Maritime Organization
IPAA	Independent Petroleum Association of America
IPCC	Intergovernmental Panel on Climate Change
LDDT	Light duty diesel truck
LDDV	Light duty diesel vehicle
LDGT	Light duty gas truck
LDGV	Light duty gas vehicle
LDPE	Low density polyethylene
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land use, land-use change, and forestry
MC	Motorcycle
MCF	Methane conversion factor
MGO	Marine Gas Oil
MLRA	Major Land Resource Area
MMCFD	Million Cubic Feet Per Day
MMS	Minerals Management Service
MMTCE	Million metric tons carbon equivalent
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MTBE	Methyl Tertiary Butyl Ether
NAHMS	National Animal Health Monitoring System
NAPAP	National Acid Precipitation and Assessment Program
NASS	USDA's National Agriculture Statistics Service
NCV	Net calorific value
NEV	Neighborhood Electric Vehicle
NGL	Natural Gas Liquids
NIAR	Norwegian Institute for Air Research
NMVOC	Non-methane volatile organic compound
NO _x	Nitrogen Oxides
NPRA	National Petroleum and Refiners Association
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NSCR	Non-selective catalytic reduction
NVFEL	National Vehicle Fuel Emissions Laboratory

NWS	National Weather Service
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone Depleting Potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
PAH	Polycyclic Aromatic Hydrocarbons
PDF	Probability Density Function
PET	Polyethylene Terephthalate
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
POTW	Publicly Owned Treatment Works
Ppbv	Parts per billion (10 ⁹) by volume
PPC	Precipitated calcium carbonate
Ppmv	Parts per million (10 ⁶) by volume
Pptv	Parts per trillion (10 ¹²) by volume
PS	Polystyrene
PSU	Primary Sample Unit
PVC	Polyvinyl chloride
QBtu	Quadrillion Btu
RCRA	Resource Conservation and Recovery Act
SAE	Society of Automotive Engineers
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SBSTA	Subsidiary Body for Scientific and Technical Advice
SCR	Selective catalytic reduction
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SOC	Soil Organic Carbon
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
TAME	Tertiary Amyl Methyl Ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total Digestible Nutrients
TgCO ₂ Eq	Teragrams carbon dioxide equivalent
TJ	Terajoule
TLEV	Traditional Low Emissions Vehicle
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TVA	Tennessee Valley Authority
U.S.	United States
UEP	United Egg Producers
ULEV	Ultra Low Emission Vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
VAIP	EPA's Voluntary Aluminum Industrial Partnership
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile Organic Compounds
VS	Volatile Solids
WIP	Waste In Place
WMO	World Meteorological Organization
ZEVs	Zero Emissions Vehicles

ANNEX AA

Chemical Formulas

Table AA-1: Guide to Chemical Formulas

Symbol	Name
Al	Aluminum
Al ₂ O ₃	Aluminum Oxide
Br	Bromine
C	Carbon
CH ₄	Methane
C ₂ H ₆	Ethane
C ₃ H ₈	Propane
CF ₄	Perfluoromethane
C ₂ F ₆	Perfluoroethane, hexafluoroethane
c-C ₃ F ₆	Perfluorocyclopropane
C ₃ F ₈	Perfluoropropane
c-C ₄ F ₈	Perfluorocyclobutane
C ₄ F ₁₀	Perfluorobutane
C ₅ F ₁₂	Perfluoropentane
C ₆ F ₁₄	Perfluorohexane
CF ₃ I	Trifluoroiodomethane
CFCl ₃	Trichlorofluoromethane (CFC-11)
CF ₂ Cl ₂	Dichlorodifluoromethane (CFC-12)
CF ₃ Cl	Chlorotrifluoromethane (CFC-13)
C ₂ F ₃ Cl ₃	Trichlorotrifluoroethane (CFC-113)*
CCl ₃ CF ₃	CFC-113a*
C ₂ F ₄ Cl ₂	Dichlorotetrafluoroethane (CFC-114)
C ₂ F ₅ Cl	Chloropentafluoroethane (CFC-115)
CHCl ₂ F	HCFC-21
CHF ₂ Cl	Chlorodifluoromethane (HCFC-22)
C ₂ F ₃ HCl ₂	HCFC-123
C ₂ F ₄ HCl	HCFC-124
C ₂ FH ₃ Cl ₂	HCFC-141b
C ₂ H ₃ F ₂ Cl	HCFC-142b
CF ₃ CF ₂ CHCl ₂	HCFC-225ca
CClF ₂ CF ₂ CHClF	HCFC-225cb
CCl ₄	Carbon tetrachloride
CHClCCl ₂	Trichloroethylene
CCl ₂ CCl ₂	Perchloroethylene, tetrachloroethene
CH ₃ Cl	Methylchloride
CH ₃ CCl ₃	Methylchloroform
CH ₂ Cl ₂	Methylenechloride
CHCl ₃	Chloroform, trichloromethane
CHF ₃	HFC-23
CH ₂ F ₂	HFC-32
CH ₃ F	HFC-41
C ₂ HF ₅	HFC-125
C ₂ H ₂ F ₄	HFC-134
CH ₂ FCF ₃	HFC-134a
C ₂ H ₃ F ₃	HFC-143*
C ₂ H ₃ F ₃	HFC-143a*
CH ₂ FCH ₂ F	HFC-152*
C ₂ H ₄ F ₂	HFC-152a*
CH ₃ CH ₂ F	HFC-161
C ₃ HF ₇	HFC-227ea
CF ₃ CF ₂ CH ₂ F	HFC-236cb
CF ₃ CHFCHF ₂	HFC-236ea

C ₃ H ₂ F ₆	HFC-236fa
C ₃ H ₃ F ₅	HFC-245ca
CHF ₂ CH ₂ CF ₃	HFC-245fa
CF ₃ CH ₂ CF ₂ CH ₃	HFC-365mfc
C ₅ H ₂ F ₁₀	HFC-43-10mee
CF ₃ OCHF ₂	HFE-125
CF ₂ HOCF ₂ H	HFE-134
CH ₃ OCF ₃	HFE-143a
CF ₃ CHFOCF ₃	HFE-227ea
CF ₃ CHClOCHF ₂	HCFE-235da2
CF ₃ CHFOCHF ₂	HFE-236ea2
CF ₃ CH ₂ OCF ₃	HFE-236fa
CF ₃ CF ₂ OCH ₃	HFE-245cb2
CHF ₂ CH ₂ OCF ₃	HFE-245fa1
CF ₃ CH ₂ OCHF ₂	HFE-245fa2
CHF ₂ CF ₂ OCH ₃	HFE-254cb2
CF ₃ CH ₂ OCH ₃	HFE-263fb2
CF ₃ CF ₂ OCF ₂ CHF ₂	HFE-329mcc2
CF ₃ CF ₂ OCH ₂ CF ₃	HFE-338mcf2
CF ₃ CF ₂ CF ₂ OCH ₃	HFE-347mcc3
CF ₃ CF ₂ OCH ₂ CHF ₂	HFE-347mcf2
CF ₃ CHFCF ₂ OCH ₃	HFE-356mec3
CHF ₂ CF ₂ CF ₂ OCH ₃	HFE-356pcc3
CHF ₂ CF ₂ OCH ₂ CHF ₂	HFE-356pcf2
CHF ₂ CF ₂ CH ₂ OCHF ₂	HFE-356pcf3
CF ₃ CF ₂ CH ₂ OCH ₃	HFE-365mcf3
CHF ₂ CF ₂ OCH ₂ CH ₃	HFE-374pcf2
C ₄ F ₉ OCH ₃	HFE-7100
C ₄ F ₉ OC ₂ H ₅	HFE-7200
CHF ₂ OCF ₂ OC ₂ F ₄ OCHF ₂	H-Galden 1040x
CHF ₂ OCF ₂ OCHF ₂	HG-10
CHF ₂ OCF ₂ CF ₂ OCHF ₂	HG-01
CH ₃ OCH ₃	Dimethyl ether
CH ₂ Br ₂	Dibromomethane
CH ₂ BrCl	Dibromochloromethane
CHBr ₃	Tribromomethane
CHBrF ₂	Bromodifluoromethane
CH ₃ Br	Methylbromide
CF ₂ BrCl	Bromodichloromethane (Halon 1211)
CF ₃ Br(CBrF ₃)	Bromotrifluoromethane (Halon 1301)
CF ₃ I	FIC-13I1
CO	Carbon monoxide
CO ₂	Carbon dioxide
CaCO ₃	Calcium carbonate, Limestone
CaMg(CO ₃) ₂	Dolomite
CaO	Calcium oxide, Lime
Cl	atomic Chlorine
F	Fluorine
Fe	Iron
Fe ₂ O ₃	Ferric oxide
FeSi	Ferrosilicon
H, H ₂	atomic Hydrogen, molecular Hydrogen
H ₂ O	Water
H ₂ O ₂	Hydrogen peroxide
OH	Hydroxyl
N, N ₂	atomic Nitrogen, molecular Nitrogen
NH ₃	Ammonia
NH ₄ ⁺	Ammonium ion
HNO ₃	Nitric Acid
NF ₃	Nitrogen trifluoride
N ₂ O	Nitrous oxide
NO	Nitric oxide

NO ₂	Nitrogen dioxide
NO ₃	Nitrate radical
Na	Sodium
Na ₂ CO ₃	Sodium carbonate, soda ash
Na ₃ AlF ₆	Synthetic cryolite
O, O ₂	atomic Oxygen, molecular Oxygen
O ₃	Ozone
S	atomic Sulfur
H ₂ SO ₄	Sulfuric acid
SF ₆	Sulfur hexafluoride
SF ₅ CF ₃	Trifluoromethylsulphur pentafluoride
SO ₂	Sulfur dioxide
Si	Silicon
SiC	Silicon carbide
SiO ₂	Quartz

* Distinct isomers.

ANNEX AB

Glossary

Abiotic.⁷ Nonliving. Compare *biotic*.

Absorption of radiation.¹ The uptake of radiation by a solid body, liquid or gas. The absorbed energy may be transferred or re-emitted.

Acid deposition.⁶ A complex chemical and atmospheric process whereby recombined emissions of sulfur and nitrogen compounds are redeposited on earth in wet or dry form. See *acid rain*.

Acid rain.⁶ Rainwater that has an acidity content greater than the postulated natural pH of about 5.6. It is formed when sulfur dioxides and nitrogen oxides, as gases or fine particles in the atmosphere, combine with water vapor and precipitate as sulfuric acid or nitric acid in rain, snow, or fog. The dry forms are acidic gases or particulates. See *acid deposition*.

Acid solution.⁷ Any water solution that has more hydrogen ions (H⁺) than hydroxide ions (OH⁻); any water solution with a pH less than 7. See *basic solution*, *neutral solution*.

Acidic.⁷ See acid solution.

Adiabatic process.⁹ A thermodynamic change of state of a system such that no heat or mass is transferred across the boundaries of the system. In an adiabatic process, expansion always results in cooling, and compression in warming.

Aerosol.^{1&9} Particulate matter, solid or liquid, larger than a molecule but small enough to remain suspended in the atmosphere. Natural sources include salt particles from sea spray and dust and clay particles as a result of weathering of rocks, both of which are carried upward by the wind. Aerosols can also originate as a result of human activities and are often considered pollutants. Aerosols are important in the atmosphere as nuclei for the condensation of water droplets and ice crystals, as participants in various chemical cycles, and as absorbers and scatterers of solar radiation, thereby influencing the radiation budget of the Earth's climate system. See *climate*, *particulate matter*.

Afforestation.² Planting of new forests on lands that have not been recently forested.

Air carrier⁸ An operator (e.g., airline) in the commercial system of air transportation consisting of aircraft that hold certificates of, Public Convenience and Necessity, issued by the Department of Transportation, to conduct scheduled or non-scheduled flights within the country or abroad.

Air pollutant. See *air pollution*.

Air pollution.⁷ One or more chemicals or substances in high enough concentrations in the air to harm humans, other animals, vegetation, or materials. Such chemicals or physical conditions (such as excess heat or noise) are called air pollutants.

Albedo.⁹ The fraction of the total solar radiation incident on a body that is reflected by it.

Alkalinity.⁶ Having the properties of a base with a pH of more than 7. A common alkaline is baking soda.

Alternative energy.⁶ Energy derived from nontraditional sources (e.g., compressed natural gas, solar, hydroelectric, wind).

Anaerobic.⁶ A life or process that occurs in, or is not destroyed by, the absence of oxygen.

Anaerobic decomposition.² The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon.² A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days. Bacteria produce methane in the absence of oxygen while breaking down waste.

Anaerobic organism.⁷ Organism that does not need oxygen to stay alive. See *aerobic organism*.

Antarctic “Ozone Hole.”⁶ Refers to the seasonal depletion of stratospheric ozone in a large area over Antarctica. See *ozone layer*.

Anthracite.² A hard, black, lustrous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Often referred to as hard coal.

Anthropogenic.² Human made. In the context of greenhouse gases, emissions that are produced as the result of human activities.

Arable land.⁷ Land that can be cultivated to grow crops.

Aromatic.⁶ Applied to a group of hydrocarbons and their derivatives characterized by the presence of the benzene ring.

Ash.⁶ The mineral content of a product remaining after complete combustion.

Asphalt.² A dark-brown-to-black cement-like material containing bitumen as the predominant constituent. It is obtained by petroleum processing. The definition includes crude asphalt as well as the following finished products: cements, fluxes, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalt.

Atmosphere.¹ The mixture of gases surrounding the Earth. The Earth's atmosphere consists of about 79.1 percent nitrogen (by volume), 20.9 percent oxygen, 0.036 percent carbon dioxide and trace amounts of other gases. The atmosphere can be divided into a number of layers according to its mixing or chemical characteristics, generally determined by its thermal properties (temperature). The layer nearest the Earth is the *troposphere*, which reaches up to an altitude of about 8 kilometers (about 5 miles) in the polar regions and up to 17 kilometers (nearly 11 miles) above the equator. The *stratosphere*, which reaches to an altitude of about 50 kilometers (31 miles) lies atop the troposphere. The *mesosphere*, which extends from 80 to 90 kilometers atop the stratosphere, and finally, the *thermosphere*, or *ionosphere*, gradually diminishes and forms a fuzzy border with outer space. There is relatively little mixing of gases between layers.

Atmospheric lifetime. See *lifetime*.

Atomic weight.⁶ The average weight (or mass) of all the isotopes of an element, as determined from the proportions in which they are present in a given element, compared with the mass of the 12 isotope of carbon (taken as precisely 12.000), that is the official international standard; measured in daltons.

Atoms.⁷ Minute particles that are the basic building blocks of all chemical elements and thus all matter.

Aviation Gasoline.⁸ All special grades of gasoline for use in aviation reciprocating engines, as given in the American Society for Testing and Materials (ASTM) specification D 910. Includes all refinery products within the gasoline range that are to be marketed straight or in blends as aviation gasoline without further processing (any refinery operation except mechanical blending). Also included are finished components in the gasoline range, which will be used for blending or compounding into aviation gasoline.

Bacteria.⁷ One-celled organisms. Many act as decomposers that break down dead organic matter into substances that dissolve in water and are used as nutrients by plants.

Barrel (bbl).⁶ A liquid-volume measure equal to 42 United States gallons at 60 degrees Fahrenheit; used in expressing quantities of petroleum-based products.

Basic solution.⁷ Water solution with more hydroxide ions (OH-) than hydrogen ions (H+); water solutions with pH greater than 7. See *acid solution*, *alkalinity*, *acid*.

Biodegradable.⁷ Material that can be broken down into simpler substances (elements and compounds) by bacteria or other decomposers. Paper and most organic wastes such as animal manure are biodegradable. See *nonbiodegradable*.

Biofuel.^{3&7} Gas or liquid fuel made from plant material (biomass). Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulfite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, other waste, and ethanol blended into motor gasoline.

Biogeochemical cycle.⁷ Natural processes that recycle nutrients in various chemical forms from the environment, to organisms, and then back to the environment. Examples are the carbon, oxygen, nitrogen, phosphorus, and hydrologic cycles.

Biological oxygen demand (BOD).⁷ Amount of dissolved oxygen needed by aerobic decomposers to break down the organic materials in a given volume of water at a certain temperature over a specified time period. See *BOD₅*.

Biomass.⁷ Total dry weight of all living organisms that can be supported at each trophic level in a food chain. Also, materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

Biomass energy.¹ Energy produced by combusting biomass materials such as wood. The carbon dioxide emitted from burning biomass will not increase total atmospheric carbon dioxide if this consumption is done on a sustainable basis (i.e., if in a given period of time, regrowth of biomass takes up as much carbon dioxide as is released from biomass combustion). Biomass energy is often suggested as a replacement for fossil fuel combustion.

Biosphere.^{2&7} The living and dead organisms found near the earth's surface in parts of the lithosphere, atmosphere, and hydrosphere. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Biotic.⁷ Living. Living organisms make up the biotic parts of ecosystems. See *abiotic*.

Bitumen.⁷ Goopy, black, high-sulfur, heavy oil extracted from tar sand and then upgraded to synthetic fuel oil. See *tar sand*.

Bituminous coal.² A dense, black, soft coal, often with well-defined bands of bright and dull material. The most common coal, with moisture content usually less than 20 percent. Used for generating electricity, making coke, and space heating.

BOD₅.² The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater. See *biological oxygen demand*.

British thermal unit (Btu).³ The quantity of heat required to raise the temperature of one pound of water one degree of Fahrenheit at or near 39.2 degrees Fahrenheit.

Bunker fuel.² Fuel supplied to ships and aircraft for international transportation, irrespective of the flag of the carrier, consisting primarily of residual and distillate fuel oil for ships and jet fuel for aircraft.

Capacity Factor.³ The ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full-power operation during the same period.

Carbon black.² An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

Carbon cycle.² All carbon reservoirs and exchanges of carbon from reservoir to reservoir by various chemical, physical, geological, and biological processes. Usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs, regions of the Earth in which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools, ranging in size from individual communities or ecosystems to the total of all living organisms (biota).

Carbon dioxide.² A colorless, odorless, non-poisonous gas that is a normal part of the ambient air. Carbon dioxide is a product of fossil fuel combustion. Although carbon dioxide does not directly impair human health, it is a greenhouse gas that traps terrestrial (i.e., infrared) radiation and contributes to the potential for global warming. See *global warming*.

Carbon dioxide equivalent (CO₂ Eq.).¹ A metric measure used to compare the emissions of the different greenhouse gases based upon their global warming potential (GWP). Greenhouse gas emissions in the United States are most commonly expressed as "teragrams of carbon dioxide equivalents" (Tg CO₂ Eq.). Global warming potentials are used to convert greenhouse gases to carbon dioxide equivalents. See *global warming potential, greenhouse gas*.

Carbon flux.⁹ The rate of exchange of carbon between pools (i.e., reservoirs).

Carbon intensity. The relative amount of carbon emitted per unit of energy or fuels consumed.

Carbon pool.⁹ The reservoir containing carbon as a principal element in the geochemical cycle.

Carbon sequestration.¹ The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon. Fossil fuels were at one time biomass and continue to store the carbon until burned. See *carbon sinks*.

Carbon sinks.¹ Carbon reservoirs and conditions that take-in and store more carbon (i.e., carbon sequestration) than they release. Carbon sinks can serve to partially offset greenhouse gas emissions. Forests and oceans are large carbon sinks. See *carbon sequestration*.

Carbon tetrachloride (CCl₄).¹¹ A compound consisting of one carbon atom and four chlorine atoms. It is an ozone depleting substance. Carbon tetrachloride was widely used as a raw material in many industrial applications, including the production of chlorofluorocarbons, and as a solvent. Solvent use was ended in the United States when it was discovered to be carcinogenic. See *ozone depleting substance*.

Chemical reaction.⁷ Interaction between chemicals in which there is a change in the chemical composition of the elements or compounds involved.

Chlorofluorocarbons (CFCs).⁷ Organic compounds made up of atoms of carbon, chlorine, and fluorine. An example is CFC-12 (CCl₂F₂), used as a refrigerant in refrigerators and air conditioners and as a foam blowing agent. Gaseous CFCs can deplete the ozone layer when they slowly rise into the stratosphere, are broken down by strong ultraviolet radiation, release chlorine atoms, and then react with ozone molecules. See *Ozone Depleting Substance*.

Climate.^{1&9} The average weather, usually taken over a 30 year time period, for a particular region and time period. Climate is not the same as weather, but rather, it is the average pattern of weather for a particular region. Weather describes the short-term state of the atmosphere. Climatic elements include precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost, and hail-storms, and other measures of the weather. See *weather*.

Climate change.¹ The term “climate change” is sometimes used to refer to all forms of climatic inconsistency, but because the Earth's climate is never static, the term is more properly used to imply a significant change from one climatic condition to another. In some cases, “climate change” has been used synonymously with the term, “global warming”; scientists however, tend to use the term in the wider sense to also include natural changes in climate. See *global warming, greenhouse effect, enhanced greenhouse effect, radiative forcing*.

Climate feedback.¹ An atmospheric, oceanic, terrestrial, or other process that is activated by direct climate change induced by changes in radiative forcing. Climate feedbacks may increase (positive feedback) or diminish (negative feedback) the magnitude of the direct climate change.

Climate lag.¹ The delay that occurs in climate change as a result of some factor that changes very slowly. For example, the effects of releasing more carbon dioxide into the atmosphere may not be known for some time because a large fraction is dissolved in the ocean and only released to the atmosphere many years later.

Climate sensitivity.¹ The equilibrium response of the climate to a change in radiative forcing; for example, a doubling of the carbon dioxide concentration. See *radiative forcing*.

Climate system (or Earth system).¹ The atmosphere, the oceans, the biosphere, the cryosphere, and the geosphere, together make up the climate system.

Coal.² A black or brownish black solid, combustible substance formed by the partial decomposition of vegetable matter without access to air. The rank of coal, which includes anthracite, bituminous coal, subbituminous coal, and lignite, is based on fixed carbon, volatile matter, and heating value. Coal rank indicates the progressive alteration, or coalification, from lignite to anthracite. See *anthracite, bituminous coal, subbituminous coal, lignite*.

Coal coke.² A hard, porous product made from baking bituminous coal in ovens at temperatures as high as 2,000 degrees Fahrenheit. It is used both as a fuel and as a reducing agent in smelting iron ore in a blast furnace.

Coal gasification.⁷ Conversion of solid coal to synthetic natural gas (SNG) or a gaseous mixture that can be burned as a fuel.

Coal liquefaction.⁷ Conversion of solid coal to a liquid fuel such as synthetic crude oil or methanol.

Coalbed methane.² Methane that is produced from coalbeds in the same manner as natural gas produced from other strata. Methane is the principal component of natural gas.

Co-control benefit.¹⁰ It is the additional benefit derived from an environmental policy that is designed to control one type of pollution, while reducing the emissions of other pollutants as well. For example, a policy to reduce carbon dioxide emissions might reduce the combustion of coal, but when coal combustion is reduced, so too are the emissions of particulates and sulfur dioxide.⁵ The benefits associated with reductions in emissions of particulates and sulfur dioxide are the co-control benefits of reductions in carbon dioxide.

Cogeneration.⁷ Production of two useful forms of energy such as high-temperature heat and electricity from the same process.

Combustion.² Chemical oxidation accompanied by the generation of light and heat.

Commercial End-Use Sector: Defined economically, consists of business establishments that are not engaged in transportation or in manufacturing or other types of industrial activities (e.g., agriculture, mining, or construction). Commercial establishments include hotels, motels, restaurants, wholesale businesses, retail stores, laundries, and other service enterprises; religious and nonprofit organizations; health, social, and educational institutions; and Federal, State, and local governments. Street lights, pumps, bridges, and public services are also included if the establishment operating them is considered commercial.

Compost.⁷ Partially decomposed organic plant and animal matter that can be used as a soil conditioner or fertilizer.

Composting.⁷ Partial breakdown of organic plant and animal matter by aerobic bacteria to produce a material that can be used as a soil conditioner or fertilizer. See *compost*.

Compound.⁷ Combination of two or more different chemical elements held together by chemical bonds. See *element*. See *inorganic compound*, *organic compound*.

Concentration.⁷ Amount of a chemical in a particular volume or weight of air, water, soil, or other medium. See *parts per billion*, *parts per million*.

Conference Of Parties (COP).¹⁰ The supreme body of the United Nations Framework Convention on Climate Change (UNFCCC). It comprises more than 170 nations that have ratified the Convention. Its first session was held in Berlin, Germany, in 1995 and is expected to continue meeting on a yearly basis. The COP's role is to promote and review the implementation of the Convention. It will periodically review existing commitments in light of the Convention's objective, new scientific findings, and the effectiveness of national climate change programs. See *United Nations Framework Convention on Climate Change*.

Conifer.⁷ See *coniferous trees*.

Coniferous trees.⁷ Cone-bearing trees, mostly evergreens, that have needle-shaped or scale-like leaves. They produce wood known commercially as softwood. See *deciduous trees*.

Cooling Degree Days: The number of degrees per day that the average daily temperature is above 65° Fahrenheit. The daily average temperature is the mean of the maximum and minimum temperatures for a 24 hour period. (See Degree Days)

Criteria pollutant.² A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime. In this report, emissions of the criteria pollutants CO, NO_x, NMVOCs, and SO₂ are reported because they are thought to be precursors to greenhouse gas formation.

Crop residue.² Organic residue remaining after the harvesting and processing of a crop.

Crop rotation.⁷ Planting the same field or areas of fields with different crops from year to year to reduce depletion of soil nutrients. A plant such as corn, tobacco, or cotton, which removes large amounts of nitrogen from the soil, is planted one year. The next year a legume such as soybeans, which add nitrogen to the soil, is planted.

Crude oil.² A mixture of hydrocarbons that exist in liquid phase in underground reservoirs and remain liquid at atmospheric pressure after passing through surface separating facilities. See *petroleum*.

Deciduous trees.⁷ Trees such as oaks and maples that lose their leaves during part of the year. See *coniferous trees*.

Decomposition.⁹ The breakdown of matter by bacteria and fungi. It changes the chemical composition and physical appearance of the materials.

Deforestation.¹ Those practices or processes that result in the conversion of forested lands for non-forest uses. This is often cited as one of the major causes of the enhanced greenhouse effect for two reasons: 1) the burning or decomposition of the wood releases carbon dioxide; and 2) trees that once removed carbon dioxide from the atmosphere in the process of photosynthesis are no longer present.

Degradable.⁷ See *biodegradable*.

Degree Days (Population Weighted): Heating or cooling degree days weighted by the population of the area in which the degree days are recorded. To compute State population-weighted degree days, each State is divided into from one to nine climatically homogeneous divisions, which are assigned weights based on the ratio of the population of the division to the total population of the State. Degree day readings for each division are multiplied by the corresponding population weight for each division and those products are then summed to arrive at the State population-weighted degree day value. To compute national population-weighted degree days, the Nation is divided into nine Census regions, each comprising from three to eight States, which are assigned weights based on the ratio of the population of the Nation. Degree day readings for each region are multiplied by the corresponding population weight for each region and those products are then summed to arrive at the national population-weighted degree day value. (See Heating Degree Days, Cooling Degree Days, and Degree Day Normals)

Degree Day Normals: Simple arithmetic averages of monthly or annual degree days over a long period of time (usually the 30 year period of 1961 through 1990). The averages may be simple degree day normals or population-weighted degree day normals.

Desertification.¹ The progressive destruction or degradation of existing vegetative cover to form a desert. This can occur due to overgrazing, deforestation, drought, and the burning of extensive areas. Once formed, deserts can only support a sparse range of vegetation. Climatic effects associated with this phenomenon include increased reflectivity of solar radiation, reduced atmospheric humidity, and greater atmospheric dust (aerosol) loading.

Distillate fuel oil.² A general classification for the petroleum fractions produced in conventional distillation operations. Included are products known as No. 1, No. 2, and No. 4 fuel oils and No. 1, No. 2, and No. 4 diesel fuels. Used primarily for space heating, on and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation.

Economy.⁷ System of production, distribution, and consumption of economic goods.

Ecosystem.¹⁰ The complex system of plant, animal, fungal, and microorganism communities and their associated non-living environment interacting as an ecological unit. Ecosystems have no fixed boundaries; instead their parameters are set to the scientific, management, or policy question being examined. Depending upon the purpose of analysis, a single lake, a watershed, or an entire region could be considered an ecosystem.

Electric Utility Sector: Privately and publicly owned establishments that generate, transmit, distribute, or sell electricity primarily for use by the public and meet the definition of an electric utility. Electric utilities include investor-owned, publicly owned, cooperative, and Federal utilities. Historically, they have generally been vertically integrated companies that provide for generation, transmission, distribution, and/or energy services for all customers in a designated service territory. Nonutility power producers are not included in the electric utility sector.

Electrons.⁷ Tiny particle moving around outside the nucleus of an atom. Each electron has one unit of negative charge (-) and almost no mass.

Element.⁷ Chemicals such as hydrogen (H), iron (Fe), sodium (Na), carbon (C), nitrogen (N), or oxygen (O), whose distinctly different atoms serve as the basic building blocks of all matter. There are 92 naturally

occurring elements. Another 15 have been made in laboratories. Two or more elements combine to form compounds that make up most of the world's matter. See *compound*.

Emission inventory. A list of air pollutants emitted into a community's, state's, nation's, or the Earth's atmosphere in amounts per some unit time (e.g. day or year) by type of source. An emission inventory has both political and scientific applications.

Emissions coefficient/factor.² A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., grams of carbon dioxide emitted per barrel of fossil fuel consumed).

Emissions.² Releases of gases to the atmosphere (e.g., the release of carbon dioxide during fuel combustion). Emissions can be either intended or unintended releases. See *fugitive emissions*.

Energy conservation.⁷ Reduction or elimination of unnecessary energy use and waste. See *energy-efficiency*.

Energy intensity.⁵ Ratio between the consumption of energy to a given quantity of output; usually refers to the amount of primary or final energy consumed per unit of gross domestic product.

Energy quality.⁷ Ability of a form of energy to do useful work. High-temperature heat and the chemical energy in fossil fuels and nuclear fuels are concentrated high quality energy. Low-quality energy such as low-temperature heat is dispersed or diluted and cannot do much useful work.

Energy.³ The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. In the United States, electrical energy is often measured in kilowatt-hours (kWh), while heat energy is often measured in British thermal units (Btu).

Energy-efficiency.^{6&8} The ratio of the useful output of services from an article of industrial equipment to the energy use by such an article; for example, vehicle miles traveled per gallon of fuel (mpg).

Enhanced greenhouse effect.¹ The concept that the natural greenhouse effect has been enhanced by anthropogenic emissions of greenhouse gases. Increased concentrations of carbon dioxide, methane, and nitrous oxide, CFCs, HFCs, PFCs, SF₆, NF₃, and other photochemically important gases caused by human activities such as fossil fuel consumption, trap more infra-red radiation, thereby exerting a warming influence on the climate. See *greenhouse gas, anthropogenic, greenhouse effect, climate*.

Enhanced oil recovery.⁷ Removal of some of the heavy oil left in an oil well after primary and secondary recovery. See *primary oil recovery, secondary oil recovery*.

Enteric fermentation.² A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Environment.⁷ All external conditions that affect an organism or other specified system during its lifetime.

Ethanol (C₂H₅OH).⁸ Otherwise known as ethyl alcohol, alcohol, or grain spirit. A clear, colorless, flammable oxygenated hydrocarbon with a boiling point of 78.5 degrees Celsius in the anhydrous state. In transportation, ethanol is used as a vehicle fuel by itself (E100), blended with gasoline (E85), or as a gasoline octane enhancer and oxygenate (10 percent concentration).

Evapotranspiration.¹⁰ The loss of water from the soil by evaporation and by transpiration from the plants growing in the soil, which rises with air temperature.

Exponential growth.⁷ Growth in which some quantity, such as population size, increases by a constant percentage of the whole during each year or other time period; when the increase in quantity over time is plotted, this type of growth yields a curve shaped like the letter J.

Feedlot.⁷ Confined outdoor or indoor space used to raise hundreds to thousands of domesticated livestock. See *rangeland*.

Fertilization, carbon dioxide.¹ An expression (sometimes reduced to 'fertilization') used to denote increased plant growth due to a higher carbon dioxide concentration.

Fertilizer.⁷ Substance that adds inorganic or organic plant nutrients to soil and improves its ability to grow crops, trees, or other vegetation. See *organic fertilizer*.

Flaring.⁹ The burning of waste gases through a flare stack or other device before releasing them to the air.

Fluidized bed combustion (FBC).⁷ Process for burning coal more efficiently, cleanly, and cheaply. A stream of hot air is used to suspend a mixture of powdered coal and limestone during combustion. About 90 to 98 percent of the sulfur dioxide produced during combustion is removed by reaction with limestone to produce solid calcium sulfate.

Fluorocarbons.¹ Carbon-fluorine compounds that often contain other elements such as hydrogen, chlorine, or bromine. Common fluorocarbons include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). See *chlorofluorocarbons*, *hydrochlorofluorocarbons*, *hydrofluorocarbons*, *perfluorocarbons*.

Forcing mechanism.¹ A process that alters the energy balance of the climate system (i.e., changes the relative balance between incoming solar radiation and outgoing infrared radiation from Earth). Such mechanisms include changes in solar irradiance, volcanic eruptions, and enhancement of the natural greenhouse effect by emission of carbon dioxide.

Forest.⁷ Terrestrial ecosystem (biome) with enough average annual precipitation (at least 76 centimeters or 30 inches) to support growth of various species of trees and smaller forms of vegetation.

Fossil fuel. A general term for buried combustible geologic deposits of organic materials, formed from decayed plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years. See *coal*, *petroleum*, *crude oil*, *natural gas*.

Fossil fuel combustion.¹ Burning of coal, oil (including gasoline), or natural gas. The burning needed to generate energy release carbon dioxide by-products that can include unburned hydrocarbons, methane, and carbon monoxide. Carbon monoxide, methane, and many of the unburned hydrocarbons slowly oxidize into carbon dioxide in the atmosphere. Common sources of fossil fuel combustion include cars and electric utilities.

Freon. See chlorofluorocarbon.

Fugitive emissions.² Unintended gas leaks from the production processing, transmission, and/or transportation of fossil fuels, CFCs from refrigeration leaks, SF₆ from electrical power distributor, etc.

Gasohol.⁷ Vehicle fuel consisting of a mixture of gasoline and ethyl or methyl alcohol; typically 10 to 23 percent ethanol by volume.

General Aviation.⁸ That portion of civil aviation, which encompasses all facets of aviation except air carriers. It includes any air taxis, commuter air carriers, and air travel clubs, which do not hold Certificates of Public Convenience and Necessity. See *air carriers*.

General circulation model (GCM).¹ A global, three-dimensional computer model of the climate system which can be used to simulate human-induced climate change. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface.

Geosphere.¹ The soils, sediments, and rock layers of the Earth's crust, both continental and beneath the ocean floors.

Geothermal energy.⁷ Heat transferred from the earth's molten core to under-ground deposits of dry steam (steam with no water droplets), wet steam (a mixture of steam and water droplets), hot water, or rocks lying fairly close to the earth's surface.

Global Warming Potential (GWP).¹ The index used to translate the level of emissions of various gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a period of time (usually 100 years). Gases involved in complex atmospheric chemical processes have not been assigned GWPs. See *lifetime*.

Global warming.¹⁰ The progressive gradual rise of the earth's surface temperature thought to be caused by the greenhouse effect and responsible for changes in global climate patterns. See *enhanced greenhouse effect, greenhouse effect, climate change*.

Grassland.⁷ Terrestrial ecosystem (biome) found in regions where moderate annual average precipitation (25 to 76 centimeters or 10 to 30 inches) is enough to support the growth of grass and small plants but not enough to support large stands of trees.

Greenhouse effect.⁷ Trapping and build-up of heat in the atmosphere (troposphere) near the earth's surface. Some of the heat flowing back toward space from the earth's surface is absorbed by water vapor, carbon dioxide, ozone, and several other gases in the atmosphere and then reradiated back toward the earth's surface. If the atmospheric concentrations of these greenhouse gases rise, the average temperature of the lower atmosphere will gradually increase. See *enhanced greenhouse effect, climate change, global warming*.

Greenhouse gas (GHG).¹ Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include, but are not limited to, water vapor, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrochlorofluorocarbons (HCFCs), ozone (O₃), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). See *carbon dioxide, methane, nitrous oxide, hydrochlorofluorocarbon, ozone, hydrofluorocarbon, perfluorocarbon, sulfur hexafluoride*.

Halocarbons.¹ Chemicals consisting of carbon, sometimes hydrogen, and either chlorine, fluorine, bromine or iodine.

Halons.¹ Compounds, also known as bromofluorocarbons, that contain bromine, fluorine, and carbon. They are generally used as fire extinguishing agents and cause ozone depletion. Bromine is many times more effective at destroying stratospheric ozone than chlorine. See *ozone depleting substance*.

Heat.⁷ Form of kinetic energy that flows from one body to another when there is a temperature difference between the two bodies. Heat always flows spontaneously from a hot sample of matter to a colder sample of matter. This is one way to state the second law of thermodynamics. See *temperature*.

Heat content.⁵ The amount of heat per unit mass released upon complete combustion.

Heating Degree Days: The number of degrees per day that the average daily temperature is below 65° Fahrenheit. The daily average temperature is the mean of the maximum and minimum temperatures for a 24 hour period. (See Degree Days)

Higher heating value.⁵ Quantity of heat liberated by the complete combustion of a unit volume or weight of a fuel assuming that the produced water vapor is completely condensed and the heat is recovered; also known as gross calorific value. See *lower heating value*.

Histosol.⁹ Wet organic soils, such as peats and mucks.

Hydrocarbons.¹ Substances containing only hydrogen and carbon. Fossil fuels are made up of hydrocarbons. Some hydrocarbon compounds are major air pollutants.

Hydrochlorofluorocarbons (HCFCs).¹ Compounds containing hydrogen, fluorine, chlorine, and carbon atoms. Although ozone depleting substances, they are less potent at destroying stratospheric ozone than chlorofluorocarbons (CFCs). They have been introduced as temporary replacements for CFCs and are also greenhouse gases. See *ozone depleting substance*.

Hydroelectric power plant.⁷ Structure in which the energy of fading or flowing water spins a turbine generator to produce electricity.

Hydrofluorocarbons (HFCs).¹ Compounds containing only hydrogen, fluorine, and carbon atoms. They were introduced as alternatives to ozone depleting substances in serving many industrial, commercial, and personal needs. HFCs are emitted as by-products of industrial processes and are also used in manufacturing. They do not significantly deplete the stratospheric ozone layer, but they are powerful greenhouse gases with global warming potentials ranging from 140 (HFC-152a) to 11,700 (HFC-23).

Hydrologic cycle. The process of evaporation, vertical and horizontal transport of vapor, condensation, precipitation, and the flow of water from continents to oceans. It is a major factor in determining climate

through its influence on surface vegetation, the clouds, snow and ice, and soil moisture. The hydrologic cycle is responsible for 25 to 30 percent of the mid-latitudes' heat transport from the equatorial to polar regions.

Hydropower.⁷ Electrical energy produced by falling or flowing water. See *hydroelectric power plant*.

Hydrosphere.⁷ All the earth's liquid water (oceans, smaller bodies of fresh water, and underground aquifers), frozen water (polar ice caps, floating ice, and frozen upper layer of soil known as permafrost), and small amounts of water vapor in the atmosphere.

Industrial End-Use Sector: Comprises manufacturing industries, which make up the largest part of the sector, along with mining, construction, agriculture, fisheries, and forestry. Establishments in this sector range from steel mills to small farms to companies assembling electronic components. Nonutility power producers are also included in the industrial end-use sector.

Infrared radiation.¹ The heat energy that is emitted from all solids, liquids, and gases. In the context of the greenhouse issue, the term refers to the heat energy emitted by the Earth's surface and its atmosphere. Greenhouse gases strongly absorb this radiation in the Earth's atmosphere, and re-radiate some of it back towards the surface, creating the greenhouse effect.

Inorganic compound.⁷ Combination of two or more elements, neither of which is carbon. See *organic compound*.

Inorganic fertilizer.⁷ See *synthetic fertilizer*.

Intergovernmental Panel on Climate Change (IPCC).¹ The IPCC was established jointly by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of climate change. The IPCC draws upon hundreds of the world's expert scientists as authors and thousands as expert reviewers. Leading experts on climate change and environmental, social, and economic sciences from some 60 nations have helped the IPCC to prepare periodic assessments of the scientific underpinnings for understanding global climate change and its consequences. With its capacity for reporting on climate change, its consequences, and the viability of adaptation and mitigation measures, the IPCC is also looked to as the official advisory body to the world's governments on the state of the science of the climate change issue. For example, the IPCC organized the development of internationally accepted methods for conducting national greenhouse gas emission inventories.

Irreversibilities.¹⁰ Changes that, once set in motion, cannot be reversed, at least on human time scales.

Jet fuel⁸ Includes both naphtha-type and kerosene-type fuels meeting standards for use in aircraft turbine engines. Although most jet fuel is used in aircraft, some is used for other purposes such as generating electricity.

Joule.¹ The energy required to push with a force of one Newton for one meter.

Kerogen.⁷ Solid, waxy mixture of hydrocarbons found in oil shale, with a fine grained sedimentary rock. When the rock is heated to high temperatures, the kerogen is vaporized. The vapor is condensed and then sent to a refinery to produce gasoline, heating oil, and other products. See *oil shale, shale oil*.

Kerosene.² A petroleum distillate that has a maximum distillation temperature of 401 degrees Fahrenheit at the 10 percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Used in space heaters, cookstoves, and water heaters, and suitable for use as an illuminant when burned in wick lamps.

Kyoto Protocol.¹⁰ This is an international agreement struck by 159 nations attending the Third Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (held in December of 1997 in Kyoto, Japan) to reduce worldwide emissions of greenhouse gases. If ratified and put into force, individual countries have committed to reduce their greenhouse gas emissions by a specified amount. See *Framework Convention on Climate Change, Conference of Parties*.

Landfill.⁷ Land waste disposal site in which waste is generally spread in thin layers, compacted, and covered with a fresh layer of soil each day.

Lifetime (atmospheric).¹ The lifetime of a greenhouse gas refers to the approximate amount of time it would take for the anthropogenic increment to an atmospheric pollutant concentration to return to its natural level (assuming emissions cease) as a result of either being converted to another chemical compound or being taken

out of the atmosphere via a sink. This time depends on the pollutant's sources and sinks as well as its reactivity. The lifetime of a pollutant is often considered in conjunction with the mixing of pollutants in the atmosphere; a long lifetime will allow the pollutant to mix throughout the atmosphere. Average lifetimes can vary from about a week (e.g., sulfate aerosols) to more than a century (e.g., CFCs, carbon dioxide). See *residence time*.

Light-duty vehicles.⁸ Automobiles and light trucks combined.

Lignite.² A brownish-black coal of low rank with high inherent moisture and volatile matter content, used almost exclusively for electric power generation. Also referred to as brown coal.

Liquefied natural gas (LNG).⁷ Natural gas converted to liquid form by cooling to a very low temperature.

Liquefied petroleum gas (LPG).² Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Litter.⁹ Undecomposed plant residues on the soil surface. See *decomposition*.

Longwave radiation.⁹ The radiation emitted in the spectral wavelength greater than 4 micrometers corresponding to the radiation emitted from the Earth and atmosphere. It is sometimes referred to as terrestrial radiation or infrared radiation, although somewhat imprecisely. See *infrared radiation*.

Low Emission Vehicle (LEV).⁸ A vehicle meeting the low-emission vehicle standards.

Lower heating value.⁵ Quantity of heat liberated by the complete combustion of a unit volume or weight of a fuel assuming that the produced water remains as a vapor and the heat of the vapor is not recovered; also known as net calorific value. See *higher heating value*.

Lubricant.² A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not include by-products of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

Manure.⁷ Dung and urine of animals that can be used as a form of organic fertilizer.

Mass balance.⁹ The application of the principle of the conservation of matter.

Mauna Loa.⁹ An intermittently active volcano 13,680 feet (4,170 meters) high in Hawaii.

Methane (CH₄).¹ A hydrocarbon that is a greenhouse gas with a global warming potential most recently estimated at 21. Methane is produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and petroleum, coal production, and incomplete fossil fuel combustion. The atmospheric concentration of methane has been shown to be increasing at a rate of about 0.6 percent per year and the concentration of about 1.7 per million by volume (ppmv) is more than twice its pre-industrial value. However, the rate of increase of methane in the atmosphere may be stabilizing.

Methanol (CH₃OH).⁸ A colorless poisonous liquid with essentially no odor and little taste. It is the simplest alcohol with a boiling point of 64.7 degrees Celsius. In transportation, methanol is used as a vehicle fuel by itself (M100), or blended with gasoline (M85).

Methanotrophic.⁷ Having the biological capacity to oxidize methane to CO₂ and water by metabolism under aerobic conditions. See *aerobic*.

Methyl bromide (CH₃Br).¹¹ An effective pesticide; used to fumigate soil and many agricultural products. Because it contains bromine, it depletes stratospheric ozone when released to the atmosphere. See *ozone depleting substance*.

Metric ton.¹ Common international measurement for the quantity of greenhouse gas emissions. A metric ton is equal to 1000 kilograms, 2204.6 pounds, or 1.1023 short tons.

Mineral.⁷ Any naturally occurring inorganic substance found in the earth's crust as a crystalline solid.

Model year. ⁸ Refers to the “sales” model year; for example, vehicles sold during the period from October 1 to the next September 31 is considered one model year.

Molecule. ⁷ Chemical combination of two or more atoms of the same chemical element (such as O₂) or different chemical elements (such as H₂O).

Montreal Protocol on Substances that Deplete the Ozone Layer. ¹¹ The Montreal Protocol and its amendments control the phaseout of ozone depleting substances production and use. Under the Protocol, several international organizations report on the science of ozone depletion, implement projects to help move away from ozone depleting substances, and provide a forum for policy discussions. In the United States, the Protocol is implemented under the rubric of the Clean Air Act Amendments of 1990. See *ozone depleting substance*, *ozone layer*.

Motor gasoline. ² A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, obtained by blending appropriate refinery streams to form a fuel suitable for use in spark-ignition engines. Motor gasoline includes both leaded and unleaded grades of finished gasoline, blending components, and gasohol.

Municipal solid waste (MSW). ² Residential solid waste and some non-hazardous commercial, institutional, and industrial wastes. This material is generally sent to municipal landfills for disposal. See *landfill*.

Naphtha. ² A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400 degrees Fahrenheit.

Natural gas. ⁷ Underground deposits of gases consisting of 50 to 90 percent methane (CH₄) and small amounts of heavier gaseous hydrocarbon compounds such as propane (C₃H₈) and butane (C₄H₁₀).

Natural gas liquids (NGLs). ² Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Nitrogen cycle. ⁷ Cyclic movement of nitrogen in different chemical forms from the environment, to organisms, and then back to the environment.

Nitrogen fixation. ⁷ Conversion of atmospheric nitrogen gas into forms useful to plants and other organisms by lightning, bacteria, and blue-green algae; it is part of the nitrogen cycle.

Nitrogen oxides (NO_x). ¹ Gases consisting of one molecule of nitrogen and varying numbers of oxygen molecules. Nitrogen oxides are produced, for example, by the combustion of fossil fuels in vehicles and electric power plants. In the atmosphere, nitrogen oxides can contribute to formation of photochemical ozone (smog), impair visibility, and have health consequences; they are considered pollutants.

Nitrous oxide (N₂O). ¹ A powerful greenhouse gas with a global warming potential most recently evaluated at 310. Major sources of nitrous oxide include soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning.

Nonbiodegradable. ⁷ Substance that cannot be broken down in the environment by natural processes. See *biodegradable*.

Nonlinearities. ¹⁰ Occur when changes in one variable cause a more than proportionate impact on another variable.

Non-methane volatile organic compounds (NMVOCs). ² Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Non-point source. ⁷ Large land area such as crop fields and urban areas that discharge pollutant into surface and underground water over a large area. See *point source*.

Nonutility Power Producer: A corporation, person, agency, authority, or other legal entity of instrumentality that owns electric generating capacity and is not an electric utility. Nonutility producers include qualifying cogenerators, qualifying small power producers, and other nonutility generators (including independent power producers) without a designated, franchised, service area that do not file forms listed in the Code of Federal Regulations, Title 18, Part 141.

Nuclear electric power. ³ Electricity generated by an electric power plant whose turbines are driven by steam generated in a reactor by heat from the fissioning of nuclear fuel.

Nuclear energy.⁷ Energy released when atomic nuclei undergo a nuclear reaction such as the spontaneous emission of radioactivity, nuclear fission, or nuclear fusion.

Oil shale.⁷ Underground formation of a fine-grained sedimentary rock containing varying amounts of kerogen, a solid, waxy mixture of hydrocarbon compounds. Heating the rock to high temperatures converts the kerogen to a vapor, which can be condensed to form a slow flowing heavy oil called shale oil. See *kerogen, shale oil*.

Oil. See crude oil, petroleum.

Ore.⁷ Mineral deposit containing a high enough concentration of at least one metallic element to permit the metal to be extracted and sold at a profit.

Organic compound.⁷ Molecule that contains atoms of the element carbon, usually combined with itself and with atoms of one or more other element such as hydrogen, oxygen, nitrogen, sulfur, phosphorus, chlorine, or fluorine. See *inorganic compound*.

Organic fertilizer.⁷ Organic material such as manure or compost, applied to cropland as a source of plant nutrients.

Oxidize.² To chemically transform a substance by combining it with oxygen.

Oxygen cycle.⁷ Cyclic movement of oxygen in different chemical forms from the environment, to organisms, and then back to the environment.

Ozone.⁶ A colorless gas with a pungent odor, having the molecular form of O₃, found in two layers of the atmosphere, the stratosphere and the troposphere. Ozone is a form of oxygen found naturally in the stratosphere that provides a protective layer shielding the Earth from ultraviolet radiation's harmful health effects on humans and the environment. In the troposphere, ozone is a chemical oxidant and major component of photochemical smog. Ozone can seriously affect the human respiratory system.

Ozone Depleting Substance (ODS).¹¹ A family of man-made compounds that includes, but are not limited to, chlorofluorocarbons (CFCs), bromofluorocarbons (halons), methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These compounds have been shown to deplete stratospheric ozone, and therefore are typically referred to as ODSs.

Ozone layer.⁷ Layer of gaseous ozone (O₃) in the stratosphere that protects life on earth by filtering out harmful ultraviolet radiation from the sun. See *stratosphere, ultraviolet radiation*.

Ozone precursors.² Chemical compounds, such as carbon monoxide, methane, non-methane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone, mainly in the troposphere. See *troposphere*

Particulate matter (PM).⁷ Solid particles or liquid droplets suspended or carried in the air.

Particulates. See *particulate matter*.

Parts per billion (ppb).⁷ Number of parts of a chemical found in one billion parts of a particular gas, liquid, or solid mixture. See *concentration*.

Parts per million (ppm).⁷ Number of parts of a chemical found in one million parts of a particular gas, liquid, or solid. See *concentration*.

Pentanes plus.² A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.

Perfluorocarbons (PFCs).¹ A group of human-made chemicals composed of carbon and fluorine only. These chemicals (predominantly CF₄ and C₂F₆) were introduced as alternatives, along with hydrofluorocarbons, to the ozone depleting substances. In addition, PFCs are emitted as by-products of industrial processes and are also used in manufacturing. PFCs do not harm the stratospheric ozone layer, but they are powerful greenhouse gases: CF₄ has a global warming potential (GWP) of 6,500 and C₂F₆ has a GWP of 9,200.

Petrochemical feedstock.² Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphtha (endpoint less than 401 degrees Fahrenheit) and other oils (endpoint equal to or greater than 401 degrees Fahrenheit).

Petrochemicals.⁷ Chemicals obtained by refining (i.e., distilling) crude oil. They are used as raw materials in the manufacture of most industrial chemicals, fertilizers, pesticides, plastics, synthetic fibers, paints, medicines, and many other products. See *crude oil*.

Petroleum coke.² A residue that is the final product of the condensation process in cracking.

Petroleum.² A generic term applied to oil and oil products in all forms, such as crude oil, lease condensate, unfinished oils, petroleum products, natural gas plant liquids, and non-hydrocarbon compounds blended into finished petroleum products. See *crude oil*.

Photosynthesis.⁷ Complex process that takes place in living green plant cells. Radiant energy from the sun is used to combine carbon dioxide (CO₂) and water (H₂O) to produce oxygen (O₂) and simple nutrient molecules, such as glucose (C₆H₁₂O₆).

Photovoltaic and solar thermal energy.² Energy radiated by the sun as electromagnetic waves (electromagnetic radiation) that is converted into electricity by means of solar (i.e., photovoltaic) cells or useable heat by concentrating (i.e., focusing) collectors.

Point source.⁷ A single identifiable source that discharges pollutants into the environment. Examples are smokestack, sewer, ditch, or pipe. See *non-point source*.

Pollution.⁷ A change in the physical, chemical, or biological characteristics of the air, water, or soil that can affect the health, survival, or activities of humans in an unwanted way. Some expand the term to include harmful effects on all forms of life.

Polyvinyl chloride (PVC).² A polymer of vinyl chloride. It is tasteless, odorless and insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Population.⁷ Group of individual organisms of the same species living within a particular area.

Prescribed burning.⁷ Deliberate setting and careful control of surface fires in forests to help prevent more destructive fires and to kill off unwanted plants that compete with commercial species for plant nutrients; may also be used on grasslands.

Primary oil recovery.⁷ Pumping out the crude oil that flows by gravity into the bottom of an oil well. See *enhanced oil recovery*, *secondary oil recovery*.

Quad.⁸ Quad stands for quadrillion, which is, 10¹⁵.

Radiation.¹ Energy emitted in the form of electromagnetic waves. Radiation has differing characteristics depending upon the wavelength. Because the radiation from the Sun is relatively energetic, it has a short wavelength (e.g., ultraviolet, visible, and near infrared) while energy re-radiated from the Earth's surface and the atmosphere has a longer wavelength (e.g., infrared radiation) because the Earth is cooler than the Sun. See *ultraviolet radiation*, *infrared radiation*, *solar radiation*, *longwave radiation*, *terrestrial radiation*.

Radiative forcing.¹ A change in the balance between incoming solar radiation and outgoing infrared (i.e., thermal) radiation. Without any radiative forcing, solar radiation coming to the Earth would continue to be approximately equal to the infrared radiation emitted from the Earth. The addition of greenhouse gases to the atmosphere traps an increased fraction of the infrared radiation, reradiating it back toward the surface of the Earth and thereby creates a warming influence.

Rail.⁸ Includes “heavy” and “light” transit rail. Heavy transit rail is characterized by exclusive rights-of-way, multi-car trains, high speed rapid acceleration, sophisticated signaling, and high platform loading. Also known as subway, elevated railway, or metropolitan railway (metro). Light transit rail may be on exclusive or shared rights of way, high or low platform, multi-car trains or single cars, automated or manually operated. In generic usage, light rail includes streetcars, trolley cars, and tramways.

Rangeland.⁷ Land, mostly grasslands, whose plants can provide food (i.e., forage) for grazing or browsing animals. See *feedlot*.

Recycling.⁷ Collecting and reprocessing a resource so it can be used again. An example is collecting aluminum cans, melting them down, and using the aluminum to make new cans or other aluminum products.

Reforestation.² Replanting of forests on lands that have recently been harvested.

Renewable energy.² Energy obtained from sources that are essentially inexhaustible, unlike, for example, the fossil fuels, of which there is a finite supply. Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy. See *hydropower*, *photovoltaic*.

Residence time.¹ Average time spent in a reservoir by an individual atom or molecule. Also, this term is used to define the age of a molecule when it leaves the reservoir. With respect to greenhouse gases, residence time usually refers to how long a particular molecule remains in the atmosphere. See *lifetime*.

Residential End-Use Sector: Consists of all private residences, whether occupied or vacant, owned or rented, including single family homes, multifamily housing units, and mobile homes. Secondary home, such as summer homes, are also included. Institutional housing, such as school dormitories, hospitals, and military barracks, generally are not included in the residential end-use sector, but are instead included in the commercial end-use sector.

Residual fuel oil.² The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations and that conform to ASTM Specifications D396 and D975. Included are No. 5, a residual fuel oil of medium viscosity; Navy Special, for use in steam-powered vessels in government service and in shore power plants; and No. 6, which includes Bunker C fuel oil and is used for commercial and industrial heating, electricity generation, and to power ships. Imports of residual fuel oil include imported crude oil burned as fuel.

Secondary oil recovery.⁷ Injection of water into an oil well after primary oil recovery to force out some of the remaining thicker crude oil. See *enhanced oil recovery*, *primary oil recovery*.

Sector. Division, most commonly used to denote type of energy consumer (e.g., residential) or according to the Intergovernmental Panel on Climate Change, the type of greenhouse gas emitter (e.g. industrial process). See *Intergovernmental Panel on Climate Change*.

Septic tank.⁷ Underground tank for treatment of wastewater from a home in rural and suburban areas. Bacteria in the tank decompose organic wastes and the sludge settles to the bottom of the tank. The effluent flows out of the tank into the ground through a field of drainpipes.

Sewage treatment (primary).⁷ Mechanical treatment of sewage in which large solids are filtered out by screens and suspended solids settle out as sludge in a sedimentation tank.

Shale oil.⁷ Slow-flowing, dark brown, heavy oil obtained when kerogen in oil shale is vaporized at high temperatures and then condensed. Shale oil can be refined to yield gasoline, heating oil, and other petroleum products. See *kerogen*, *oil shale*.

Short ton.¹ Common measurement for a ton in the United States. A short ton is equal to 2,000 lbs. or 0.907 metric tons.

Sink.¹ A reservoir that uptakes a pollutant from another part of its cycle. Soil and trees tend to act as natural sinks for carbon.

Sludge.⁷ Goopy solid mixture of bacteria and virus laden organic matter, toxic metals, synthetic organic chemicals, and solid chemicals removed from wastewater at a sewage treatment plant.

Soil.⁷ Complex mixture of inorganic minerals (i.e., mostly clay, silt, and sand), decaying organic matter, water, air, and living organisms.

Soil carbon.⁹ A major component of the terrestrial biosphere pool in the carbon cycle. The amount of carbon in the soil is a function of the historical vegetative cover and productivity, which in turn is dependent in part upon climatic variables.

Solar energy.⁷ Direct radiant energy from the sun. It also includes indirect forms of energy such as wind, falling or flowing water (hydropower), ocean thermal gradients, and biomass, which are produced when direct solar energy interact with the earth. See *solar radiation*.

Solar radiation.¹ Energy from the Sun. Also referred to as short-wave radiation. Of importance to the climate system, solar radiation includes ultra-violet radiation, visible radiation, and infrared radiation.

Source.⁴ Any process or activity that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere.

Special naphtha.² All finished products within the naphtha boiling range that are used as paint thinners, cleaners, or solvents. Those products are refined to a specified flash point.

Still gas.² Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

Stratosphere.⁷ Second layer of the atmosphere, extending from about 19 to 48 kilometers (12 to 30 miles) above the earth's surface. It contains small amounts of gaseous ozone (O₃), which filters out about 99 percent of the incoming harmful ultraviolet (UV) radiation. Most commercial airline flights operate at a cruising altitude in the lower stratosphere. See *ozone layer, ultraviolet radiation*.

Stratospheric ozone. See *ozone layer*.

Strip mining.⁷ Cutting deep trenches to remove minerals such as coal and phosphate found near the earth's surface in flat or rolling terrain. See *surface mining*.

Subbituminous coal.² A dull, black coal of rank intermediate between lignite and bituminous coal.

Sulfur cycle.⁷ Cyclic movement of sulfur in different chemical forms from the environment, to organisms, and then back to the environment.

Sulfur dioxide (SO₂).¹ A compound composed of one sulfur and two oxygen molecules. Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes is changed in a complex series of chemical reactions in the atmosphere to sulfate aerosols. These aerosols are believed to result in negative radiative forcing (i.e., tending to cool the Earth's surface) and do result in acid deposition (e.g., acid rain). See *aerosols, radiative forcing, acid deposition, acid rain*.

Sulfur hexafluoride (SF₆).¹ A colorless gas soluble in alcohol and ether, slightly soluble in water. A very powerful greenhouse gas used primarily in electrical transmission and distribution systems and as a dielectric in electronics. The global warming potential of SF₆ is 23,900. See *Global Warming Potential*.

Surface mining.⁷ Removal of soil, sub-soil, and other strata and then extracting a mineral deposit found fairly close to the earth's surface. See *strip mining*.

Synthetic fertilizer.⁷ Commercially prepared mixtures of plant nutrients such as nitrates, phosphates, and potassium applied to the soil to restore fertility and increase crop yields. See *organic fertilizer*.

Synthetic natural gas (SNG).³ A manufactured product chemically similar in most respects to natural gas, resulting from the conversion or reforming of petroleum hydrocarbons. It may easily be substituted for, or interchanged with, pipeline quality natural gas.

Tailings.⁷ Rock and other waste materials removed as impurities when minerals are mined and mineral deposits are processed. These materials are usually dumped on the ground or into ponds.

Tar sand.⁷ Swamp-like deposit of a mixture of fine clay, sand, water, and variable amounts of tar-like heavy oil known as bitumen. Bitumen can be extracted from tar sand by heating. It can then be purified and upgraded to synthetic crude oil. See *bitumen*.

Temperature.⁷ Measure of the average speed of motion of the atoms or molecules in a substance or combination of substances at a given moment. See *heat*.

Terrestrial.⁷ Pertaining to land.

Terrestrial radiation.⁹ The total infrared radiation emitted by the Earth and its atmosphere in the temperature range of approximately 200 to 300 Kelvin. Terrestrial radiation provides a major part of the potential energy changes necessary to drive the atmospheric wind system and is responsible for maintaining the surface air temperature within limits of livability.

Trace gas.¹ Any one of the less common gases found in the Earth's atmosphere. Nitrogen, oxygen, and argon make up more than 99 percent of the Earth's atmosphere. Other gases, such as carbon dioxide, water vapor, methane,

oxides of nitrogen, ozone, and ammonia, are considered trace gases. Although relatively unimportant in terms of their absolute volume, they have significant effects on the Earth's weather and climate.

Transportation End-Use Sector: Consists of private and public vehicles that move people and commodities. Included are automobiles, trucks, buses, motorcycles, railroads and railways (including streetcars and subways), aircraft, ships, barges, and natural gas pipelines.

Troposphere.^{1&7} The lowest layer of the atmosphere and contains about 95 percent of the mass of air in the Earth's atmosphere. The troposphere extends from the Earth's surface up to about 10 to 15 kilometers. All weather processes take place in the troposphere. Ozone that is formed in the troposphere plays a significant role in both the greenhouse gas effect and urban smog. See *ozone precursor, stratosphere, atmosphere*.

Tropospheric ozone precursor. See *ozone precursor*.

Tropospheric ozone.¹ See *ozone*.

Ultraviolet radiation (UV).¹¹ A portion of the electromagnetic spectrum with wavelengths shorter than visible light. The sun produces UV, which is commonly split into three bands of decreasing wavelength. Shorter wavelength radiation has a greater potential to cause biological damage on living organisms. The longer wavelength ultraviolet band, UVA, is not absorbed by ozone in the atmosphere. UVB is mostly absorbed by ozone, although some reaches the Earth. The shortest wavelength band, UVC, is completely absorbed by ozone and normal oxygen in the atmosphere.

Unfinished oils.³ All oils requiring further refinery processing, except those requiring only mechanical blending. Includes naphtha and lighter oils, kerosene and light gas oils, heavy gas oils, and residuum.

United Nations Framework Convention on Climate Change (UNFCCC).¹ The international treaty unveiled at the United Nations Conference on Environment and Development (UNCED) in June 1992. The UNFCCC commits signatory countries to stabilize anthropogenic (i.e. human-induced) greenhouse gas emissions to "levels that would prevent dangerous anthropogenic interference with the climate system". The UNFCCC also requires that all signatory parties develop and update national inventories of anthropogenic emissions of all greenhouse gases not otherwise controlled by the Montreal Protocol. Out of 155 countries that have ratified this accord, the United States was the first industrialized nation to do so.

Vehicle miles traveled (VMT).⁸ One vehicle traveling the distance of one mile. Thus, total vehicle miles is the total mileage traveled by all vehicles.

Volatile organic compounds (VOCs).⁶ Organic compounds that evaporate readily into the atmosphere at normal temperatures. VOCs contribute significantly to photochemical smog production and certain health problems. See *non-methane volatile organic compounds*.

Wastewater.² Water that has been used and contains dissolved or suspended waste materials. See *sewage treatment*.

Water vapor.¹ The most abundant greenhouse gas; it is the water present in the atmosphere in gaseous form. Water vapor is an important part of the natural greenhouse effect. While humans are not significantly increasing its concentration, it contributes to the enhanced greenhouse effect because the warming influence of greenhouse gases leads to a positive water vapor feedback. In addition to its role as a natural greenhouse gas, water vapor plays an important role in regulating the temperature of the planet because clouds form when excess water vapor in the atmosphere condenses to form ice and water droplets and precipitation.

Waxes.² Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

Weather.¹ Weather is the specific condition of the atmosphere at a particular place and time. It is measured in terms of such things as wind, temperature, humidity, atmospheric pressure, cloudiness, and precipitation. In most places, weather can change from hour-to-hour, day-to-day, and season-to-season. Climate is the average of weather over time and space. A simple way of remembering the difference is that climate is what you expect (e.g. cold winters) and 'weather' is what you get (e.g. a blizzard). See *climate*.

Wetland.⁷ Land that stays flooded all or part of the year with fresh or salt water.

Wetlands.² Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy.² Wood and wood products used as fuel, including roundwood (i.e., cordwood), limbwood, wood chips, bark, sawdust, forest residues, and charcoal.

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³ Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0387(97), U.S. Department of Energy, Washington, DC., July 1998.

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⁹ Carbon Dioxide Information Analysis Center, Web site at <<http://cdiac.esd.ornl.gov>>, Oak Ridge National Laboratory, U.S. Department of Energy, February 26, 1999.

¹⁰ Resources for the Future, Weathervane Web site <<http://www.weathervane.rff.org/glossary/index.html>>, February 26, 1999.

¹¹ U.S. Environmental Protection Agency, Ozone Depletion Glossary, <<http://www.epa.gov/ozone/defns.html>>, February 26, 1999.