ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

3.1. Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Stationary Combustion

Estimates of CH_4 and N_2O Emissions

Methane (CH_4) and nitrous oxide (N_2O) emissions from stationary combustion were estimated using IPCC emission factors and methods. Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This "top-down" methodology is characterized by two basic steps, described below. Data are presented in Table 3-1 through Table 3-5.

Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electricity generation, and U.S. territories. For CH_4 and N_2O, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption data for the United States were obtained from EIA's *Monthly Energy Review, July 2003 and Unpublished Supplemental Tables on Petroleum Product detail* (EIA 2003). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were collected separately from the EIA.[1] The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.9 for natural gas and wood and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency. Table 3-1 provides annual energy consumption data for the years 1990 through 2002.

Step 2: Determine the Amount of CH_4 and N_2O Emitted

Activity data for each sector and fuel type were then multiplied by emission factors to obtain emission estimates. Emission factors for the residential, commercial, industrial, and electricity generation sectors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). These N_2O emission factors by fuel type (consistent across sectors) were also assumed for U.S. territories. The CH_4 emission factors by fuel type for U.S. territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table 3-2 provides emission factors used for each sector and fuel type.

Estimates of NO_x, CO, and NMVOC Emissions

For ambient air pollutants, the major source categories included were those identified in EPA (2003): coal, fuel oil, natural gas, wood, other fuels (i.e., bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion, which includes emissions from internal combustion engines not used in transportation. The National Emission Inventory (NEI) Air Pollutant Emission Trends web site, which will contain the final iteration of the data in EPA (2003), periodically estimates emissions of NO_x, CO, and NMVOCs by sector and fuel type using a "bottom-up" estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries, etc.) as indicators of emissions. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity.

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

Table 3-3 through Table 3-5 present ambient air pollutant emission estimates for 1990 through 2002.

The basic calculation procedure for most source categories presented in EPA (2003) is represented by the following equation:

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

Where:

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

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

Table 3-1: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1996	1997	1998	1999	2000	2001	2002
Coal	18,035	20,123	20,614	20,799	20,819	21,765	21,075	21,471
Residential	26	17	16	13	14	12	12	12
Commercial	129	122	129	92	103	91	97	97
Industrial	1,612	1,545	1,555	1,468	1,413	1,433	1,399	1,368
Electricity Generation	16,261	18,429	18,904	19,216	19,279	20,220	19,558	19,984
U.S. Territories	7	10	10	10	10	10	10	10
Petroleum	8,024	7,636	7,658	7,522	7,645	7,790	8,265	7,841
Residential	1,407	1,488	1,428	1,314	1,473	1,563	1,539	1,521
Commercial	953	751	704	661	661	756	742	737
Industrial	3,996	4,096	4,108	3,748	3,809	3,846	4,249	4,204
Electricity Generation	1,293	821	931	1,312	1,217	1,151	1,275	903
U.S. Territories	375	481	488	487	485	473	461	476
Natural Gas	18,378	21,733	21,797	21,448	21,591	22,573	21,639	21,860
Residential	4,523	5,383	5,118	4,669	4,858	5,121	4,915	5,061
Commercial	2,701	3,244	3,302	3,098	3,130	3,301	3,126	3,208
Industrial	7,821	9,224	9,230	8,984	8,679	8,821	8,099	7,903
Electricity Generation	3,333	3,882	4,147	4,698	4,924	5,318	5,477	5,665
U.S. Territories	0	0	0	0	0	13	23	23
Wood	2,191	2,467	2,350	2,175	2,224	2,257	2,017	2,032
Residential	581	595	433	387	414	433	407	350
Commercial	39	50	49	48	52	53	41	41
Industrial	1,442	1,683	1,731	1,603	1,620	1,636	1,443	1,506
Electricity Generation	129	138	137	137	138	134	126	135
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-2: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[2]

Fuel/End-Use Sector	CH_4	N_2O
Coal		
Residential	300	1.4
Commercial	10	1.4
Industrial	10	1.4
Electricity Generation	1	1.4
U.S. Territories	1	1.4

[2] GJ (Gigajoule) = 10^9 joules. One joule = 9.486×10^{-4} Btu

Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	2	0.6
Electricity Generation	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	5	0.1
Electricity Generation	1	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	30	4.0
Electricity Generation	30	4.0
U.S. Territories	NA	NA

NA (Not Applicable)

Table 3-3: NO_x Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Electricity Generation	6,045	5,914	5,901	6,034	5,956	5,792	5,595	5,697	5,653	5,139	4,819	4,437	4,091
Coal	5,119	5,043	5,062	5,211	5,113	5,061	5,081	5,120	4,932	4,394	4,115	3,782	3,480
Fuel Oil	200	192	154	163	148	87	107	132	202	177	146	148	136
Natural gas	513	526	526	500	536	510	259	289	346	396	382	330	304
Other Fuels[a]	NA	NA	NA	NA	NA	NA	5	6	24	33	36	37	34
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	152	159	160	159	134	142	150	149	140	140	140	137
Industrial	2,754	2,703	2,786	2,859	2,855	2,852	2,859	2,813	2,768	2,586	2,411	2,393	2,491
Coal	530	517	521	534	546	541	490	487	475	500	473	496	516
Fuel Oil	240	215	222	222	219	224	203	196	190	200	162	147	153
Natural gas	1,072	1,134	1,180	1,207	1,210	1,202	1,092	1,079	1,066	926	881	875	911
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	117	115	113	113	111	109	103	104	105	106	111	115
Internal Combustion	792	720	748	783	767	774	965	948	933	855	789	764	795
Commercial	336	333	348	360	365	365	360	369	347	379	384	384	371
Coal	36	33	35	37	36	35	30	32	34	32	30	28	27
Fuel Oil	88	80	84	84	86	94	86	88	73	75	73	72	69
Natural gas	181	191	204	211	215	210	224	229	220	217	224	227	218
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	31	29	25	28	28	27	20	21	21	55	57	57	56
Residential	749	829	879	827	817	813	726	699	651	611	611	611	589
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	45	48	40	40	44	27	27	27	34	30	30	29
Other Fuels[a]	708	784	831	787	777	769	699	671	624	577	582	582	560
Total	9,884	9,779	9,914	10,080	9,993	9,822	9,540	9,578	9,419	8,716	8,226	7,826	7,542

IE (Included elsewhere)
NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003).
Note: Totals may not sum due to independent rounding.

Table 3-4: CO Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Electricity Generation	329	317	318	329	335	338	369	385	409	562	455	445	486
Coal	213	212	214	224	224	227	228	233	220	233	230	223	244
Fuel Oil	18	17	14	15	13	9	11	13	17	45	28	28	31

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Natural gas	46	46	47	45	48	49	72	76	88	188	100	93	102
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	NA	NA	NA	NA	NA	NA	7	8	30	30	33	33	36
Internal Combustion	52	41	43	46	50	52	52	54	54	65	65	68	74
Industrial	798	835	867	946	944	958	1,079	1,055	1,044	1,089	1,053	1,071	1,107
Coal	95	92	92	92	91	88	100	99	96	112	112	118	122
Fuel Oil	67	54	58	60	60	64	49	47	46	54	45	43	44
Natural gas	205	257	272	292	306	313	308	308	305	347	338	345	356
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	242	239	259	260	270	317	302	303	283	286	303	313
Internal Combustion	177	189	205	243	228	222	306	299	294	293	271	263	272
Commercial	205	196	204	207	212	211	122	126	122	146	147	149	133
Coal	13	13	13	14	13	14	13	13	14	15	14	13	11
Fuel Oil	16	16	16	16	16	17	17	18	15	16	16	16	15
Natural gas	40	40	46	48	49	49	58	59	57	76	79	80	71
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	128	128	129	134	132	34	36	36	38	38	40	36
Residential	3,668	3,965	4,195	3,586	3,515	3,876	2,364	2,361	2,352	3,144	2,508	2,503	2,235
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,711	3,930	3,337	3,272	3,628	2,133	2,133	2,133	2,928	2,292	2,292	2,046
Other Fuels[a]	238	255	265	249	243	248	231	229	220	217	216	211	189
Total	4,999	5,313	5,583	5,068	5,007	5,383	3,935	3,927	3,927	4,941	4,163	4,169	3,961

IE (Included elsewhere)
NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003).
Note: Totals may not sum due to independent rounding.

Table 3-5: NMVOC Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Electricity Generation	43	40	40	41	41	40	44	47	51	50	58	57	57
Coal	25	25	25	26	26	26	25	26	26	25	28	27	27
Fuel Oil	5	5	4	4	4	2	3	4	5	4	5	5	5
Natural gas	2	2	2	2	2	2	7	7	9	9	13	13	13
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	NA	NA	NA	NA	NA	NA	+	+	1	2	2	2	2
Internal Combustion	11	9	9	9	9	9	9	10	10	10	11	11	11
Industrial	165	177	169	169	178	187	163	160	159	159	152	152	152
Coal	7	5	7	5	7	5	6	6	6	9	9	10	10
Fuel Oil	11	10	11	11	11	11	8	7	7	10	9	8	8
Natural gas	52	54	47	46	57	66	54	54	54	53	52	52	52
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	47	45	46	45	45	33	31	31	26	26	28	28
Internal Combustion	49	61	60	60	58	59	63	62	61	61	56	54	54
Commercial	18	18	20	22	21	21	22	22	21	37	38	38	40
Coal	1	1	1	1	1	1	1	1	1	1	1	1	1
Fuel Oil	3	2	3	3	3	3	3	3	3	4	4	4	4
Natural gas	7	8	9	10	10	10	13	13	12	15	15	15	16
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	7	7	8	8	8	5	5	5	18	19	19	19
Residential	686	739	782	670	657	726	788	787	786	1,066	839	839	898
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	704	746	633	621	689	756	756	756	1,039	812	812	869
Other Fuels[a]	35	35	36	36	36	37	33	32	30	27	27	27	29
Total	912	975	1,011	901	898	973	1,018	1,016	1,016	1,312	1,088	1,087	1,147

IE (Included elsewhere)

NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003).
Note: Totals may not sum due to independent rounding.

3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions

Estimates of CH_4 and N_2O Emissions

Greenhouse gas emissions from mobile combustion other than CO_2 are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emission estimates for CH_4 and N_2O were derived using a methodology similar to that outlined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Activity data were obtained from a number of U.S. government agencies and other publications. Depending on the category, these basic activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT).

Methodology for Highway Gasoline and Diesel Vehicles

Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year

VMT by vehicle type were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2003). As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type using fuel economy and consumption data, so that the appropriate emission factors could be applied. First, fuel economy and consumption data from FHWA's *Highway Statistics* were disaggregated by fuel type using a number of sources, including the Department of Energy's (DOE) *Transportation Energy Data Book* (DOE 1993 through 2003), FHWA's *Highway Statistics* (FHWA 1996 through 2003), EPA and DOE's *Fuel Economy 2001 Datafile* (EPA/DOE 2001), and the *Vehicle Inventory and Use Survey* (Census 2000). These data were used to distribute national VMT estimates across vehicle categories,[1] including passenger cars (0-8500 GVWR[2]), light-duty trucks (0-8500 GVWR), heavy-duty vehicles (>8500 GVWR)[3] and motorcycles. For a more detailed description of vehicle types, see *Technical Description of Mobile 6.2 and Guidance on Its Use for Emission Inventory Preparation Draft Report* (EPA420-R-02-011).

VMT for alternative fuel and advanced technology vehicles (henceforth known simply as AFVs) were calculated separately, and the methodology is explained in the following section on AFVs. Since the VMT estimates from FHWA include total VMT in the United States, subtracting VMT from AFVs from this total was necessary. National VMT data for gasoline and diesel highway vehicles are presented in Table 3-6 and Table 3-7, respectively. Total VMT for each highway category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, heavy-duty diesel vehicles, and motorcycles) were distributed across 25 model years based on the VMT distribution by vehicle age shown in Table 3-12. This distribution was derived by weighting the temporally fixed age distribution of the U.S. vehicle fleet according to vehicle registrations (Table 3-10) by the average annual age-specific vehicle mileage accumulation of U.S. vehicles (Table 3-11). Both were obtained from EPA's MOBILE6 model (EPA 2000).

Step 2: Allocate VMT Data to Control Technology Type

VMT by vehicle type for each model year were distributed across various control technologies as shown in Table 3-14 through Table 3-17. The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. EPA Tier 0, EPA Tier 1, and LEV actually refer to U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design.

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[1] This methodology is presented in more detail in ICF Consulting (2001).

[2] GVWR is gross vehicle weight rating (i.e., vehicle weight plus weighted cargo capacity).

[3] The category "heavy-duty trucks" includes vehicles that are sometimes classified as medium-duty trucks (those with a GVWR between 8,500 and 14,000 lbs.). The only exception is Table 3-9, which provides VMT data for medium-duty alternative fuel vehicles.

EPA Tier 1 and its predecessor EPA Tier 0 both apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced three-way catalysts," as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).[4]

Control technology assignments for light and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 were estimated in EPA (1998). Assignments for 1998 through 2002 were determined using confidential engine family sales data submitted to EPA (EPA 2003b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2003a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, and LEV standards. Assignments for 1996 and 1997 were estimated based on the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996.

Step 3: Determine CH_4 and N_2O Emission Factors by Vehicle, Fuel, and Control Technology Type

CH_4 emission factors were primarily obtained from the IPCC (IPCC/UNEP/OECD/IEA 1997), which were derived from EPA's MOBILE5a mobile source emissions model (EPA 1997). The MOBILE5a model uses information on ambient temperature, diurnal temperature range, altitude, vehicle speeds, national vehicle registration distributions, gasoline volatility, emission control technologies, fuel composition, and the presence or absence of vehicle inspection/maintenance programs in order to produce these factors. Since MOBILE5a, many heavy-duty gasoline vehicles are now compliant with EPA Tier 1 and LEV emission standards. Methane emission factors for these vehicles were determined using emission factors from the California Air Resources Board (CARB 2000).

Emissions of N_2O have not been extensively studied and are currently not well characterized. The limited number of studies that have been performed on highway vehicle emissions of N_2O have shown that emissions are generally greater from vehicles with catalytic converter systems than those without such controls, and greater from aged than from new catalysts. These systems control tailpipe emissions of NO_x (i.e., NO and NO_2) by catalytically reducing NO_x to N_2. Sub-optimal catalyst performance, caused by as yet poorly understood factors, results in incomplete reduction and the conversion of some NO_x to N_2O rather than to N_2. Fortunately, newer vehicles with catalyst and engine designs meeting the more recent EPA Tier 1 and LEV standards have shown reduced emission rates of both NO_x and N_2O compared with earlier catalyst designs.

In order to better characterize the process by which N_2O is formed by catalytic controls and to develop a more accurate national emission estimate, EPA's Office of Transportation and Air Quality—at its National Vehicle and Fuel Emissions Laboratory (NVFEL)—conducted a series of tests in order to measure emission rates of N_2O from used EPA Tier 1 and LEV gasoline-fueled passenger cars and light-duty trucks equipped with catalytic converters. These tests and a review of the literature were used to develop the emission factors for N_2O (EPA 1998) and were revised slightly in 2001 based on ICF (2001). The following references were used in developing the N_2O emission factors for gasoline-fueled highway passenger cars presented in Table 3-18:

- *LEVs*. Tests performed at NVFEL (EPA 1998)[5]
- *EPA Tier 1*. Tests performed at NVFEL (EPA 1998)
- *EPA Tier 0*. Smith and Carey (1982), Barton and Simpson (1994), and one car tested at NVFEL (EPA 1998)
- *Oxidation Catalyst*. Smith and Carey (1982), Urban and Garbe (1980)
- *Non-Catalyst*. Prigent and de Soete (1989), Dasch (1992), and Urban and Garbe (1979)

Nitrous oxide emission factors for other types of gasoline-fueled vehicles—light-duty trucks, heavy-duty vehicles, and motorcycles—were estimated by adjusting the factors for gasoline passenger cars, as described above, by their relative fuel economies. This adjustment was performed using estimates of miles per gallon by vehicle type and fuel type derived from DOE (1993 through 2003), FHWA (1996 through 2003), EPA/DOE (2001), and Census (2000). Data from the literature and tests performed at NVFEL support the conclusion that light-duty trucks and

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[4] For further description, see "Definitions of Emission Control Technologies and Standards" section of this annex.

[5] LEVs are assumed to be operated using low-sulfur fuel (i.e., Indolene at 24 ppm sulfur). All other NVFEL tests were performed using a standard commercial fuel (CAAB at 285 ppm sulfur). Emission tests by NVFEL have consistently exhibited higher N_2O emission rates from higher sulfur fuels on EPA Tier 1 and LEV vehicles.

other vehicles have higher emission rates than passenger cars. However, the use of fuel-consumption ratios to determine emission factors is considered an estimate, with a moderate level of uncertainty.

Nitrous oxide emission factors for heavy-duty gasoline vehicles compliant with EPA Tier 1 and LEV emission standards were estimated from the ratio of NO_x emissions to N_2O emissions for EPA Tier 0 heavy-duty gasoline trucks. For EPA Tier 0 heavy-duty gasoline trucks, a NO_x to N_2O ratio of 60 was found. This ratio was applied to the NO_x emissions from EPA Tier 1 and LEV heavy-duty gasoline vehicles to approximate N_2O emissions from these control technology classes for heavy-duty gasoline vehicles.

The resulting N_2O emission factors employed for gasoline highway vehicles are lower than the U.S. default values presented in the *Revised 1996 IPCC Guidelines*, but are higher than the European default values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. defaults in the *Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test procedures.

Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) since little data addressing N_2O emissions from U.S. diesel-fueled vehicles exists.

Compared to regulated tailpipe emissions, relatively little data are available to estimate emission factors for N_2O. Nitrous oxide is not a regulated ambient air pollutant, and measurements of it in automobile exhaust have not been routinely collected. Further testing would be needed to reduce the uncertainty in N_2O emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

Step 4: Determine the Amount of CH_4 and N_2O Emitted by Vehicle, Fuel, and Control Technology Type

VMT for each highway category for each year were first converted to vehicle kilometers traveled (VKT) so that emission factors could be applied. Emissions of CH_4 and N_2O were then calculated by multiplying total VKT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

Methodology for Alternative Fuel Vehicles (AFVs) and Gas-Electric Hybrids

Step 1: Determine Vehicle Miles Traveled by Vehicle and Fuel Type

VMT for alternative fuel and advanced technology vehicles were calculated from "VMT Projections for Alternative Fueled and Advanced Technology Vehicles through 2025" (Browning 2003). Alternative Fuels include Compressed Natural Gas (CNG), Liquid Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Ethanol, Methanol, and Electric Vehicles (battery powered). Most of the vehicles that use these fuels run an Internal Combustion Engine (ICE) powered by the alternative fuel, although many of the vehicles can run on either the alternative fuel or gasoline (or diesel), or some combination.[6] The data obtained include vehicle fuel use and total number of vehicles in use from 1992 through 2002. Fuel economy for each vehicle type and calendar year was determined by estimating the gasoline equivalent fuel economy for each technology. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles were taken from full fuel cycle studies done for the California Air Resources Board (Unnasch and Browning, 2000). These ratios were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that would use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. Average vehicle VMT was then calculated by dividing total VMT per vehicle type by the number of vehicles. Average vehicle VMT for each vehicle type was checked against the Federal Highway Administration Highway Statistics Series for each calendar year (FHWA 1996 through 2003). Note that for AFVs capable of running on both/either traditional and alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2003). For gas-electric

[6] Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol or methanol; some vehicles are also designed to run on gasoline or an alternative fuel -- either natural gas or LPG -- but not at the same time, while other vehicles are designed to run on E85 (85% ethanol) or gasoline, or any mixture of the two. Heavy-duty vehicles are more likely to run on a combination of diesel fuel and either natural gas, LPG, ethanol, or methanol.

hybrids, VMT estimates reflect total vehicle travel. Overall VMT estimates for AFVs and gas-electric hybrids are shown in Table 3-8, while more detailed estimates of VMT are shown in Table 3-9.

Step 2: Determine CH_4 and N_2O Emission Factors by Vehicle and Alternative Fuel Type

Limited data exist on N_2O and CH_4 emission factors for alternative fuel vehicles, and most of these data are for older emission control technologies. Several studies have estimated emission factors for alternative fuel vehicles, but similarly do not cover all of the various technologies and weight classes. Light-duty alternative fuel vehicle emission factors are estimated in Argonne National Laboratory's GREET 1.5—Transportation Fuel Cycle Model (Wang 1999). In addition, Lipman and Delucchi estimate emission factors for some light and heavy-duty alternative fuel vehicles (Lipman and Delucchi 2002). The approach taken here is to calculate CH_4 emissions from actual test data and determine N_2O emissions from NO_x emissions from the same tests. Since most alternative fuel vehicles likely use the same or similar catalysts as their conventional counterpart, the amount of N_2O emissions will depend upon the amount of NO_x emissions that the engine produces. For a given emission control system, the higher the NO_x emissions from the engine, the higher the tailpipe N_2O emissions that are formed in the catalyst. Since most alternative fuel vehicles use catalysts similar to EPA Tier 1 gasoline cars, as a first approximation, the NO_x to N_2O ratio of EPA Tier 1 cars was used to determine the N_2O emissions from alternative fueled vehicles. Based upon gasoline data for EPA Tier 1 cars, the tailpipe NO_x to N_2O ratio is 5.75. Lipman and Delucchi (2002) found NO_x to N_2O ratios for light-duty alternative fuel vehicles with three-way catalyst systems to vary from 3 to 5.5 for older technology.

Methane emission factors for light-duty vehicles were taken from the Auto/Oil Air Quality Improvement Research Program dataset (CRC 1997). This dataset provided CH_4 emission factors for all light-duty vehicle technologies except for LPG (propane). Light-duty propane emission factors were determined from reports on LPG-vehicle emissions from the California Air Resources Board (Brasil and McMahon, 1999) and the University of California Riverside (Norbeck, et al., 1998).

Medium/heavy-duty emission factors for alternative fuel vehicles were determined from test data using the West Virginia University mobile dynamometer (NREL 2002). Emission factors were determined based on the ratio of total hydrocarbon emissions to CH_4 emissions found for light-duty vehicles using the same fuel. Nitrous oxide emissions for heavy-duty engines were calculated from NO_x emission results using a NO_x to N_2O ratio of 50, which is more typical for heavy-duty engines with oxidation catalysts. These emission factors are shown in Table 3-19.

Step 3: Determine the Amount of CH_4 and N_2O Emitted by Vehicle and Fuel Type

Emissions of CH_4 and N_2O were calculated by multiplying total VMT for each vehicle and fuel type (Step 1) by the appropriate emission factors (Step 2).

Methodology for Non-Highway Mobile Sources

Activity data for non-highway vehicles were based on annual fuel consumption statistics by transportation mode and fuel type and are shown in Table 3-13. Consumption data for distillate fuel by construction equipment and farm equipment were obtained from EIA's Fuel Oil and Kerosene Sales (1991 through 2003). Consumption data for ships and boats (i.e., vessel bunkering) were obtained from EIA (1991-2003 and 2003b) (for distillate fuel) and EIA (2003a) (for residual fuel); marine transport fuel consumption data for U.S. territories (EIA 2003b and 2003c) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[7] Annual diesel consumption for Class I railroad locomotives was obtained from AAR (2003), while consumption by Class II and III railroad locomotives was provided by Benson (2002). Diesel consumption by commuter and intercity rail was obtained from DOE (2003). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2003a), as described in Annex 2.1: Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion, and were reduced by the amount allocated to international bunker fuels. Data on the consumption of motor gasoline by ships and boats, construction equipment, and farm equipment were drawn from FHWA (1996 through 2003).

[7] See International Bunker Fuels section of the Energy Chapter.

Emissions of CH_4 and N_2O from non-highway mobile sources were calculated by multiplying U.S. default emission factors in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) by activity data for each source type (see Table 3-20).

Table 3-21 and Table 3-22 provide complete emissions of CH_4 and N_2O emissions, respectively, for 1990 through 2002.

Estimates of NO_x, CO, and NMVOC Emissions

The emission estimates of NO_x, CO, and NMVOCs for mobile combustion were obtained from preliminary data (EPA 2003c), which in its final iteration, will be published on the EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site. This EPA report provides emission estimates for these gases by sector and fuel type using a procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions.

Table 3-23 through Table 3-25 provide complete emissions estimates for 1990 through 2002.

Table 3-6: Vehicle Miles Traveled for Gasoline Highway Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles	Motorcycles
1990	1,395.39	558.35	29.82	8.67
1991	1,346.09	632.27	31.69	8.78
1992	1,359.63	687.65	30.68	9.09
1993	1,363.07	724.43	29.82	9.29
1994	1,394.86	742.59	30.18	9.53
1995	1,426.89	767.31	30.13	9.80
1996	1,458.81	792.88	30.17	9.92
1997	1,491.51	825.16	30.13	10.08
1998	1,539.00	842.47	30.63	10.28
1999	1,558.84	873.85	30.76	10.58
2000	1,590.19	894.90	29.64	10.47
2001	1,618.27	914.25	28.50	9.64
2002	1,648.52	936.55	27.92	9.55

Source: Derived from FHWA (1996 through 2003).

Table 3-7: Vehicle Miles Traveled for Diesel Highway Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	13.70	15.38	121.24
1991	12.41	16.35	122.72
1992	12.30	18.51	127.64
1993	12.12	20.43	135.11
1994	11.76	21.17	145.40
1995	11.21	21.87	153.42
1996	10.82	22.75	158.26
1997	10.78	24.58	166.96
1998	10.29	24.75	171.49
1999	9.91	26.01	178.25
2000	9.57	26.89	181.98
2001	9.17	27.57	185.85
2002	8.74	28.16	191.66

Source: Derived from FHWA (1996 through 2003).

Table 3-8: Vehicle Miles Traveled for Alternative Fuel Highway Vehicles and Gas-Electric Hybrids (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	0.07	0.85	0.92
1991	0.08	0.77	0.88

1992	0.10	0.70	0.84
1993	0.14	0.89	1.09
1994	0.17	0.87	1.04
1995	0.19	0.85	1.03
1996	0.22	0.91	1.10
1997	0.27	1.00	1.22
1998	0.29	1.06	1.26
1999	0.35	1.16	1.34
2000	0.52	1.27	1.49
2001	0.89	1.38	1.76
2002	1.37	1.47	1.80

Source: Derived from Browning (2003).

Note: The sharp rise in VMT from passenger cars is due primarily to increased VMT from gasoline-electric hybrid cars (as shown in Table 3-9), which use gasoline in combination with an electric motor; these vehicles use gasoline, but emissions are estimated in the inventory as part of the AFV methodology since these vehicles have significantly higher average fuel economy and different emissions profiles than conventional gasoline vehicles.

Table 3-9: Detailed Vehicle Miles Traveled for Alternative Fuel Highway Vehicles and Gas-Electric Hybrids (10^6 Miles)

Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Light-Duty Cars	67.4	79.8	104.2	141.7	171.4	189.8	218.2	265.5	292.3	352.9	522.3	888.6	1,371.7
Methanol-Flex Fuel ICE	0.0	9.0	21.8	33.9	50.5	44.2	39.3	35.8	28.3	25.3	14.2	10.8	8.2
Ethanol-Flex Fuel ICE	0.0	0.0	0.1	0.2	0.3	0.8	2.9	5.5	7.6	16.9	32.4	40.5	47.2
CNG ICE	7.5	9.5	11.5	16.1	19.5	25.9	34.4	46.0	54.9	67.7	76.4	100.5	106.5
CNG Bi-fuel	15.9	18.8	24.5	35.9	43.9	61.4	79.4	109.5	127.5	157.9	175.9	232.9	244.9
LPG ICE	5.0	4.7	4.4	5.8	5.5	5.2	5.5	5.5	5.8	6.1	6.4	6.7	7.0
LPG Bi-fuel	38.9	37.7	36.4	42.4	42.0	39.7	42.1	42.6	44.2	46.1	47.0	48.0	50.4
NEVs	0.0	0.0	5.0	6.7	8.9	11.4	13.3	18.4	21.7	29.4	50.9	77.9	88.1
Electric	0.0	0.0	0.4	0.6	0.9	1.2	1.4	2.0	2.4	3.3	5.5	8.4	9.8
Electric-Gasoline Hybrid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	113.5	362.9	809.6
Light-Duty Trucks	845.9	768.6	699.8	890.6	872.4	851.8	906.3	999.9	1,059.5	1,156.5	1,271.3	1,384.8	1,471.1
Ethanol-Flex Fuel ICE	0.0	0.1	0.3	0.6	1.0	2.5	9.3	17.8	24.4	54.3	104.2	130.3	152.0
CNG ICE	7.0	9.9	13.0	17.7	22.8	30.5	38.4	58.6	67.2	81.3	100.4	124.1	136.9
CNG Bi-fuel	15.8	18.6	21.7	28.1	35.5	45.1	56.3	106.2	125.0	151.0	174.6	215.3	237.8
LPG ICE	18.8	18.3	17.9	19.6	19.1	18.1	18.8	19.4	19.8	20.3	20.7	21.1	22.0
LPG Bi-fuel	804.3	721.7	646.2	823.5	792.6	753.5	781.0	794.5	819.0	843.9	861.6	879.6	905.4
Electric	0.0	0.0	0.8	1.1	1.5	2.1	2.5	3.5	4.2	5.7	9.7	14.4	17.0
Medium-Duty Trucks	192.9	176.5	159.7	198.4	187.3	179.2	190.2	195.7	200.1	204.6	221.3	251.9	259.6
CNG Bi-fuel	1.5	1.8	2.1	2.6	3.4	4.3	5.5	6.7	7.8	9.2	10.5	11.9	12.7
LPG ICE	16.4	16.2	15.6	17.2	16.6	15.6	16.8	17.3	17.8	18.1	19.6	22.4	23.0
LPG Bi-fuel	174.9	158.5	141.9	178.7	167.4	159.3	167.9	171.7	174.5	177.3	191.2	217.6	223.9
Heavy-Duty Trucks	632.7	619.7	600.9	780.7	743.5	726.3	765.7	842.0	863.1	903.7	997.2	1,175.8	1,206.9
Neat Methanol ICE	0.0	4.6	9.6	12.7	13.2	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Neat Ethanol ICE	0.0	0.0	0.0	0.0	0.0	2.9	10.4	6.6	0.1	0.3	0.1	0.0	0.0
CNG ICE	14.2	18.2	22.9	29.6	31.6	51.2	68.6	88.4	96.5	123.8	139.2	176.4	174.8
LPG ICE	522.0	498.5	474.1	640.0	606.1	575.2	590.7	642.1	655.5	663.6	726.1	838.5	860.8
LPG Bi-fuel	96.5	98.3	93.6	94.8	88.4	83.9	89.3	96.5	98.8	100.3	114.1	136.2	142.7
LNG	0.0	0.0	0.7	3.6	4.3	5.6	6.7	8.3	12.1	15.7	17.7	24.8	28.5
Buses	90.5	86.4	83.6	111.7	112.1	122.7	145.9	184.7	201.6	232.5	269.9	327.7	332.4
Neat Methanol ICE	3.7	3.7	3.8	4.3	4.3	3.8	1.3	1.4	1.8	1.8	1.8	1.6	0.0
Neat Ethanol ICE	0.1	0.2	0.3	0.3	0.5	1.7	3.3	0.1	0.1	0.0	0.0	0.0	0.0
CNG ICE	17.1	19.3	21.5	27.2	29.7	44.3	62.4	97.0	107.5	134.9	160.3	195.2	195.1
LPG ICE	69.7	63.3	56.7	76.4	73.1	67.9	72.9	78.9	81.4	81.9	92.2	108.9	110.0
LNG	0.0	0.0	1.3	3.5	4.4	5.0	5.9	7.3	10.6	13.7	15.4	21.7	27.0
Electric	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.4
Total VMT	1,829.4	1,731.1	1,648.1	2,123.2	2,086.7	2,069.9	2,226.3	2,487.8	2,616.6	2,850.2	3,282.0	4,028.9	4,641.7

Source: Derived from Browning (2003).

Table 3-10: Age Distribution by Vehicle/Fuel Type for Highway Vehicles[a]

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
1	5.3%	5.8%	4.9%	5.3%	5.9%	4.2%	14.4%
2	7.1%	7.6%	8.9%	7.1%	7.4%	7.8%	16.8%
3	7.1%	7.5%	8.1%	7.1%	6.9%	7.2%	13.5%
4	7.1%	7.3%	7.4%	7.1%	6.4%	6.7%	10.9%
5	7.0%	7.1%	6.8%	7.0%	6.0%	6.2%	8.8%
6	7.0%	6.8%	6.2%	7.0%	5.6%	5.8%	7.0%
7	6.9%	6.5%	5.6%	6.9%	5.2%	5.3%	5.6%
8	6.8%	6.1%	5.1%	6.8%	4.8%	5.0%	4.5%
9	6.6%	5.7%	4.7%	6.6%	4.5%	4.6%	3.6%
10	6.3%	5.2%	4.3%	6.3%	4.2%	4.3%	2.9%
11	5.9%	4.7%	3.9%	5.9%	3.9%	4.0%	2.3%
12	5.4%	4.2%	3.6%	5.4%	3.6%	3.7%	9.7%
13	4.6%	3.6%	3.3%	4.6%	3.4%	3.4%	-
14	3.6%	3.1%	3.0%	3.6%	3.2%	3.2%	-
15	2.9%	2.6%	2.7%	2.9%	2.9%	2.9%	-
16	2.3%	2.2%	2.5%	2.3%	2.7%	2.7%	-
17	1.8%	1.8%	2.3%	1.8%	2.5%	2.5%	-
18	1.4%	1.4%	2.1%	1.4%	2.4%	2.4%	-
19	1.1%	1.2%	1.9%	1.1%	2.2%	2.2%	-
20	0.9%	1.1%	1.7%	0.9%	2.1%	2.0%	-
21	0.7%	1.1%	1.6%	0.7%	1.9%	1.9%	-
22	0.6%	1.0%	1.5%	0.6%	1.8%	1.8%	-
23	0.4%	1.0%	1.3%	0.4%	1.7%	1.6%	-
24	0.4%	0.9%	1.2%	0.4%	1.6%	1.5%	-
25+	1.0%	4.6%	5.4%	1.0%	7.3%	7.2%	-
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Source: EPA (2000).

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles),LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).

[b] Because of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are aggregated together.

Table 3-11: Annual Average Vehicle Mileage Accumulation per Vehicle (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[a]
1	14,910	19,906	20,218	14,910	26,371	28,787	4,786
2	14,174	18,707	18,935	14,174	24,137	26,304	4,475
3	13,475	17,559	17,100	13,475	22,095	24,038	4,164
4	12,810	16,462	16,611	12,810	20,228	21,968	3,853
5	12,178	15,413	15,560	12,178	18,521	20,078	3,543
6	11,577	14,411	14,576	11,577	16,960	18,351	3,232
7	11,006	13,454	13,655	11,006	15,533	16,775	2,921
8	10,463	12,541	12,793	10,463	14,227	15,334	2,611
9	9,947	11,671	11,987	9,947	13,032	14,019	2,300
10	9,456	10,843	11,231	9,456	11,939	12,817	1,989
11	8,989	10,055	10,524	8,989	10,939	11,719	1,678
12	8,546	9,306	9,863	8,546	10,024	10,716	1,368
13	8,124	8,597	9,243	8,124	9,186	9,799	-
14	7,723	7,925	8,662	7,723	8,420	8,962	-
15	7,342	7,290	8,028	7,342	7,718	8,196	-
16	6,980	6,690	7,610	6,980	7,075	7,497	-
17	6,636	6,127	7,133	6,636	6,487	6,857	-
18	6,308	5,598	6,687	6,308	5,948	6,273	-
19	5,997	5,103	6,269	5,997	5,454	5,739	-
20	5,701	4,642	5,877	5,701	5,002	5,250	-
21	5,420	4,214	5,510	5,420	4,588	4,804	-
22	5,152	3,818	5,166	5,152	4,209	4,396	-
23	4,898	3,455	4,844	4,898	3,861	4,023	-
24	4,656	3,123	4,542	4,656	3,542	3,681	-
25	4,427	2,822	4,259	4,427	3,250	3,369	-

Source: EPA (2000).

[a] Because of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are aggregated together.

Table 3-12: VMT Distribution by Vehicle Age and Vehicle/Fuel Type

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
1	7.51%	9.41%	7.89%	7.51%	11.50%	8.27%	19.39%
2	9.52%	11.56%	13.48%	9.52%	13.07%	14.00%	21.15%
3	9.05%	10.62%	11.11%	9.05%	11.15%	11.86%	15.82%
4	8.59%	9.70%	9.85%	8.59%	9.51%	10.05%	11.82%
5	8.14%	8.80%	8.43%	8.14%	8.11%	8.52%	8.77%
6	7.68%	7.92%	7.21%	7.68%	6.92%	7.22%	6.37%
7	7.22%	7.04%	6.16%	7.22%	5.90%	6.13%	4.60%
8	6.72%	6.19%	5.27%	6.72%	5.04%	5.20%	3.31%
9	6.20%	5.36%	4.51%	6.20%	4.30%	4.41%	2.33%
10	5.64%	4.57%	3.86%	5.64%	3.67%	3.74%	1.62%
11	5.03%	3.82%	3.31%	5.03%	3.13%	3.18%	1.09%
12	4.38%	3.14%	2.83%	4.38%	2.67%	2.70%	3.73%
13	3.54%	2.52%	2.42%	3.54%	2.28%	2.29%	-
14	2.67%	1.99%	2.07%	2.67%	1.95%	1.94%	-
15	2.01%	1.54%	1.76%	2.01%	1.66%	1.65%	-
16	1.52%	1.16%	1.52%	1.52%	1.42%	1.40%	-
17	1.14%	0.87%	1.30%	1.14%	1.21%	1.19%	-
18	0.86%	0.64%	1.12%	0.86%	1.04%	1.01%	-
19	0.65%	0.50%	0.96%	0.65%	0.89%	0.86%	-
20	0.49%	0.43%	0.82%	0.49%	0.76%	0.73%	-
21	0.37%	0.37%	0.70%	0.37%	0.65%	0.62%	-
22	0.28%	0.32%	0.60%	0.28%	0.55%	0.53%	-
23	0.21%	0.27%	0.52%	0.21%	0.47%	0.45%	-
24	0.16%	0.23%	0.44%	0.16%	0.40%	0.38%	-
25	0.43%	1.04%	1.85%	0.43%	1.75%	1.65%	-
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note: Estimated by weighting data in Table 3-10 by data in Table 3-11.

Table 3-13: Fuel Consumption for Non-Highway Vehicles by Fuel Type (thousand gallons)

Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Aircraft													
Gasoline[a]	374,216	347,126	341,582	319,449	317,307	329,319	310,797	330,285	295,345	325,913	301,893	290,677	280,643
Jet Fuel	18,280,137	17,513,520	17,295,236	17,428,168	18,270,784	17,806,687	18,746,346	18,600,663	18,827,216	19,428,260	20,129,171	19,107,836	18,499,519
Ships and Boats													
Diesel	1,697,600	1,693,361	1,706,144	1,546,311	1,630,093	1,518,608	1,839,335	1,801,798	1,597,011	1,863,606	1,854,297	1,998,048	2,014,416
Gasoline	1,300,400	1,709,700	1,316,170	873,687	896,700	1,060,394	993,671	987,193	956,232	1,098,137	1,124,269	993,837	1,081,157
Residual	2,060,708	1,553,714	2,727,447	2,511,169	2,451,117	2,646,106	2,168,468	976,197	584,334	1,238,111	3,027,560	1,130,550	2,404,778
Construction Equipment													
Diesel	1,581,500	1,492,000	1,514,205	1,526,043	1,531,300	1,472,827	1,645,647	1,678,482	1,749,317	1,723,597	1,899,837	2,086,388	1,818,411
Gasoline	318,200	287,200	272,900	245,299	272,852	280,046	283,911	300,491	234,705	177,758	191,516	506,682	532,998
Agricultural Equipment													
Diesel	3,164,200	3,144,200	3,274,811	3,077,122	3,062,436	3,093,224	3,225,029	3,206,359	2,965,006	2,805,157	3,079,664	3,350,683	3,233,874
Gasoline	812,800	776,200	805,500	845,320	911,996	926,732	918,085	984,450	906,941	702,700	652,256	801,552	831,828
Locomotives													
Diesel	3,450,643	3,243,801	3,340,575	3,435,263	3,721,218	3,868,531	3,953,763	3,951,644	4,004,540	4,141,606	4,125,893	4,139,035	4,160,463
Other[b]													
Diesel	926,800	955,400	773,437	797,140	905,842	800,335	741,326	706,754	682,865	685,634	610,078	738,212	709,339
Gasoline	1,205,400	1,097,700	1,219,300	1,025,088	1,039,310	1,071,597	1,081,640	1,097,258	1,139,229	1,021,836	1,040,138	1,755,320	1,810,509

Sources: AAR (2003), BEA (1991 through 2003), Benson (2002), DESC (2002), DOC (1991 through 2003), DOE (2003), DOT (1991 through 2003), EIA (2002a), EIA (2002b), EIA (2003a), EIA (2003b), EIA (2003c), EIA (1991 through 2003), and FHWA (1996 through 2003).

[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.

[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 3-14: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV
1973-1974	100%	-	-	-	-
1975	20%	80%	-	-	-
1976-1977	15%	85%	-	-	-
1978-1979	10%	90%	-	-	-
1980	5%	88%	7%	-	-
1981	-	15%	85%	-	-
1982	-	14%	86%	-	-
1983	-	12%	88%	-	-
1984-1993	-	-	100%	-	-
1994	-	-	60%	40%	-
1995	-	-	20%	80%	-
1996	-	-	1%	97%	2%
1997	-	-	0.5%	96.5%	3%
1998	-	-	0.01%	87%	13%
1999	-	-	0.01%	67%	33%
2000	-	-	-	44%	56%
2001	-	-	-	3%	97%
2002	-	-	-	1%	99%

Sources: EPA (1998), EPA (2003a), and EPA (2003b)
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.
- Not applicable

Table 3-15: Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV[b]
1973-1974	100%	-	-	-	-
1975	30%	70%	-	-	-
1976	20%	80%	-	-	-
1977-1978	25%	75%	-	-	-
1979-1980	20%	80%	-	-	-
1981	-	95%	5%	-	-
1982	-	90%	10%	-	-
1983	-	80%	20%	-	-
1984	-	70%	30%	-	-
1985	-	60%	40%	-	-
1986	-	50%	50%	-	-
1987-1993	-	5%	95%	-	-
1994	-	-	60%	40%	-
1995	-	-	20%	80%	-
1996	-	-	-	100%	-
1997	-	-	-	100%	-
1998	-	-	-	80%	20%
1999	-	-	-	57%	43%
2000	-	-	-	65%	35%
2001	-	-	-	1%	99%
2002	-	-	-	10%	90%

Sources: EPA (1998), EPA (2003a), and EPA (2003b)
[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.
[b] The proportion of LEVs as a whole has decreased since 2001, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.
- Not applicable.

Table 3-16: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

Model Years	Uncontrolled	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV[b]
≤1981	100%	-	-	-	-	-
1982-1984	95%	-	5%	-	-	-
1985-1986	-	95%	5%	-	-	-

1987	-	70%	15%	15%	-	-
1988-1989	-	60%	25%	15%	-	-
1990-1995	-	45%	30%	25%	-	-
1996	-	-	25%	10%	65%	-
1997	-	-	10%	5%	85%	-
1998	-	-	-	-	96%	4%
1999	-	-	-	-	78%	22%
2000	-	-	-	-	54%	46%
2001	-	-	-	-	64%	36%
2002	-	-	-	-	69%	31%

Sources: EPA (1998), EPA (2003a), and EPA (2003b)

[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.

[b] The proportion of LEVs as a whole has decreased since 2000, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

- Not applicable

Table 3-17: Control Technology Assignments for Diesel Highway and Motorcycle VMT

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1966-1982
Moderate control	1983-1995
Advanced control	1996-2002
Heavy-Duty Diesel Vehicles	
Uncontrolled	1966-1982
Moderate control	1983-1995
Advanced control	1996-2002
Motorcycles	
Uncontrolled	1966-1995
Non-catalyst controls	1996-2002

Source: EPA (1998)

Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.

Table 3-18: Emission Factors for CH_4 and N_2O for Highway Vehicles

Vehicle Type/Control Technology	N_2O (g/mi)	N_2O (g/km)	CH_4 (g/mi)	CH_4 (g/km)
Gasoline Passenger Cars				
Low Emission Vehicles	0.0283	0.0176	0.0402	0.0250
EPA Tier 1[a]	0.0463	0.0288	0.0483	0.0300
EPA Tier 0 [a]	0.0816	0.0507	0.0644	0.0400
Oxidation Catalyst	0.0518	0.0322	0.1127	0.0700
Non-Catalyst Control	0.0166	0.0103	0.1931	0.1200
Uncontrolled	0.0166	0.0103	0.2173	0.1350
Gasoline Light-Duty Trucks				
Low Emission Vehicles	0.0355	0.0220	0.0483	0.0300
EPA Tier 1[a]	0.0580	0.0361	0.0563	0.0350
EPA Tier 0[a]	0.1022	0.0635	0.1127	0.0700
Oxidation Catalyst	0.0649	0.0403	0.1448	0.0900
Non-Catalyst Control	0.0208	0.0129	0.2253	0.1400
Uncontrolled	0.0208	0.0129	0.2173	0.1350
Gasoline Heavy-Duty Vehicles				
Low Emission Vehicles	0.1133	0.0704	0.0708	0.0440
EPA Tier 1[a]	0.1394	0.0866	0.0966	0.0600
EPA Tier 0[a]	0.2361	0.1467	0.1207	0.0750
Oxidation Catalyst[b]	0.1499	0.0932	0.1448	0.0900
Non-Catalyst Control	0.0480	0.0298	0.2012	0.1250
Uncontrolled	0.0480	0.0298	0.4345	0.2700
Diesel Passenger Cars				
Advanced	0.0161	0.0100	0.0161	0.0100
Moderate	0.0161	0.0100	0.0161	0.0100

Uncontrolled	0.0161	0.0100	0.0161	0.0100
Diesel Light-Duty Trucks				
Advanced	0.0322	0.0200	0.0161	0.0100
Moderate	0.0322	0.0200	0.0161	0.0100
Uncontrolled	0.0322	0.0200	0.0161	0.0100
Diesel Heavy-Duty Vehicles				
Advanced	0.0483	0.0300	0.0644	0.0400
Moderate	0.0483	0.0300	0.0805	0.0500
Uncontrolled	0.0483	0.0300	0.0966	0.0600
Motorcycles				
Non-Catalyst Control	0.0073	0.0045	0.2092	0.1300
Uncontrolled	0.0073	0.0045	0.4184	0.2600

Source: Derived from Barton and Simpson (1994), CARB (2000), Census (2000), Dasch (1992), DOE (1993 through 2003), EPA (1998), EPA (1997), EPA/DOE (2001), FHWA (1996 through 2003), ICF (2001), IPCC/UNEP/OECD/IEA (1997), Prigent and de Soete (1989), Smith and Carey (1982), and Urban and Garbe (1980).

[a] The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this annex.

[b] The CH_4 emission factor was assumed based on the oxidation catalyst value for gasoline light-duty trucks.

Table 3-19: Emission Factors for CH_4 and N_2O for Alternative Fuel Vehicle Technology Highway Vehicles

Vehicle Type/Control Technology	N_2O (g/mi)	N_2O (g/km)	CH_4 (g/mi)	CH_4 (g/km)
Light-duty Vehicles				
Methanol	0.063	0.039	0.014	0.009
CNG	0.113	0.070	0.914	0.568
LPG	0.008	0.005	0.038	0.024
Ethanol	0.076	0.047	0.043	0.027
Heavy-duty Vehicles				
Methanol	0.217	0.135	0.646	0.401
CNG	0.297	0.185	9.629	5.983
LNG	0.440	0.274	6.857	4.261
LPG	0.150	0.093	0.108	0.067
Ethanol	0.307	0.191	1.975	1.227
Buses				
Methanol	0.217	0.135	0.646	0.401
CNG	0.162	0.101	12.416	7.715
Ethanol	0.364	0.226	2.079	1.292

Source: Developed from Browning (2003), Wang (1999), Lipman and Delucchi (2002), CRC (1997), Brasil and McMahon (1999), and Norbeck, et al (1998).

Table 3-20: Emission Factors for CH_4 and N_2O Emissions from Non-Highway Mobile Combustion (g gas/kg fuel)

Vehicle Type/Fuel Type	N_2O	CH_4
Ships and Boats		
Residual	0.08	0.230
Distillate	0.08	0.230
Gasoline	0.08	0.230
Locomotives		
Diesel	0.08	0.250
Agricultural Equipment		
Gas	0.08	0.450
Diesel	0.08	0.450
Construction		
Gas	0.08	0.180
Diesel	0.08	0.180
Other Non-Highway		
Gas Snowmobile	0.08	0.180
Gas Small Utility	0.08	0.180

Gas HD Utility	0.08	0.180
Diesel HD Utility	0.08	0.180
Aircraft		
Jet Fuel	0.10	0.087
Aviation Gasoline	0.04	2.640

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

Table 3-21: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gasoline Highway	4.3	4.2	4.2	4.2	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.4	3.3
Passenger Cars	2.4	2.2	2.2	2.1	2.1	2.0	2.0	2.0	2.0	1.9	1.9	1.8	1.8
Light-Duty Trucks	1.6	1.7	1.9	1.9	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.5	1.4
Heavy-Duty Vehicles	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+
Diesel Highway	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Alternative Fuel Highway[a]	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Non-Highway	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5
Ships and Boats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Agricultural Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Construction Equipment	+	+	+	+	+	+	+	+	+	+	+	+	+
Aircraft	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1
Other[b]	+	+	+	+	+	+	+	+	+	+	+	+	+
Total	5.0	4.9	5.0	4.9	4.9	4.9	4.8	4.7	4.5	4.5	4.4	4.3	4.2

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[a] AFV emissions include emissions from gasoline-electric hybrid cars, which in fact derive their power from gasoline and not from an "alternative" fuel, as defined by the Department of Energy.
[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 3-22: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gasoline Highway	45.6	48.0	51.1	53.4	54.9	55.3	54.9	54.5	53.7	52.5	51.0	48.6	46.4
Passenger Cars	30.9	30.7	31.8	32.5	33.3	33.4	33.0	32.5	32.2	31.2	30.2	28.8	27.4
Light-Duty Trucks	13.9	16.4	18.5	20.0	20.6	20.9	20.8	20.9	20.4	20.2	19.7	18.8	17.9
Heavy-Duty Vehicles	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1
Motorcycles	+	+	+	+	+	+	+	+	+	+	+	+	+
Diesel Highway	2.0	2.1	2.2	2.3	2.4	2.6	2.6	2.8	2.9	3.0	3.0	3.1	3.2
Passenger Cars	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+	+	+
Light-Duty Trucks	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Heavy-Duty Vehicles	1.8	1.8	1.9	2.0	2.2	2.3	2.4	2.5	2.6	2.7	2.7	2.8	2.9
Alternative Fuel Highway[a]	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Non-Highway	3.0	2.9	3.0	2.9	3.0	3.0	3.1	3.0	2.9	3.0	3.3	3.1	3.2
Ships and Boats	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.3	0.2	0.3	0.5	0.3	0.4
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Agricultural Equipment	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Construction Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2
Aircraft	1.7	1.6	1.6	1.6	1.7	1.7	1.8	1.7	1.8	1.8	1.9	1.8	1.7
Other[b]	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Total	50.7	52.9	56.3	58.6	60.4	60.9	60.7	60.3	59.6	58.6	57.4	55.0	52.9

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[a] AFV emissions include emissions from gasoline-electric hybrid cars, which in fact derive their power from gasoline and not from an "alternative" fuel, as defined by the Department of Energy.
[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 3-23: NO_x Emissions from Mobile Combustion, 1990-2002 (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gasoline Highway	5,746	5,508	5,271	5,034	4,797	4,559	4,322	4,268	4,090	3,913	3,812	3,942	3,934
Passenger Cars	3,847	3,628	3,409	3,190	2,971	2,752	2,533	2,447	2,316	2,152	2,084	2,150	2,146
Light-Duty Trucks	1,364	1,356	1,349	1,341	1,333	1,325	1,318	1,334	1,294	1,264	1,303	1,363	1,360
Heavy-Duty Vehicles	515	505	496	487	478	469	459	475	467	484	411	414	413
Motorcycles	20	19	17	16	15	14	13	13	13	13	13	14	14
Diesel Highway	2,956	3,064	3,171	3,278	3,386	3,493	3,600	3,708	3,729	3,660	3,803	3,542	3,535
Passenger Cars	39	35	31	27	23	19	15	13	11	10	7	6	6
Light-Duty Trucks	20	19	17	16	14	12	11	10	9	8	6	6	6
Heavy-Duty Vehicles	2,897	3,010	3,123	3,236	3,349	3,462	3,575	3,685	3,709	3,643	3,791	3,530	3,523
Alternative Fuel Highway[a]	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
Non-Highway	3,432	3,492	3,552	3,612	3,672	3,732	3,791	3,792	3,772	4,009	3,780	3,770	3,883
Ships and Boats	953	962	971	980	990	999	1,008	963	919	885	966	971	1,000
Locomotives	857	873	888	904	920	935	951	962	973	984	908	907	934
Agricultural Equipment	437	445	453	461	470	478	486	487	487	538	484	480	494
Construction Equipment	641	652	663	675	686	697	708	708	706	827	697	690	710
Aircraft[b]	63	64	65	65	66	67	67	75	83	91	80	73	76
Other[c]	480	496	511	526	541	556	572	597	604	683	645	650	669
Total	12,134	12,064	11,994	11,924	11,854	11,784	11,714	11,768	11,592	11,582	11,395	11,254	11,352

IE = Included Elsewhere

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

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

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

Note: Totals may not sum due to independent rounding.

Table 3-24: CO Emissions from Mobile Combustion, 1990-2002 (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gasoline Highway	98,328	93,597	88,866	84,135	79,403	74,672	69,941	67,509	65,246	60,727	60,657	66,857	58,653
Passenger Cars	60,757	57,019	53,281	49,542	45,804	42,065	38,327	36,825	35,686	32,661	32,867	37,250	32,679
Light-Duty Trucks	29,237	28,799	28,361	27,923	27,486	27,048	26,610	25,748	24,754	23,159	24,532	26,611	23,345
Heavy-Duty Vehicles	8,093	7,555	7,017	6,480	5,942	5,404	4,867	4,787	4,642	4,744	3,104	2,842	2,493
Motorcycles	240	223	206	189	172	155	138	150	163	163	154	155	136
Diesel Highway	1,696	1,642	1,587	1,533	1,479	1,424	1,370	1,301	1,202	1,113	1,088	1,025	899
Passenger Cars	35	31	28	25	21	18	15	13	10	10	7	7	6
Light-Duty Trucks	22	21	20	18	17	16	14	13	12	9	6	6	5
Heavy-Duty Vehicles	1,639	1,589	1,539	1,490	1,440	1,391	1,341	1,276	1,179	1,094	1,075	1,011	887
Alternative Fuel Highway[a]	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
Non-Highway	19,459	19,899	20,339	20,778	21,218	21,658	22,098	21,474	21,493	22,733	21,935	22,387	22,511
Ships and Boats	1,679	1,724	1,770	1,815	1,861	1,906	1,951	1,948	1,943	2,280	1,945	1,952	1,963
Locomotives	85	86	88	90	91	93	94	89	83	105	90	90	90
Agricultural Equipment	582	591	600	610	619	628	638	636	633	677	626	621	625
Construction Equipment	1,090	1,098	1,107	1,115	1,123	1,132	1,140	1,098	1,081	1,154	1,047	1,041	1,047
Aircraft[b]	217	218	220	221	222	224	225	250	274	307	245	233	235
Other[c]	15,807	16,181	16,554	16,928	17,302	17,676	18,049	17,453	17,478	18,210	17,981	18,449	18,551
Total	119,482	115,137	110,791	106,446	102,100	97,755	93,409	90,284	87,940	84,574	83,680	90,268	82,063

IE = Included Elsewhere

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

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

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

Note: Totals may not sum due to independent rounding.

Table 3-25: NMVOCs Emissions from Mobile Combustion, 1990-2002 (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gasoline Highway	8,110	7,652	7,194	6,735	6,277	5,819	5,360	5,167	5,067	4,865	4,615	4,217	4,132
Passenger Cars	5,120	4,774	4,429	4,084	3,739	3,394	3,049	2,928	2,895	2,777	2,610	2,355	2,308
Light-Duty Trucks	2,374	2,303	2,232	2,161	2,090	2,019	1,947	1,882	1,812	1,713	1,750	1,638	1,605
Heavy-Duty Vehicles	575	536	498	459	420	382	343	336	335	347	232	203	199
Motorcycles	42	38	35	31	28	24	21	22	25	27	23	22	21

Diesel Highway	406	386	365	345	324	304	283	263	249	227	216	204	200
Passenger Cars	16	15	13	12	10	8	7	6	5	5	3	3	3
Light-Duty Trucks	14	13	12	11	10	9	9	8	7	6	4	4	4
Heavy-Duty Vehicles	377	358	340	322	304	286	268	249	237	216	209	198	194
Alternative Fuel Highway[a]	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
Non-Highway	2,416	2,457	2,498	2,540	2,581	2,622	2,663	2,498	2,427	2,567	2,398	2,379	2,439
Ships and Boats	608	634	660	687	713	739	765	766	763	811	744	730	748
Locomotives	33	34	35	35	36	36	37	35	33	40	35	35	36
Agricultural Equipment	85	85	85	86	86	86	86	83	81	86	76	72	74
Construction Equipment	149	150	150	151	152	152	153	142	137	149	130	125	128
Aircraft[b]	28	28	28	28	28	28	28	32	35	40	24	19	20
Other[c]	1,513	1,527	1,540	1,553	1,567	1,580	1,593	1,441	1,378	1,442	1,390	1,397	1,432
Total	10,933	10,495	10,058	9,620	9,182	8,744	8,306	7,928	7,742	7,658	7,230	6,800	6,771

IE = Included Elsewhere

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

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

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

Note: Totals may not sum due to independent rounding.

Definitions of Emission Control Technologies and Standards

The N_2O and CH_4 emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table 3-14 through Table 3-17 show the years in which these technologies or standards were in place and the penetration level for each vehicle type. These categories are defined below.

Uncontrolled

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline light-duty cars and trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to not have significant control technologies in place.

Gasoline Emission Controls

Below are the control technologies and emissions standards applicable to gasoline vehicles.

Non-catalyst

These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles beginning in 1996. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle NO_x standards.

Oxidation Catalyst

This control technology designation represents the introduction of the catalytic converter, and was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used in some heavy-duty gasoline vehicles between 1982 and 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

EPA Tier 0

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, therefore this technology was used in gasoline passenger cars and light-duty gasoline trucks sold beginning in the early 1980s, and remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to CO_2 and H_2O, reducing NO_x to nitrogen and oxygen, and using an on-board diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and NO_x to 1.0 g/mile by 1981.

EPA Tier 1

This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car NO_x emissions to 0.4 g/mi, and HC emissions to 0.25 g/mi. These bounds represented a 60 and 40 percent reduction, respectively, from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mi for NO_x, and 0.25 to 0.39 g/mi for HCs, depending on the weight of the truck. Emission reductions were met through the use of more advanced emission control systems, and applied to light-duty gasoline vehicles beginning in 1994. These advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

Low Emission Vehicles (LEV)

This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990s, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs) and super ultra-low emission vehicles (SULEVs). In this analysis, all categories of LEVs are treated the same due to the fact that there are very limited CH_4 or N_2O emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

Diesel Emission Controls

Below are the two levels of emissions control for diesel vehicles.

Moderate control

Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (generally in place in model years 1983 to 1995) are considered moderate control technologies. These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

Advanced control

EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the level of emission control necessary to comply with standards in place from 1996 through 2003.

Supplemental Information on GHG Emissions from Transportation and Other Mobile Sources

Although the inventory is not required to provide detail beyond what is contained in the body of this report, the IPCC allows presentation of additional data and detail on the inventory. Since the transportation end-use sector is a large consumer of fossil fuels in the United States, this Annex includes supplemental information on emissions from the transportation sector, organized by mode or source. In the main body of the Inventory report, emissions estimates are organized by greenhouse gas, with figures for CO_2, N_2O, CH_4, and HFC emissions generally presented separately. This section of the Annex reports on total emissions from all of these gases in terms of CO_2 equivalent, and is designed to make it easier to identify the contribution of individual modes of transportation to total GHG emissions in terms of global warming potential.

This section includes information on transportation and other mobile sources. Transportation is often defined as the movement of persons or goods from one location to another. As a result, transportation sources include highway vehicles, aircraft, boats and ships, locomotives and transit rail, which are all mobile sources, as well as pipelines, which are stationary but are used to transport fuel. Other mobile sources include construction equipment, agricultural equipment, and other sources that are mobile but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, lawnmowers, other small gasoline powered utility equipment, etc.).

Table 3-26 and Figure 3-1 present estimates of emissions from transportation and other mobile sources for all of the primary GHGs combined, in CO_2 equivalent. The estimates were prepared by summing the estimates of CO_2 presented in Table 3-7 of Chapter 3, estimates of N_2O and CH_4 presented in Table 3-20 and Table 3-21 of Chapter 3, and estimates of HFCs presented in Chapter 4 so that each transportation mode and/or vehicle type is presented with its total greenhouse gas emissions.

In the case of N_2O and CH_4, additional calculations were performed to develop emissions estimates by type of aircraft and type of heavy-duty vehicle (i.e., heavy-duty trucks or buses) to match the level of detail for CO_2 emissions. N_2O and CH_4 estimates were developed for individual aircraft types by multiplying the emissions estimates for aircraft for each fuel type (jet fuel and aviation gasoline, from Table 3-13) by the portion of fuel used by each aircraft type (from FAA 1995 through 2003). Similarly, N_2O and CH_4 estimates were developed for heavy-duty trucks and buses by multiplying the emissions estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from Table 3-20 and Table 3-21 of Chapter 3 by the portion of fuel used by each vehicle type (from DOE 1993 through 2003). Otherwise, the table and figure are drawn directly from emission estimates presented elsewhere in the inventory, and are dependent on the methodologies presented in Annex 2.1 (for CO_2), Chapter 4, and Annex 3.8 (for HFCs), and earlier in this Annex (for CH_4 and N_2O).

Freight and Passenger Transportation

Table 3-27, Table 3-28, Figure 3-2, and Figure 3-3, present GHG estimates from transportation broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general and commercial aviation), recreational boats, and mobile air conditioners, and are illustrated in Table 3-27 and Figure 3-2. Freight modes include heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, and pipelines, and are illustrated in Table 3-28 and Figure 3-3. Note that freight trucks (and other freight modes) do carry people, as well as freight (they transport the driver), but these are not typically considered passenger modes. Also, some aircraft do carry some freight, but separating out the emissions associated with freight versus passenger aircraft travel is difficult. To avoid double-counting emissions, this report assigns each of these modes to a single category.

The estimates in these tables and figures are drawn from the estimates in Table 3-26. In addition, estimates of fuel consumption from DOE (1993 through 2003) were used to allocate rail and watercraft emissions between passenger and freight categories.

Overall, emissions from transportation and mobile sources increased by 23.0 percent between 1990 and 2002. Particularly notable is the rapid increase in emissions from mobile air conditioners and refrigerated transport. In 1990, emissions from these sources were negligible; however, due to the phase-out of ozone-depleting substances (ODSs) under the Montreal Protocol and the Clean Air Act Amendments of 1990[1], the United States is replacing ODSs, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) with hydrofluorocarbons (HFCs) and other substitutes. While HFCs do not deplete the ozone layer, they are GHGs, so a significant increase in GHG emissions from mobile air conditioners and refrigerated transport is observed over the 1990 through 2002 timeframe. Due to changes in estimation methodology, the emissions estimates from these sources have increased significantly compared to last year's estimates. See Section 4.15 for more information on these changes.

In 2002, passenger transportation modes emitted 1,335.0 Tg CO_2 Eq. (72 percent of all transportation and mobile emissions), while freight transportation modes emitted 420.9 Tg CO_2 Eq. (23 percent of all transportation

[1] [42 U.S.C § 7671, CAA § 601]

and mobile emissions). The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction and agricultural equipment).

Table 3-26: U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (Tg CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1996	1997	1998	1999	2000	2001	2002	Contribution to U.S. Mobile Total	Change from 1990-2002
Highway Vehicles	1,163.8	1,308.3	1,330.3	1,371.3	1,412.8	1,427.7	1,432.0	1,458.2	78.2%	25.3%
Passenger Cars	633.4	625.1	622.7	642.3	652.3	653.8	654.0	666.2	35.7%	5.2%
Gasoline	627.3	620.4	618.1	637.9	648.0	649.8	650.0	662.6	35.5%	5.6%
Diesel	6.1	4.7	4.6	4.4	4.3	4.1	3.9	3.6	0.2%	-41.1%
AFVs[a]	+	+	+	+	+	+	+	+	0.0%	NE
Light-Duty Trucks	321.9	426.8	439.0	450.1	468.5	471.6	473.9	485.1	26.0%	50.7%
Gasoline	312.8	414.1	425.4	436.4	453.9	456.9	458.8	470.2	25.2%	50.4%
Diesel	8.6	12.2	13.2	13.3	14.2	14.4	14.7	14.5	0.8%	68.5%
AFVs[a]	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.4	0.0%	-36.0%
Heavy-Duty Trucks	199.4	246.3	258.2	268.3	280.3	290.8	293.4	296.7	15.9%	48.8%
Gasoline	40.6	36.9	35.6	35.8	35.0	34.6	32.7	32.7	1.8%	-19.4%
Diesel	158.0	208.8	222.1	231.8	244.8	255.7	260.1	263.4	14.1%	66.7%
AFVs[a]	0.9	0.5	0.5	0.7	0.6	0.5	0.6	0.7	0.0%	-23.5%
Buses	7.3	8.3	8.6	8.8	9.8	9.6	9.1	8.5	0.5%	16.3%
Gasoline	1.7	0.9	0.8	0.7	0.7	0.6	0.5	0.4	0.0%	-75.6%
Diesel	5.6	7.3	7.5	7.8	8.8	8.5	8.0	7.5	0.4%	33.9%
AFVs[a]	+	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.0%	NE
Motorcycles	1.8	1.8	1.8	1.8	1.9	1.9	1.7	1.7	0.1%	-5.0%
Gasoline	1.8	1.8	1.8	1.8	1.9	1.9	1.7	1.7	0.1%	-5.0%
Aircraft	178.7	182.1	180.8	182.7	188.7	195.2	185.3	179.4	9.6%	0.4%
General Aviation Aircraft	9.5	8.4	8.9	10.3	12.0	12.1	11.4	12.1	0.6%	26.9%
Jet Fuel	6.4	5.8	6.1	7.8	9.3	9.6	9.0	9.7	0.5%	52.5%
Aviation Gasoline	3.1	2.6	2.8	2.5	2.7	2.5	2.4	2.4	0.1%	-25.0%
Commercial Aircraft	119.4	126.2	130.7	132.8	137.8	142.1	134.2	123.0	6.6%	3.0%
Jet Fuel	119.4	126.2	130.7	132.8	137.8	142.1	134.2	123.0	6.6%	3.0%
Military Aircraft[b]	35.1	23.3	21.2	21.7	20.8	21.2	23.1	20.8	1.1%	-41.0%
Jet Fuel	35.1	23.3	21.2	21.7	20.8	21.2	23.1	20.8	1.1%	-41.0%
Other Aircraft[c]	14.7	24.1	19.9	17.9	18.0	19.9	16.7	23.6	1.3%	60.8%
Jet Fuel	14.7	24.1	19.9	17.9	18.0	19.9	16.7	23.6	1.3%	60.8%
Boats and Ships	48.4	48.2	33.7	27.4	38.5	59.7	37.6	52.9	2.8%	9.3%
Gasoline	11.3	8.5	8.4	8.2	9.4	9.7	8.5	9.3	0.5%	-17.9%
Distillate Fuel	13.5	14.9	14.6	13.0	15.2	15.1	16.5	16.1	0.9%	19.0%
Residual Fuel	23.6	24.8	10.8	6.2	13.8	34.9	12.6	27.6	1.5%	16.6%
Locomotives and Other Rail	28.0	32.6	32.6	33.2	34.5	34.4	35.0	33.9	1.8%	21.0%
Distillate Fuel	27.4	32.0	31.9	32.5	33.9	33.7	34.2	33.2	1.8%	21.0%
Electricity	0.6	0.6	0.7	0.6	0.7	0.7	0.8	0.7	0.0%	21.5%
Pipelines	38.3	41.1	43.3	37.3	37.8	37.7	36.1	37.1	2.0%	-3.1%
Natural Gas	35.9	38.7	40.9	34.9	35.3	35.0	33.4	34.7	1.9%	-3.4%
Electricity	2.4	2.4	2.4	2.5	2.5	2.6	2.7	2.4	0.1%	0.5%
Agricultural Equipment	32.3	34.1	34.3	31.9	29.0	30.8	34.6	33.0	1.8%	2.2%
Gasoline	7.1	7.9	8.4	7.8	6.0	5.6	6.9	7.2	0.4%	1.1%

Diesel	25.2	26.2	26.0	24.1	23.0	25.2	27.8	25.8	1.4%	2.5%
Construction Equipment	15.3	15.8	16.1	16.2	15.6	17.2	21.6	19.1	1.0%	24.4%
Gasoline	2.8	2.4	2.6	2.0	1.5	1.6	4.3	4.6	0.2%	65.5%
Diesel	12.6	13.3	13.6	14.2	14.1	15.5	17.2	14.5	0.8%	15.3%
Lubricants	11.7	10.9	11.5	12.0	12.1	12.0	11.0	10.8	0.6%	-7.7%
Mobile Air Conditioners	+	10.1	13.8	17.4	20.8	24.0	26.7	28.8	1.5%	NA
Refrigerated Transport	+	3.8	5.5	7.0	8.5	9.8	10.8	11.5	0.6%	NA
Other[d]	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.0%	15.8%
Total	1,516.8	1,687.1	1,702.2	1,736.6	1,798.4	1,848.6	1,830.9	1,865.0	100.0%	23.0%

[a] AFV emissions include emissions from gasoline-electric hybrid cars, which are not defined as "alternative fuel vehicles" by the U.S. Department of Energy.

[b] Data are not yet available for military aircraft for 2002, so the 2001 figure has been used as a placeholder.

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

[d] "Other" includes snowmobiles, small gasoline-powered utility equipment, heavy-duty gasoline-powered utility equipment, and heavy-duty diesel-powered utility equipment.

+ Does not exceed 0.05 Tg CO_2 Eq.

NA = Not Applicable

NE = Not Estimated, because emissions in 1990 were insignificant.

Figure 3-1: 2002 Domestic Greenhouse Gas Emissions by Mode and Vehicle Type (Tg CO_2 Eq.)

*Other includes non-highway sources not in other categories, such as construction and agricultural equipment, pipelines, lubricants, mobile air conditioners, and refrigerated transport, but does not include bunkers.

Table 3-27: Greenhouse Gas Emissions from Passenger Transportation (Tg CO_2 Eq.)

Vehicle Type	1990	1996	1997	1998	1999	2000	2001	2002	% Change 1990-2002
Highway Vehicles	962.6	1,060.2	1,070.3	1,101.2	1,130.6	1,135.0	1,136.9	1,159.8	20%
Passenger Cars	633.4	625.1	622.7	642.3	652.3	653.8	654.0	666.2	5%
Light-duty Trucks	321.9	426.8	439.0	450.1	468.5	471.6	473.9	485.1	51%
Buses	7.3	8.3	8.6	8.8	9.8	9.6	9.1	8.5	16%
Aircraft	128.9	134.6	139.7	143.1	149.8	154.2	145.6	135.0	5%
General Aviation	9.5	8.4	8.9	10.3	12.0	12.1	11.4	12.1	27%
Commercial Aviation	119.4	126.2	130.7	132.8	137.8	142.1	134.2	123.0	3%
Recreational Boats	11.3	8.5	8.4	8.2	9.4	9.7	8.5	9.3	-18%
Passenger Rail	1.6	1.7	1.8	1.8	1.9	2.1	2.2	2.1	30%
Mobile Air Conditioners	+	10.1	13.8	17.4	20.8	24.0	26.7	28.8	NA
Total	1,104.4	1,215.2	1,234.0	1,271.7	1,312.4	1,324.9	1,319.9	1,335.0	21%

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Data from DOE (1993 through 2003) was used to disaggregate emissions from rail and buses.

Figure 3-2: Greenhouse Gas Emissions from Passenger Transportation by Mode (Tg CO_2 Eq.)

Table 3-28: Greenhouse Gas Emissions from Domestic Freight Transportation (Tg CO_2 Eq.)

By Mode	1990	1996	1997	1998	1999	2000	2001	2002	% Change 1990-2002
Trucking	199.4	246.3	258.2	268.3	280.3	290.8	293.4	296.7	49%
Rail	26.4	31.0	30.8	31.3	32.6	32.4	32.8	31.8	20%
Waterborne	37.1	39.7	25.3	19.2	29.1	50.1	29.1	43.6	18%
Pipeline	38.3	41.1	43.3	37.3	37.8	37.7	36.1	37.1	-3%
Refrigerated Transport	+	3.8	5.5	7.0	8.5	9.8	10.8	11.5	NA
Total	301.3	361.9	363.1	363.2	388.3	420.7	402.2	420.9	40%

+ Does not exceed 0.05 Tg CO_2 Eq.
NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.
Note: Data from DOE (1993 through 2003) was used to allocate the passenger/freight split of rail emissions.

Figure 3-3: Greenhouse Gas Emissions from Domestic Freight Transportation by Mode (Tg CO_2 Eq.)

3.3. Methodology for Estimating CH_4 Emissions from Coal Mining

The methodology for estimating methane emissions from coal mining consists of two distinct steps. The first step addresses emissions from underground mines. For these mines, emissions are estimated on a mine-by-mine basis and then are summed to determine total emissions. The second step of the analysis involves estimating methane emissions for surface mines and post-mining activities. In contrast to the methodology for underground mines, which uses mine-specific data, the surface mine and post-mining activities analysis consists of multiplying basin-specific coal production by basin-specific emission factors.

Step 1: Estimate Methane Liberated and Methane Emitted from Underground Mines

Underground mines generate methane from ventilation systems and from degasification systems. Some mines recover and use methane generated from degasification systems, thereby reducing emissions to the atmosphere. Total methane emitted from underground mines equals the methane liberated from ventilation systems, plus the methane liberated from degasification systems, minus methane recovered and used.

Step 1.1: Estimate Methane Liberated from Ventilation Systems

All coal mines with detectable methane emissions[1] use ventilation systems to ensure that methane levels remain within safe concentrations. Many coal mines do not have detectable levels of methane, while others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures methane emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of methane in their ventilation air. Based on the four quarterly measurements, MSHA estimates average daily methane liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996 and 1998 through 2002, MSHA emissions data were obtained for a large but incomplete subset of all mines with detectable emissions. This subset includes mines emitting at least 0.1 MMCFD for some years and at least 0.5 MMCFD for other years, as shown in Table 3-29. Well over 90 percent of all ventilation emissions were concentrated in these subsets. For 1997, the complete MSHA database for all 586 mines with detectable methane emissions was obtained. These mines were assumed to account for 100 percent of methane liberated from underground mines. Using the complete database from 1997, the proportion of total emissions accounted for by mines emitting less than 0.1 MMCFD or 0.5 MMCFD was estimated (see Table 3-29). The proportion was then applied to the years 1990 through 2002 to account for the less than 10 percent of ventilation emissions coming from mines without MSHA data.

For 1990 through 1999, average daily methane emissions were multiplied by 365 to determine the annual emissions for each mine. For 2000, 2001, and 2002 MSHA provided quarterly emissions. The average daily methane emissions were multiplied by the number of days corresponding to the number of quarters the mine vent was operating. For example, if the mine vent was operational in one out of the four quarters, the average daily methane emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

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

Table 3-29: Mine-Specific Data Used to Estimate Ventilation Emissions

Year	Individual Mine Data Used
1990	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1991	1990 Emissions Factors Used Instead of Mine-Specific Data
1992	1990 Emissions Factors Used Instead of Mine-Specific Data
1993	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1994	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1995	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)*
1996	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)*
1997	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)
1998	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1999	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2000	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2001	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2002	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*

* Factor derived from a complete set of individual mine data collected for 1997.

Step 1.2: Estimate Methane Liberated from Degasification Systems

Coal mines use several different types of degasification systems to remove methane, including vertical wells and horizontal boreholes to recover methane prior to mining of the coal seam. Gob wells and cross-measure boreholes recover methane from the overburden (i.e., GOB area) after mining of the seam (primarily in longwall mines).

MSHA collects information about the presence and type of degasification systems in some mines, but does not collect quantitative data on the amount of methane liberated. Thus, the methodology estimated degasification emissions on a mine-by-mine basis based on other sources of available data. Many of the coal mines employing degasification systems have provided EPA with information regarding methane liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell methane recovered from degasification systems to a pipeline, gas sales were used to estimate methane liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell methane to a pipeline and have not provided information to EPA, methane liberated from degasification systems was estimated based on the type of system employed. For example, for coal mines employing gob wells and horizontal boreholes, the methodology assumes that degasification emissions account for 40 percent of total methane liberated from the mine.

Step 1.3: Estimate Methane Recovered from Degasification Systems and Used (Emissions Avoided)

In 2002, ten active coal mines had methane recovery and use projects and sold the recovered methane to a pipeline. One coal mine also used some recovered methane in a thermal dryer in addition to selling gas to a pipeline. In order to calculate emissions avoided from pipeline sales, information was needed regarding the amount of gas recovered and the number of years in advance of mining that wells were drilled. Several state agencies provided gas sales data, which were used to estimate emissions avoided for these projects. Additionally, coal mine operators provided information on gas sales and/or the number of years in advance of mining. Emissions avoided were attributed to the year in which the coal seam was mined. For example, if a coal mine recovered and sold methane using a vertical well drilled five years in advance of mining, the emissions avoided associated with those gas sales (cumulative production) were attributed to the well up to the time it was mined through (e.g., five years of gas production). Where individual well data is not available, estimated percentages of the operator's annual gas sales within the field around the coal mine are attributed to emissions avoidance. For some mines, individual well data were used to assign gas sales to the appropriate emissions avoided year. In most cases, coal mine operators provided this information, which was then used to estimate emissions avoided for a particular year. Additionally, several state agencies provided production data for individual wells.

Step 2: Estimate Methane Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were not available for estimating methane emissions from surface coal mines or for post-mining activities. For surface mines and post-mining activities, basin-specific coal production was multiplied by a basin-specific emission factor to determine methane emissions.

Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data

The first step in estimating methane emissions from surface mining and post-mining activities was to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis was conducted by coal basin as defined in Table 3-30, which presents coal basin definitions by basin and by state.

The Energy Information Agency's (EIA) Coal Industry Annual reports state- and county-specific underground and surface coal production by year. To calculate production by basin, the state level data were grouped into coal basins using the basin definitions listed in Table 3-30. For two states—West Virginia and Kentucky—county-level production data was used for the basin assignments because coal production occurred from geologically distinct coal basins within these states. Table 3-31 presents the coal production data aggregated by basin.

Step 2.2: Estimate Emissions Factors for Each Emissions Type

Emission factors for surface mined coal were developed from the *in situ* methane content of the surface coal in each basin. Based on an analysis presented in EPA (1993), surface mining emission factors were estimated to be from 1 to 3 times the average *in situ* methane content in the basin. For this analysis, the surface mining emission factor was determined to be twice the *in situ* methane content in the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* methane content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* methane content in the basin. Table 3-32 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate Methane Emitted

The total amount of methane emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual methane emissions are equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions. Table 3-33 and Table 3-34 present estimates of methane liberated, used, and emitted for 1990 through 2001. Table 3-35 provides emissions by state.

Table 3-30: Coal Basin Definitions by Basin and by State

Basin	States
Northern Appalachian Basin	Maryland, Ohio, Pennsylvania, West Virginia North
Central Appalachian Basin	Kentucky East, Tennessee, Virginia, West Virginia South
Warrior Basin	Alabama, Mississippi
Illinois Basin	Illinois, Indiana, Kentucky West
South West and Rockies Basin	Arizona, California, Colorado, New Mexico, Utah
North Great Plains Basin	Montana, North Dakota, Wyoming
West Interior Basin	Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas
Northwest Basin	Alaska, Washington
State	**Basin**
Alabama	Warrior Basin
Alaska	Northwest Basin
Arizona	South West and Rockies Basin
Arkansas	West Interior Basin
California	South West and Rockies Basin
Colorado	South West and Rockies Basin
Illinois	Illinois Basin

Indiana	Illinois Basin
Iowa	West Interior Basin
Kansas	West Interior Basin
Kentucky East	Central Appalachian Basin
Kentucky West	Illinois Basin
Louisiana	West Interior Basin
Maryland	Northern Appalachian Basin
Mississippi	Warrior Basin
Missouri	West Interior Basin
Montana	North Great Plains Basin
New Mexico	South West and Rockies Basin
North Dakota	North Great Plains Basin
Ohio	Northern Appalachian Basin
Oklahoma	West Interior Basin
Pennsylvania.	Northern Appalachian Basin
Tennessee	Central Appalachian Basin
Texas	West Interior Basin
Utah	South West and Rockies Basin
Virginia	Central Appalachian Basin
Washington	Northwest Basin
West Virginia South	Central Appalachian Basin
West Virginia North	Northern Appalachian Basin
Wyoming	North Great Plains Basin

Table 3-31: Annual Coal Production (Thousand Short Tons)

Underground Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
N. Appalachia	103,865	103,450	105,220	77,032	100,122	98,103	106,729	112,135	116,718	107,575	105,374	107,025	98,643
Cent. Appalachia	198,412	181,873	177,777	164,845	170,893	166,495	171,845	177,720	171,279	157,058	150,584	152,457	137,224
Warrior	17,531	17,062	15,944	15,557	14,471	17,605	18,217	18,505	17,316	14,799	15,895	15,172	14,916
Illinois	69,167	69,947	73,154	55,967	69,050	69,009	67,046	64,728	64,463	63,529	53,720	54,364	54,016
S. West/Rockies	32,754	31,568	31,670	35,409	41,681	42,994	43,088	44,503	45,983	46,957	45,742	51,193	52,121
N. Great Plains	1,722	2,418	2,511	2,146	2,738	2,018	2,788	2,854	1,723	1,673	1,210	0	0
West Interior	105	26	59	100	147	25	137	212	247	200	241	416	464
Northwest	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	423,556	406,344	406,335	351,056	399,102	396,249	409,850	420,657	417,729	391,791	372,766	380,627	357,384

Surface Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
N. Appalachia	60,761	51,124	50,512	48,641	44,960	39,372	39,788	40,179	41,043	33,928	34,908	35,334	30,008
Cent. Appalachia	94,343	91,785	95,163	94,433	106,129	106,250	108,869	113,275	108,345	107,507	110,479	116,983	111,340
Warrior	11,413	10,104	9,775	9,211	8,795	7,036	6,420	5,963	5,697	4,723	4,252	4,796	6,320
Illinois	72,000	63,483	58,814	50,535	51,868	40,376	44,754	46,862	47,715	40,474	33,631	40,894	39,380
S. West/Rockies	43,863	42,985	46,052	48,765	49,119	46,643	43,814	48,374	49,635	50,349	49,587	52,180	50,006
N. Great Plains	249,356	259,194	258,281	275,873	308,279	331,367	343,404	349,612	385,438	407,683	407,670	438,367	441,346
West Interior	64,310	61,889	63,562	60,574	58,791	59,116	60,912	59,061	57,951	58,309	54,170	50,613	50,459
Northwest	6,707	6,579	6,785	6,340	6,460	6,566	6,046	5,945	5,982	5,666	5,911	6,138	6,973
Total	602,753	587,143	588,944	594,372	634,401	636,726	654,007	669,271	699,608	708,639	700,608	745,306	735,912

Total Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
N. Appalachia	164,626	154,574	155,732	125,673	145,082	137,475	146,517	152,314	157,761	141,145	140,282	142,360	128,731
Cent. Appalachia	292,755	273,658	272,940	259,278	277,022	272,745	280,714	290,995	279,624	262,660	261,063	269,440	248,564
Warrior	28,944	27,166	25,719	24,768	23,266	24,641	24,637	24,468	23,013	19,499	20,147	19,967	21,236
Illinois	141,167	133,430	131,968	106,502	120,918	109,385	111,800	111,590	110,176	103,966	87,351	95,258	93,396
S. West/Rockies	76,617	74,553	77,722	84,174	90,800	89,637	86,902	92,877	95,618	96,207	95,239	103,373	102,127
N. Great Plains	251,078	261,612	260,792	278,019	311,017	333,385	346,192	352,466	387,161	406,324	408,880	438,367	441,346
West Interior	64,415	61,915	63,621	60,674	58,938	59,141	61,049	59,273	58,198	58,509	54,411	51,028	50,923
Northwest	6,707	6,579	6,785	6,340	6,460	6,566	6,046	5,945	5,982	5,665	5,911	6,138	6,973
Total	1,026,309	993,487	995,279	945,428	1,033,503	1,032,975	1,063,857	1,089,928	1,118,132	1,093,975	1,073,374	1,127,689	1,093,296

Source for 1990-02 data: EIA (1990-02), Coal Industry Annual. U.S. Department of Energy, Washington, DC, Table 3.
Note: Totals may not sum due to independent rounding.

Table 3-32: Coal Surface and Post-Mining Methane Emission Factors (ft^3 per Short Ton)

Basin	Surface Average *in situ* Content	Underground Average *In situ* Content	Surface Mine Factors	Post-Mining Surface Factors	Post Mining Underground

Northern Appalachia	59.5	138.4	119.0	19.3	45.0
Central Appalachia (WV)	24.9	136.8	49.8	8.1	44.5
Central Appalachia (VA)	24.9	399.1	49.8	8.1	129.7
Central Appalachia (E KY)	24.9	61.4	49.8	8.1	20.0
Warrior	30.7	266.7	61.4	10.0	86.7
Illinois	34.3	64.3	68.6	11.1	20.9
Rockies (Piceance Basin)	33.1	196.4	66.2	10.8	63.8
Rockies (Unita Basin)	16.0	99.4	32.0	5.2	32.3
Rockies (San Juan Basin)	7.3	104.8	14.6	2.4	34.1
Rockies (Green River Basin)	33.1	247.2	66.2	10.8	80.3
Rockies (Raton Basin)	33.1	127.9	66.2	10.8	41.6
N. Great Plains	5.6	15.8	11.2	1.8	5.1
West Interior (Forest City, Cherokee Basins)	34.3	64.3	68.6	11.1	20.9
West Interior (Arkoma Basin)	74.5	331.2	149.0	24.2	107.6
West Interior (Gulf Coast Basin)	33.1	127.9	66.2	10.8	41.6
Northwest (AK)	5.6	160.0	11.2	1.8	52.0
Northwest (WA)	5.6	47.3	11.2	1.8	18.9

Source: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*, 1983 U.S. DOE Report (DOE/METC/83-76), *Methane Recovery from Coalbeds: A Potential Energy Source*, 1986-88 Gas Research Institute Topical Reports, *A Geologic Assessment of Natural Gas from Coal Seams.*

Table 3-33: Underground Coal Mining Methane Emissions (Billion Cubic Feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Ventilation Output	112	NA	NA	95	96	102	90	96	94	92	87	84	79
Adjustment Factor for Mine Data*	97.8%	NA	NA	97.8%	97.8%	91.4%	91.4%	100%	97.8%	97.8%	97.8%	97.8%	97.8%
Adjusted Ventilation Output	114	NA	NA	97	98	111	99	96	96	94	89	86	80
Degasification System Liberated	54	NA	NA	45	46	46	50	42	49	41	45	48	52
Total Underground Liberated	167	164	162	142	144	157	149	138	146	135	134	135	132
Recovered & Used	(14)	(15)	(16)	(23)	(28)	(30)	(36)	(28)	(35)	(32)	(36)	(40)	(44)
Total	154	150	146	119	117	127	113	110	110	103	98	95	88

* Refer to Table E-1.

Note: Totals may not sum due to independent rounding.

Table 3-34: Total Coal Mining Methane Emissions (Billion Cubic Feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Underground Mining	154	149	144	119	117	127	113	110	110	103	98	95	88
Surface Mining	26	24	24	23	23	22	23	23	23	22	22	23	22
Post-Mining (Underground)	19	18	18	16	17	17	18	18	18	17	17	17	16
Post-Mining (Surface)	4	4	4	4	4	4	4	4	4	4	4	4	4
Total	203	196	191	162	16	170	157	156	156	146	140	138	130

Note: Totals may not sum due to independent rounding.

Table 3-35: Total Coal Mining Methane Emissions by State (Million Cubic Feet)

State	1990	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Alabama	32,313	25,927	29,595	38,641	29,229	25,731	26,401	25,653	23,554	22,196	19,013
Alaska	22	21	20	22	19	19	17	20	21	20	15
Arizona	192	207	222	203	177	199	192	200	223	228	217
Arkansas	7	8	8	5	4	3	4	4	2	2	2
California	1	0	0	0	0	0	0	0	0	0	0
Colorado	10,325	7,225	9,192	8,663	5,960	9,189	9,181	9,390	10,784	11,117	12,082
Illinois	10,502	8,684	10,585	11,084	10,850	8,534	7,847	7,810	8,521	7,270	5,972
Indiana	2,795	2,334	2,495	1,866	2,192	2,742	2,878	2,650	2,231	3,373	3,496
Iowa	30	14	4	0	0	0	0	0	0	0	0
Kansas	57	27	23	23	19	29	27	33	16	14	16
Kentucky	10,956	10,111	11,259	9,748	8,978	10,451	10,005	9,561	9,056	9,363	8,464
Louisiana	245	241	267	286	248	273	247	227	284	286	293
Maryland	519	228	237	237	259	267	251	225	331	340	401
Mississippi	-	0	0	0	0	0	0	1	57	43	165
Missouri	211	52	67	44	57	32	30	31	35	29	20
Montana	490	468	542	514	492	534	558	535	449	510	487
New Mexico	451	641	679	466	408	459	489	497	464	630	1,280
North Dakota	380	416	420	392	389	385	389	405	407	397	401
Ohio	5,065	4,393	4,583	4,029	4,064	4,349	4,350	3,914	3,515	3,619	2,831
Oklahoma	285	298	359	323	286	385	395	469	453	620	660
Pennsylvania	22,735	26,436	24,024	26,995	26,382	30,026	29,491	23,626	22,253	22,253	19,667
Tennessee	296	104	101	112	143	148	116	119	99	142	142
Texas	4,291	4,199	4,028	4,054	4,245	4,104	4,047	4,084	3,732	3,466	3,482
Utah	3,587	3,505	2,616	2,410	2,805	3,566	3,859	3,633	2,811	2,081	2,709
Virginia	46,137	30,387	26,742	19,820	19,675	16,851	13,978	13,321	11,981	11,506	11,227
Washington	65	62	64	63	59	59	60	53	56	60	76
West Virginia	49,039	33,110	30,588	36,657	36,307	33,572	36,962	35,416	31,311	33,745	31,716
Wyoming	2,385	2,719	3,065	3,419	3,604	3,652	4,080	4,376	4,408	4,801	4,859
Total	203,381	161,817	161,784	170,076	156,851	155,559	155,856	146,255	139,625	138,111	129,694

\+ Does not exceed 0.5 Million Cubic Feet

Note: The emission estimates provided above are inclusive of emissions from underground mines, surface mines and post-mining activities. The following states have neither underground nor surface mining and thus report no emissions as a result of coal mining: Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Maine, Massachusetts, Michigan, Minnesota, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, South Carolina, South Dakota, Vermont, and Wisconsin. Emission estimates are not given for 1991 and 1992 because underground mine data was not available for those years.

3.4. Methodology for Estimating CH_4 Emissions from Natural Gas Systems

The following steps were used to estimate methane emissions from natural gas systems.

Step 1: Calculate Emission Estimates for Base Year 1992 Using GRI/EPA Study

The first step in estimating methane emissions from natural gas systems was to develop a detailed base year estimate of emissions. The study by GRI/EPA (1996) divides the industry into four stages to construct a detailed emission inventory for the year 1992. These stages include: field production, processing, transmission and storage (i.e., both underground and liquefied gas storage), and distribution. This study produced emission factors and activity data for over 100 different emission sources within the natural gas system. Emissions for 1992 were estimated by multiplying activity levels by emission factors for each system component and then summing by stage. Since publication, the EPA has updated activity data for some of the components in the system. Table 3-36 displays the 1992 GRI/EPA activity levels and emission factors for venting and flaring from the field production stage, and the current EPA activity levels and emission factors. These data are shown to illustrate the kind of data used to calculate emissions from all stages.

Step 2: Collect Aggregate Statistics on Main Driver Variables

As detailed data on each of the over 100 sources were not available for the period 1990 through 2002, activity levels were estimated using aggregate statistics on key drivers, including: number of producing wells (API 2002, EIA 2003d), number of gas plants (AGA 1990 through 1998; OGJ 1999 through 2002), miles of transmission pipeline (OPS 2002a), miles of distribution pipeline (OPS 2002b), miles of distribution services (OPS 2002b), and energy consumption (EIA 2001, 2003c, 2003f). Data on the distribution of gas mains and services by material type was not available for 1990 through 1992 from OPS. For those years, the distribution by type was back calculated from 1993 using compound growth rates determined for the years 1993 through 2000. Table 3-37 provides the activity levels of some of the key drivers in the natural gas analysis.

Step 3: Estimate Emission Factor Changes Over Time

In the past, emissions factors were reduced at a rate of 0.2 percent per year such that by year 2020, emissions factors would have declined by 5 percent from 1995. These reductions were made to reflect underlying technological improvements through both innovation and normal replacement of equipment. However, the analysis already incorporates the emissions reductions from some of these technological improvements as reported by EPA's Natural Gas STAR Partners. Thus, to eliminate this double counting, the emissions factors were kept constant throughout the time series for this year's Inventory.

Step 4: Estimate Emissions for Each Year and Stage

Emissions from each stage of the natural gas industry were estimated by multiplying the activity factors by the appropriate emission factors, summing all sources for each stage, and then subtracting the Natural Gas STAR Program emission reductions. Methane reductions from the Natural Gas STAR Program for the years 1990 through 2002 are presented in Table 3-38. Emission reductions by project are reported by industry partners using actual measurement data or equipment-specific emission factors. Before incorporating the reductions into the Inventory, quality assurance and quality control checks are undertaken to identify errors, inconsistencies, or irregular data. Total emissions were estimated by adding the emission estimates from each stage. Table 3-39 illustrates emission estimates for venting and flaring emissions from the field production stage using this methodology. Table 3-40 presents total natural gas production and associated methane emissions.

Table 3-36: 1992 Data and Emissions (Mg) for Venting and Flaring from Natural Gas Field Production Stage

Activity	GRI/EPA Values					EPA Adjusted Values				
	Activity Data		Emission Factor		Emissions	Activity Data		Emission Factor		Emissions
Drilling and Well Completion										
Completion Flaring	844	compl/yr	733	scf/comp	12	400	compl/yr	733	scf/comp	6
Normal Operations										
Pneumatic Device Vents	249,111	controllers	345	scfd/device	602,291	249,111	controllers	345	scfd/device	602,291
Chemical Injection Pumps	16,971	active pumps	248	scfd/pump	29,501	16,971	active pumps	248	scfd/pump	29,501
Kimray Pumps	11,050,000	MMscf/yr	992	scf/MMscf	210,463	7,380,194	MMscf/yr	992	scf/MMscf	140,566
Dehydrator Vents	12,400,000	MMscf/yr	276	scf/MMscf	65,608	8,200,215	MMscf/yr	276	scf/MMscf	43,387
Compressor Exhaust Vented										
Gas Engines	27,460	MMHPhr	0.24	scf/HPhr	126,536	27,460	MMHPhr	0.24	scf/HPhr	126,536
Routine Maintenance										
Well Workovers										
Gas Wells	9,392	w.o./yr	2,454	scfy/w.o.	443	9,392	w.o./yr	2,454	scfy/w.o.	443
Well Clean Ups (LP Gas Wells)	114,139	LP gas wells	49,570	scfy/LP well	108,631	114,139	LP gas wells	49,570	scfy/LP well	108,631
Blowdowns										
Vessel BD	255,996	vessels	78	scfy/vessel	383	242,306	vessels	78	scfy/vessel	363
Pipeline BD	340,000	miles (gath)	309	scfy/mile	2,017	340,200	miles (gath)	309	scfy/mile	2,018
Compressor BD	17,112	compressors	3,774	scfy/comp	1,240	17,112	compressors	3,774	scfy/comp	1,240
Compressor Starts	17,112	compressors	8,443	scfy/comp	2,774	17,112	compressors	8,443	scfy/comp	2,774
Upsets										
Pressure Relief Valves	529,440	PRV	34.0	scfy/PRV	346	529,440	PRV	34.0	scfy/PRV	346
Emergency Safety Device	1,115	platforms	256,888	scfy/plat	5,499	1,372	platforms	256,888	scfy/plat	6,767
Mishaps	340,000	miles	669	scfy/mile	4,367	340,200	miles	669	scfy/mile	4,370

Table 3-37: Activity Factors for Key Drivers

Variable	Units	1990		1997	1998	1999	2000	2001	2002
Transmission Pipelines Length	miles	291,990		294,304	302,706	296,581	293,774	278,269	278,269
Wells									
GSAM Appalachia Wells*	No. wells	120,443		120,037	117,878	118,723	135,065	136,987	136,987
GSAM N Central Associated Wells*	No. wells	3,780		3,409	3,361	3,275	2,439	2,278	2,278
GSAM N Central Non-Associated Wells*	No. wells	3,277		8,910	8,917	8,800	9,113	9,517	9,517
GSAM Rest of U.S. Wells*	No. wells	145,380		182,024	190,134	174,898	197,500	220,345	220,345
GSAM Rest of U.S. Associated Wells*	No. wells	270,958		264,385	254,848	251,686	245,967	244,557	244,557
Appalch. + N. Central Non-Assoc. + Rest of U.S.	No. wells	269,100		310,971	316,929	302,421	341,678	366,849	366,849
N. Central Non-Assoc. + Rest of U.S. Wells	No. wells	148,657		190,934	199,051	183,698	206,613	229,862	229,862
Platforms									
Gulf of Mexico Off-shore Platforms	No. platforms	3,798		3,846	3,963	3,975	4,019	4,009	3,494
Rest of U.S. (offshore platforms)	No. platforms	24		23	23	23	23	23	23
Gas Plants		761		615	558	581	585	570	590
Distribution Services		43,065,846		53,895,713	54,035,004	54,317,439	56,555,782	57,511,048	60,753,920
Steel – Unprotected	No. of services	5,500,993		5,518,795	5,463,253	5,751,250	5,675,373	5,469,468	5,328,485
Steel - Protected	No. of services	19,916,202		19,078,467	18,478,344	18,310,719	17,786,955	17,899,877	18,120,504
Plastic	No. of services	16,269,414		27,800,401	28,629,388	28,796,952	31,659,363	32,741,971	35,777,119
Copper	No. of services	1,379,237		1,498,050	1,464,019	1,458,518	1,434,091	1,399,732	1,527,812
Distribution Mains		837,300		997,486	1,019,816	1,004,907	1,044,473	1,098,545	1,141,759
Steel – Unprotected	miles	91,267		85,166	86,639	84,534	82,855	81,273	82,610
Steel – Protected	miles	491,120		479,278	484,963	459,298	469,306	475,016	487,667
Cast Iron	miles	52,644		47,669	47,587	45,865	44,726	44,404	45,523
Plastic	miles	202,269		385,373	400,627	415,210	447,586	497,852	525,959

* GSAM (Gas Systems Analysis Model) is a natural gas supply, demand, and transportation model used by the Federal Energy Technology Center of the U.S. Department of Energy (GSAM 1997).

Table 3-38: Methane Reductions from the Natural Gas STAR program (Tg)

Process	1990	1996	1997	1998	1999	2000	2001	2002
Production	.01	0.17	0.22	0.26	0.29	0.33	0.37	0.49
Processing	--	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Transmission and Storage	--	0.10	0.13	0.18	0.22	0.27	0.34	0.34
Distribution	--	0.02	0.03	0.03	0.02	0.02	0.03	0.19

Table 3-39: CH_4 Emission Estimates for Venting and Flaring from the Field Production Stage (Mg)

Activity	1990	1996	1997	1998	1999	2000	2001	2002
Drilling and Well Completion								
Completion Flaring	5.5	6.17	6.36	6.48	6.18	6.98	7.50	7.50
Normal Operations								
Pneumatic Device Vents	589,673	710,474	757,372	789,570	728,669	819,566	911,787	911,787
Chemical Injection Pumps	37,761	46,547	49,768	51,783	47,943	53,712	59,588	59,588
Kimray Pumps	137,344	153,856	158,434	161,408	154,106	174,125	186,842	186,842
Dehydrator Vents	42,392	47,489	48,902	49,820	47,566	53,745	57,670	57,670
Compressor Exhaust Vented Gas Engines	123,884	149,264	159,116	165,881	153,086	172,182	191,557	191,557
Routine Maintenance								
Well Workovers Gas Wells	543	609	627	639	610	689	739	739
Well Clean Ups (LP Gas Wells)	103,451	115,888	119,337	121,577	116,076	131,156	140,734	140,734
Blowdowns								
Vessel BD	265	312	329	340	318	357	393	393
Pipeline BD	1,749	1,938	2,005	2,053	1,956	2,142	2,295	2,295
Compressor BD	1,598	1,840	1,927	1,988	1,862	2,096	2,293	2,293
Compressor Starts	3,575	4,116	4,311	4,448	4,167	4,689	5,130	5,130
Upsets								
Pressure Relief Valves	338	408	435	453	418	470	523	523
ESD	6,764	6,848	6,843	7,048	7,069	7,146	7,128	6,226
Mishaps	947	1,049	1,085	1,111	1,058	1,159	1,242	1,242

Table 3-40: U.S. Total Natural Gas Production (Trillion Ft^3/yr) and Associated CH_4 Emissions (Gg)

Activity	1990	1996	1997	1998	1999	2000	2001	2002
Production	17.8	18.9	18.9	19.0	18.83	19.2	19.7	19.0
CH_4 Emissions from Production	1,445	1,538	1,579	1,606	1,467	1,668	1,833	1,817

3.5. Methodology for Estimating CH_4 Emissions from Petroleum Systems

The methodology for estimating methane emissions from petroleum systems is based on the 1999 EPA draft report, *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999) and the study, *Methane Emissions from the U.S. Petroleum Industry* (Radian 1996). Seventy activities that emit methane from petroleum systems were examined from these reports. Most of the activities analyzed involve crude oil production field operations, which accounted for over 97 percent of total oil industry emissions. Crude transportation and refining accounted for the remaining emissions of one-half and two and a half percent, respectively.

The following steps were taken to estimate methane emissions from petroleum systems.

Step 1: Determine Emission Factors for all Activities

The emission factors for sixty-seven of the seventy activities for 1995 are taken from the 1999 EPA draft report, which contained the most recent and comprehensive determination of methane emission factors for the seventy methane emitting activities in the oil industry at that time. Emission factors for pneumatic devices in the production sector were recalculated in 2002 using emissions data in the EPA GRI 1996 study, averaging high bleed data for those devices that were judged to be in the production sector and low bleed data for those devices in the production sector. Gas engine emissions factor is taken from Radian (1996). The emission factors determined for 1995 were assumed to be representative of emissions from each source type over the period 1990 through 2002. Therefore, the same emission factors are used for each year throughout this period.

Step 2: Determine Activity Levels for Each Year

Activity levels change from year to year. Some factors change in proportion to crude oil rates: production, transportation, refinery runs. Some change in proportion to the number of facilities: oil wells, petroleum refineries. Some factors change proportional to both rate and number of facilities.

For fifty-seven activities, activity levels for 1995 are taken from EPA (1999). For the remaining thirteen activities, the activity levels for 1993 are taken from Radian (1996). These thirteen activity levels were derived from field data collected in 1993, along with 1993 crude oil production and number of wells.

For both sets of data, a determination is made on a case-by-case basis as to which measure of petroleum industry activity best reflects the change in annual activity relative to the base years (1993 and 1995). Publicly reported data from the Minerals Management Service (MMS), Energy Information Administration (EIA), American Petroleum Institute (API), and the Oil & Gas Journal (O&GJ) are used to extrapolate the activity levels from the base year to each year between 1990 and 2002. Data used include total domestic crude oil production, number of domestic crude oil wells, total imports and exports of crude oil, and total petroleum refinery crude runs. The activity data for the transportation sector were not yet available. In this case, all the crude oil that is transported is assumed to go to refineries. Therefore, the activity data for the refining sector was used also for the transportation sector. For a small number of sources, 2002 data were not yet available. In these cases, the 2001 activity factors were used. In the few cases where no data was located, oil industry data based on expert judgment was used.

Step 3: Estimate Methane Emissions for Each Activity for Each Year

Annual emissions from each of the 70 petroleum system activities were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then were summed to estimate the total annual methane emissions. For the production sector, the amount of emission reductions achieved by the EPA's Natural Gas STAR Program were subtracted from estimated production emissions. Table 3-41, Table 3-42, and Table 3-43 provide 2002 activity factors, emissions factors and emission estimates. CH_4 emissions from the Natural STAR Program for the years 1990 through 2002 are presented in Table 3-44. Table 3-45 provides a summary of emissions estimates for the years 1990 through 2002.

Table 3-41: 2002 CH_4 Emissions from Petroleum Production Field Operations

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					53.047
Oil Tanks	18	scf of CH_4/bbl crude	1,491	MMbbl/yr (non stripper wells)	26.684
Pneumatic Devices, High Bleed	330	scfd CH_4/device	141,771	No. of high-bleed devices	17.097
Pneumatic Devices, Low Bleed	52	scfd CH_4/device	263,299	No. of low-bleed devices	4.997
Chemical Injection Pumps	248	scfd CH_4/pump	28,380	No. of pumps	2.570
Vessel Blowdowns	78	scfy CH_4/vessel	185,106	No. of vessels	0.014
Compressor Blowdowns	3,775	scf/yr of CH_4/compressor	2,512	No. of compressors	0.009
Compressor Starts	8,443	scf/yr. of CH_4/compressor	2,512	No. of compressors	0.021
Stripper wells	2,345	scf/yr of CH_4/stripper well	322,767	No. of stripper wells vented	0.818
Well Completion Venting	733	scf/completion	4,964	Oil well completions	0.004
Well Workovers	96	scf CH_4/workover	39,750	Oil well workovers	0.004
Pipeline Pigging	2.40	scfd of CH_4/pig station	0	No. of crude pig stations	0.000
Offshore Platforms, Gulf of Mexico	1,283	scfd CH_4/platform	1,876	No. of oil platforms	0.878
Offshore Platforms, Other U.S. Areas	1,283	scfd CH_4/platform	23	No. of oil platforms	0.011
Fugitive Emissions					2.592
Offshore Platforms, Gulf of Mexico	56	scfd CH_4/platform	1,876	No. of oil platforms	0.038
Offshore Platforms, Other U.S. Areas	56	scfd CH_4/platform	23	No. of oil platforms	0.000
Oil Wellheads (heavy crude)	0.13	scfd/well	14,610	No. of hvy. crude wells *	0.001
Oil Wellheads (light crude)	16.6	scfd/well	192,623	No. of lt. crude wells *	1.169
Separators (heavy crude)	0.15	scfd CH_4/separator	10,888	No. of hvy. crude seps.	0.001
Separators (light crude)	14	scfd CH_4/separator	99,099	No. of lt. crude seps.	0.501
Heater/Treaters (light crude)	19	scfd CH_4/heater	75,128	No. of heater treaters	0.526
Headers (heavy crude)	0.08	scfd CH_4/header	13,825	No. of hvy. crude hdrs.	0.000
Headers (light crude)	11	scfd CH_4/header	42,859	No. of lt. crude hdrs.	0.170
Floating Roof Tanks	338,306	scf CH_4/floating roof tank/yr.	24	No. of floating roof tanks	0.008
Compressors	100	scfd CH_4/compressor	2,512	No. of compressors	0.092
Large Compressors	16,360	scfd CH_4/compressor	0	No. of large comprs.	0.000
Sales Areas	41	scf CH_4/loading	1,747,462	Loadings/year	0.071
Pipelines	0	scfd of CH_4/mile of pipeline	19,149	Miles of gathering line	0.000
Well Drilling	0	scfd of CH_4/oil well drilled	8,825	No. of oil wells drilled	0.000
Battery Pumps	0.24	scfd of CH_4/pump	159,000	No. of battery pumps	0.014
Combustion Emissions					4.159
Gas Engines	0.24	scf CH_4/HP-hr	15,8260	MMHP-hr	3.798
Heaters	0.52	scf CH_4/bbl	2,097.3	MBbl/yr	0.001
Well Drilling	2,453	scf CH_4/well drilled	5,825	Oil wells drilled, 1995	0.014
Flares	20	scf CH_4/Mcf flared	587,049582	Mcf flared/yr	0.012
Offshore Platforms, Gulf of Mexico	481	scfd CH_4/platform	1,876	No. of oil platforms	0.329
Offshore Platforms, Other U.S. Areas	481	scfd CH_4/platform	23	No. of oil platforms	0.004
Process Upset Emissions					0.554
Platform Emergency Shutdowns	256,888	scfy/platform	1,899	No. of platforms	0.488
Pressure Relief Valves	35	scf/yr/PR valve	175,187	No. of PR valves	0.006
Well Blowouts Offshore	5.0	MMscf/blowout	2.25	No. of blowouts/yr	0.011
Well Blowouts Onshore	2.5	MMscf/blowout	19.4	No. of blowouts/yr	0.049
Total					60.35

Note: These estimates do not include emission reductions reported by the Natural Gas STAR Program.

Table 3-42: 2002 CH_4 Emissions from Petroleum Transportation

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					0.221
Tanks	0.021	scf CH_4/yr/bbl of crude delivered to refineries	5,456	MMbbl crude feed/yr	0.112
Truck Loading	0.520	scf CH_4/yr/bbl of crude transported by truck	51.1	MMbbl crude feed/yr	0.027
Marine Loading	2.544	scf CH_4/1000 gal. crude marine loadings	24,149,670	1,000 gal./yr loaded	0.061
Rail Loading	0.520	scf CH_4/yr/bbl of crude transported by rail	7.5	MMbbl. Crude by rail/yr	0.004
Pump Station Maintenance	36.80	scf CH_4/station/yr	575	No. of pump stations	0.000
Pipeline Pigging	39	scfd of CH_4/pig station	1,150	No. of pig stations	0.016
Fugitive Emissions					0.050

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Pump Stations	25	scfCH_4/mile/yr.	57,509	No. of miles of crude p/l	0.001
Pipelines	0	scf CH_4/bbl crude transported by pipeline	7,082	MM bbl crude piped	0.000
Floating Roof Tanks	58,965	scf CH_4/floating roof tank/yr.	824	No. of floating roof tanks	0.049
Combustion Emissions					0.000
Pump Engine Drivers	0.24	scf CH_4/hp-hr	NA	No. of hp-hrs	NA
Heaters	0.521	scf CH_4/bbl.burned	NA	No. of bbl. Burned	NA
Total					0.271

Table 3-43: 2002 CH_4 Emissions from Petroleum Refining

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					1.220
Tanks	20.6	scfCH_4/Mbbl	1,9181	Mbbl/cd heavy crude feed	0.014
System Blowdowns	137	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.746
Asphalt Blowing	2,555	scfCH_4/Mbbl	492	Mbbl/cd production	0.459
Fugitive Emissions					0.087
Fuel Gas System	439	McfCH_4/refinery/yr	145	Refineries	0.064
Floating Roof Tanks	587	scf CH_4/floating roof tank/yr.	767	No. of floating roof tanks	0.000
Wastewater Treating	1.88	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.010
Cooling Towers	2.36	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.013
Combustion Emissions					0.091
Atmospheric Distillation	3.61	scfCH_4/Mbbl	15,180	Mbbl/cd refinery feed	0.020
Vacuum Distillation	3.61	scfCH_4/Mbbl	6,665	Mbbl/cd feed	0.009
Thermal Operations	6.02	scfCH_4/Mbbl	2,075	Mbbl/cd feed	0.005
Catalytic Cracking	5.17	scfCH_4/Mbbl	5,194	Mbbl/cd feed	0.010
Catalytic Reforming	7.22	scfCH_4/Mbbl	3,186	Mbbl/cd feed	0.008
Catalytic Hydrocracking	7.22	scfCH_4/Mbbl	1,338	Mbbl/cd feed	0.004
Hydrorefining	2.17	scfCH_4/Mbbl	1,826	Mbbl/cd feed	0.001
Hydrotreating	6.50	scfCH_4/Mbbl	8,376	Mbbl/cd feed	0.020
Alkylation/Polymerization	12.6	scfCH_4/Mbbl	1,119	Mbbl/cd feed	0.005
Aromatics/Isomeration	1.80	scfCH_4/Mbbl	932	Mbbl/cd feed	0.001
Lube Oil Processing	0.00	scfCH_4/Mbbl	152	Mbbl/cd feed	0.000
Engines	0.006	scfCH_4/hp-hr	1,467	MMhp-hr/yr	0.008
Flares	0.189	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.001
Total					1.3996

Table 3-44: CH_4 Reductions from Natural Gas STAR Program (Gg) and (Tg CO_2 Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Production Field Operations (Gg)	2	7	14	28	48	54	61	75	79	89	89	85	88
Tank venting (Gg)	2	7	14	28	48	54	61	75	79	89	89	85	88
Crude Oil Transportation	-	-	-	-	-	-	-	-	-	-	-	-	-
Refining	-	-	-	-	-	-	-	-	-	-	-	-	-
Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Production Field Operations (Tg CO_2 Eq.)	0.0	0.1	0.3	0.6	1.0	1.1	1.3	1.6	1.7	1.9	1.9	1.8	1.9
Tank venting, (Tg CO_2 Eq.)	0.0	0.1	0.3	0.6	1.0	1.1	1.3	1.6	1.7	1.9	1.9	1.8	1.9
Crude Oil Transportation	-	-	-	-	-	-	-	-	-	-	-	-	-
Refining	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3-45: Summary of CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Production Field Operations[(a)]	1,344	1,355	1,303	1,251	1,208	1,194	1171	1,182	1,157	1,097	1,086	1,086	1072
Tank venting	606	608	588	566	546	546	547	555	549	520	523	523	513
Pneumatic device venting	545	556	537	527	524	516	516	515	504	488	478	475	474

Wellhead fugitives	26	26	24	24	24	25	25	25	25	24	22	22	22
Combustion & process upsets	104	105	101	99	98	98	98	98	96	92	91	91	91
Misc. venting & fugitives	65	66	65	64	64	63	63	63	62	61	60	60	60
Crude Oil Transportation	7	6	6	6	6	6	6	6	6	6	5	5	5
Refining	25	24	24	25	25	25	26	27	27	27	28	27	27
Total	1,375	1,385	1,333	1,283	1,239	1,225	1,218	1,215	1,190	1,129	1,119	1,118	1,104

(a) Including CH_4 emission reductions achieved by the Natural Gas STAR Program, Table 3-38.

3.6. Methodology for Estimating CO_2 and N_2O Emissions from Municipal Solid Waste Combustion

Emissions of CO_2 from municipal solid waste (MSW) combustion include CO_2 generated by the combustion of plastics, synthetic rubber and synthetic fibers in MSW, and combustion of synthetic rubber and carbon black in tires. Combustion of MSW also results in emissions of N_2O. The methodology for calculating emissions from each of these waste combustion sources is described in this Annex.

CO_2 from Plastics Combustion

In the *Characterization of Municipal Solid Waste in the United States* reports (EPA 1997, 1998, 1999, 2000c, 2002, 2003), the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2001, the most recent year for which these data are reported, the quantity generated, recovered, and discarded for each resin is shown in Table 3-46. The data set for 1990-2002 is incomplete, and several assumptions were employed to bridge the data gaps. The EPA reports do not provide estimates for individual materials landfilled and combusted, although they do provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and combusted, total discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. waste stream for each year in the time series. For those years when distribution by resin category was not reported (1990-1994), total values were apportioned according to 1995 (the closest year) distribution ratios. Generation and recovery figures for 2002 are held constant at the year 2001 level.

Table 3-46: 2001 Plastics in the Municipal Solid Waste Stream by Resin (Gg)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	2,341	4,463	1,288	5,334	3,139	2,077	4,382	23,025
Recovery	426	390	0	136	9	0	299	1,261
Discard	1,914	4,073	1,288	5,198	3,130	2,077	4,082	21,764
Landfill	1,514	3,222	1,019	4,111	2,475	1, 643	3,229	17,213
Combustion	400	852	269	1,087	654	434	854	4,551
Recovery*	18%	9%	0%	3%	0%	0%	7%	5%
Discard*	82%	91%	100%	97%	100%	100%	93%	95%
Landfill*	65%	72%	79%	77%	79%	79%	74%	75%
Combustion*	17%	19%	21%	20%	21%	21%	19%	20%

*As a percent of waste generation.
Note: Totals may not sum due to independent rounding. Abbreviations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE (linear low density polyethylene), PP (polypropylene), PS (polystyrene).

Fossil fuel-based CO_2 emissions were calculated as the product of plastic combusted, carbon content, and fraction oxidized (see Table 3-47, which shows calculations for 2001). The carbon content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal to the weighted average of the six categories. The fraction oxidized was assumed to be 98 percent.

Table 3-47: 2001 Plastics Combusted (Gg), Carbon Content (%), Fraction Oxidized (%) and Carbon Combusted (Gg)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	400	852	269	1,087	654	434	854	4,551
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66% [a]	-
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	-
Carbon in Resin Combusted	245	715	101	913	550	393	551	3,468
Emissions (Tg CO_2 Eq.)	0.9	2.6	0.4	3.3	2.0	1.4	2.0	12.7

[a] Weighted average of other plastics produced.
Note: Totals may not sum due to independent rounding.

CO_2 from Combustion of Synthetic Rubber and Carbon Black in Tires

Emissions from tire combustion require two pieces of information: the amount of tires combusted and the carbon content of the tires. *U.S. Scrap Tire Markets 2001* (RMA 2002) reports that 115 million of the 218 million scrap tires generated in 2001 (approximately 53 percent of generation) were used for fuel purposes. Using RMA's

Scrap Tire Management Council (STMC) estimates of average tire composition and weight, the mass of synthetic rubber and carbon black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent carbon by weight, based on the weighted average carbon contents of the major elastomers used in new tire consumption.[1] Table 3-48 shows consumption and carbon content of elastomers used for tires and other products in 1998.

- Carbon black is 100 percent carbon (Miller 1999).

Multiplying the mass of scrap tires combusted by the total carbon content of the synthetic rubber and carbon black portions of scrap tires and by a 98 percent oxidation factor yielded CO_2 emissions, as shown in Table 3-49. Note that the disposal rate of rubber in tires (0.3 Tg C/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table 3-48 (1.3 Tg/yr); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and due to the lag time between consumption and disposal of tires. Tire production and fuel use for 1990 through 2002 were taken from RMA 2002; when data were not reported, they were linearly interpolated between bracketing years' data or, for the ends of time series, set equal to the closest year with reported data.

Table 3-48: Elastomers Consumed in 1998 (Gg)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	908	91%	828
For Tires	743	91%	677
For Other Products*	165	91%	151
Polybutadiene	561	89%	499
For Tires	404	89%	359
For Other Products	157	89%	140
Ethylene Propylene	320	86%	274
For Tires	10	86%	8
For Other Products	310	86%	266
Polychloroprene	69	59%	40
For Tires	0	59%	0
For Other Products	69	59%	40
Nitrile butadiene rubber solid	87	77%	67
For Tires	1	77%	1
For Other Products	86	77%	67
Polyisoprene	78	88%	69
For Tires	65	88%	57
For Other Products	13	88%	12
Others	369	88%	324
For Tires	63	88%	56
For Other Products	306	88%	268
Total	2,392	-	2,101
For Tires	1,285	-	1,158

*Used to calculate carbon content of non-tire rubber products in municipal solid waste.
- Not applicable
Note: Totals may not sum due to independent rounding.

Table 3-49: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Combustion in 2001

Material	Weight of Material (Tg)	Fraction Oxidized	Carbon Content	Emissions (Tg CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	0.9
Carbon Black	0.3	98%	100%	1.2
Total	0.6	-	-	2.1

- Not applicable

[1] The carbon content of tires (1,158 Gg C) divided by the mass of rubber in tires (1,285 Gg) equals 90 percent.

CO_2 from Combustion of Synthetic Rubber in Municipal Solid Waste

Similar to the methodology for scrap tires, CO_2 emissions from synthetic rubber in MSW were estimated by multiplying the amount of rubber combusted by an average rubber carbon content. The amount of rubber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* reports (EPA 1996, 1997, 1998, 1999, 2000c, 2002, 2003). The reports divide rubber found in MSW into three product categories: other durables (not including tires), non-durables (which includes clothing and footwear and other non-durables), and containers and packaging. Since there was negligible recovery for these product types, all the waste generated can be considered discarded. Similar to the plastics method, discards were apportioned into landfilling and combustion based on their relative proportions, for each year, for the entire U.S. waste stream. The report aggregates rubber and leather in the MSW stream; an assumed synthetic rubber content was assigned to each product type, as shown in Table 3-50.[2] A carbon content of 85 percent was assigned to synthetic rubber for all product types (based on the weighted average carbon content of rubber consumed for non-tire uses), and a 98 percent fraction oxidized was assumed. For 2002, waste generation values were not available, so values were held constant at the 2001 level.

Table 3-50: Rubber and Leather in Municipal Solid Waste in 2001

Product Type	Generation (Gg)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (Tg CO_2 Eq.)
Durables (not Tires)	2,422	100%	85%	98%	1.6
Non-Durables	329	-	85%	98%	0.2
Clothing and Footwear	132	25%	85%	98%	0.1
Other Non-Durables	197	75%	85%	98%	0.1
Containers and Packaging	18	100%	85%	98%	+
Total	2,769	-	-	-	2.0

+ Less than 0.05 Tg CO_2 Eq.
- Not applicable

CO_2 from Combustion of Synthetic Fibers

Carbon dioxide emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average carbon content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c, 2002, 2003) reports for textiles. The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table 3-51). As with the other materials in the MSW stream, discards were apportioned based on the annually variable proportions of landfilling and combustion for the entire U.S. waste stream. It was assumed that approximately 55 percent of the fiber was synthetic in origin, based on information received from the Fiber Economics Bureau (DeZan 2000). An average carbon content of 70 percent was assigned to synthetic fiber using the production-weighted average of the carbon contents of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 2000 (see Table 3-52). The equation relating CO_2 emissions to the amount of textiles combusted is shown below. Since 2002 values were not provided in the *Characterization* reports, generation and recovery rates for 2002 were held constant at the 2001 values.

CO_2 Emissions from the Combustion of Synthetic Fibers = Annual Textile Combustion (Gg) ×

(Percent of Total Fiber that is Synthetic) × (Average Carbon Content of Synthetic Fiber) ×

(44g CO_2/12 g C)

Table 3-51: Textiles in MSW (Gg)

[2] As a sustainably harvested biogenic material, the combustion of leather is assumed to have no net CO_2 emissions.

Year	Generation	Recovery	Discards	Combustion
1990	2,884	328	2,557	473
1991	3,008	347	2,661	504
1992	3,286	387	2,899	561
1993	3,386	397	2,988	586
1994	3,604	432	3,172	631
1995	3,674	447	3,227	725
1996	3,832	472	3,361	801
1997	4,090	526	3,564	817
1998	4,269	556	3,713	788
1999	4,498	611	3,887	797
2000	4,656	630	4,026	825
2001	4,840	705	4,135	865
2002*	4,840	705	4,135	865

* Set equal to 2001 data.

Table 3-52: Synthetic Fiber Production in 2000

Fiber	Production (Tg)	Carbon Content
Polyester	1.8	63%
Nylon	1.2	64%
Olefin	1.4	86%
Acrylic	0.2	68%
Total	4.5	70%

N_2O from Municipal Solid Waste Combustion

Estimates of N_2O emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995). According to this methodology, emissions of N_2O from MSW combustion are the product of the mass of MSW combusted, an emission factor of N_2O emitted per unit mass of waste combusted, and an N_2O emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 44 g N_2O/metric ton MSW (the average of the values provided for hearth/ grate combustors as listed in the IPCC Good Practice Guidance, 2000) and an estimated emissions control removal efficiency of zero percent were used. No information was available on the mass of waste combusted in 2001 or 2002; for these years, the quantity of waste combusted was estimated using a population-based linear regression model.

3.7. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emission estimates for the Department of Defense (DoD) were developed using data generated by the Defense Energy Support Center for aviation and naval fuels (DESC 2003). The DESC of the Defense Logistics Agency (DLA) prepared a special report based on data in the Defense Fuels Automated Management System (DFAMS). DFAMS contains data for 1995 through 2002, but the data set was not complete for years prior to 1995. Fuel quantities for 1990 to 1994 were estimated based on a back-calculation of the 1995 DFAMS values using DLA aviation and marine fuel procurement data. The back-calculation was refined in 1999 to better account for the jet fuel conversion from JP4 to JP8 that occurred within the DoD between 1992 and 1995.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete DFAMS data set for each year, the first step in the development of DoD related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as that term is defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Therefore, fuel data were categorized by the location of fuel delivery in order to identify and omit all extra-territorial fuel transactions/deliveries (i.e., sales abroad).

After summarizing all transportation fuel deliveries and considering additional Service data describing jet fuel used in land-based vehicles, it was determined that a portion of 2001 jet fuel consumption should be attributed to ground fuel use. Based on available Service data and expert judgment, it was determined that a small fraction of the total jet fuel should be reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years.

Table 3-53 displays DoD's consumption of fuels that remain at the completion of Step 1, summarized by fuel type. Table 3-53 reflects the adjustments for jet fuel used in land-based equipment, as described above.

Step 2: Omit Fuel Transactions Received by Military Services that are not Considered to be International Bunker Fuels

Next, the records were sorted by Military Service. The following assumptions were used regarding bunker fuel use by Service, leaving only the Navy and Air Force as users of military international bunker fuels.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a bunker fuel.

- Based on discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of its watercraft emissions, qualified as bunker fuel emissions. The magnitude of these emissions was judged to be insignificant when compared to Air Force and Navy emissions. Based on this, Army bunker fuel emissions were assumed to be zero.

- Marine Corps aircraft operating while embarked consumed fuel reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft were reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training were assumed to be zero.

- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchased fuel from DESC were assumed to be zero.

Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuels (i.e., fuel not used by ships or aircraft) were also omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- Marine: naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).

- Aviation: jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).

Step 4: Determine Bunker Fuel Percentages

Next it was necessary to determine what percent of the marine and aviation fuels were used as international bunker fuels. Military aviation bunkers include international operations (i.e., sorties that originate in the United States and end in a foreign country), operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea (e.g., anti-submarine warfare flights). For the Air Force, a bunker fuel weighted average was calculated based on flying hours by major command. International flights were weighted by an adjustment factor to reflect the fact that they typically last longer than domestic flights. In addition, a fuel use correction factor was used to account for the fact that transport aircraft burn more fuel per hour of flight than most tactical aircraft. The Air Force bunker fuel percentage was determined to be 13.2 percent. This percentage was multiplied by total annual Air Force aviation fuel delivered for U.S. activities, producing an estimate for international bunker fuel consumed by the Air Force. The Naval Aviation bunker fuel percentage of total fuel was calculated using flying hour data from Chief of Naval Operations Flying Hour Projection System Budget for fiscal year 1998, and estimates of bunker fuel percent of flights provided by the fleet. The Naval Aviation bunker fuel percentage, determined to be 40.4 percent, was multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.

For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. In 2000, the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside). Therefore, the Navy maritime bunker fuel percentage was determined to be 79 percent. The percentage of time underway may vary from year-to-year. For example, for years prior to 2000, the bunker fuel percentage was 87 percent. Table 3-54 and Table 3-55 display DoD bunker fuel use totals for the Navy and Air Force.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas emissions.

The rows labeled “U.S. Military” and “U.S. Military Naval Fuels” within Table 3-54 and Table 3-55 in the Energy Chapter were based on the international bunker fuel totals provided in Table 3-54 and Table 3-55, below. Carbon dioxide emissions from aviation bunkers and distillate marine bunkers presented in Table 3-52 are the total of military plus civil aviation and civil marine bunker fuels, respectively. The military component of each total is based on fuels tallied in Table 3-54 and Table 3-55.

Table 3-53: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Aviation	4,598.45	4,562.84	3,734.49	3,610.85	3,246.23	3,099.93	2,941.91	2,685.60	2,741.40	2,635.25	2,664.45	2,900.58	2,609.75
Total Jet Fuels	4,598.42	4,562.81	3,734.46	3,610.83	3,246.21	3,099.91	2,941.90	2,685.59	2,741.38	2,635.24	2,664.44	2,900.55	2,609.64
JP8	*285.75*	*283.54*	*234.46*	*989.38*	*1,598.07*	*2,182.80*	*2,253.15*	*2,071.96*	*2,122.53*	*2,066.48*	*2,122.70*	*2,326.19*	*2,091.36*
JP5	*1,025.36*	*1,017.42*	*832.71*	*805.14*	*723.84*	*691.22*	*615.83*	*552.77*	*515.56*	*505.50*	*472.10*	*503.17*	*442.21*
Other Jet Fuels	*3,287.31*	*3,261.86*	*2,667.29*	*1,816.30*	*924.30*	*225.89*	*72.92*	*60.86*	*103.29*	*63.25*	*69.65*	*71.19*	*76.07*
Aviation Gasoline	0.03	0.03	0.02	0.02	0.02	0.02	0.01	+	0.02	0.01	0.01	0.03	0.11
Marine	686.80	632.61	646.18	589.37	478.59	438.91	493.34	639.85	674.22	598.86	454.36	418.45	455.85
Middle Distillate (MGO)	+	+	+	+	+	+	38.52	47.48	51.14	49.22	48.29	33.02	41.21
Naval Distillate (F76)	686.80	632.61	646.18	589.37	478.59	438.91	448.96	583.41	608.39	542.94	397.97	369.14	395.10
Intermediate Fuel Oil (IFO)[b]	+	+	+	+	+	+	5.86	8.95	14.69	6.70	8.09	16.28	19.53
Other[c]	717.11	590.41	491.68	415.10	356.06	310.95	276.90	263.34	256.83	255.95	248.16	109.75	211.09
Diesel	93.04	97.88	102.96	108.31	113.94	119.86	126.09	132.64	139.53	146.78	126.63	26.65	57.66
Gasoline	624.07	492.53	388.72	306.78	242.12	191.09	150.81	119.02	93.94	74.14	74.81	24.72	27.49
Jet Fuel[d]	+	+	+	+	+	+	+	11.68	23.36	35.04	46.71	58.39	125.94
Total (Including Bunkers)	6,002.37	5,785.85	4,872.34	4,615.32	4,080.89	3,849.78	3,712.15	3,588.79	3,672.45	3,490.06	3,366.97	3,428.78	3,276.69

Note: Totals may not sum due to independent rounding.

[a] Includes fuel consumption in the United States and U.S. Territories.

[b] Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

[c] Prior to 2001, gasoline and diesel fuel totals were estimated using data provided by the military Services for 1990 and 1996. The 1991 through 1995 data points were interpolated from the Service inventory data. The 1997 through 1999 gasoline and diesel fuel data were initially extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 and -21.1 percent, respectively. However, prior diesel fuel estimates from 1997 through 2000 were reduced according to the estimated consumption of jet fuel that is assumed to have replaced the diesel fuel consumption in land-based vehicles. Data sets for other diesel and gasoline consumed by the military in 2000 were estimated based on ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000. In 2001, other gasoline and diesel fuel totals were generated by DESC.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated using Service data, DESC data, and expert judgment.

+ Does not exceed 0.005 million gallons.

Table 3-54: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
JP8	56.74	56.30	46.40	145.33	223.99	300.40	308.81	292.01	306.39	301.35	307.57	341.15	309.46
Navy	56.74	56.30	46.08	44.56	40.06	38.25	39.84	46.92	53.81	55.46	53.38	73.78	86.59
Air Force	0	0	0.32	100.77	183.93	262.15	268.97	245.09	252.59	245.89	254.19	267.37	222.87
JP5	370.53	367.66	300.92	290.95	261.57	249.78	219.40	194.16	184.38	175.37	160.35	169.73	158.31
Navy	365.29	362.46	296.66	286.83	257.87	246.25	216.09	191.15	181.36	170.59	155.60	163.68	152.97
Air Force	5.25	5.21	4.26	4.12	3.70	3.54	3.31	3.01	3.02	4.77	4.74	6.05	5.35
JP4	420.77	417.52	341.40	229.64	113.11	21.50	1.05	0.05	0.03	0.02	0.01	0.02	0.01
Navy	0.02	0.02	0.02	0.02	0.01	0.01	+	+	+	+	+	+	+
Air Force	420.75	417.50	341.39	229.62	113.10	21.49	1.05	0.05	0.03	0.02	0.01	0.02	0.01
JAA	13.70	13.60	11.13	10.76	9.67	9.24	10.27	9.42	10.84	10.78	12.46	12.61	0.22
Navy	8.45	8.39	6.86	6.64	5.97	5.70	6.58	5.88	6.63	6.32	7.95	8.02	0.19
Air Force	5.25	5.21	4.27	4.12	3.71	3.54	3.69	3.54	4.21	4.47	4.51	4.59	0.03
JA1	+	+	+	+	+	+	+	+	0.01	+	0.03	0.13	0.62
Navy	+	+	+	+	+	+	+	+	+	+	0.02	0.02	0
Air Force	+	+	+	+	+	+	+	+	0.01	+	0.01	0.11	0.62
JAB	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy Subtotal	430.50	427.17	349.62	338.05	303.91	290.21	262.51	243.95	241.80	232.37	216.95	245.50	239.75
Air Force Subtotal	431.25	427.91	350.23	338.63	304.44	290.72	277.02	251.70	259.86	255.14	263.47	278.15	228.87
Total	861.75	855.08	699.85	676.68	608.35	580.93	539.53	495.65	501.66	487.52	480.42	523.64	468.63

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

Table 3-55: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Navy - MGO	+	+	+	+	+	+	30.34	35.57	31.88	39.74	23.83	22.50	27.15
Navy - F76	522.37	481.15	491.47	448.27	364.01	333.82	331.88	441.65	474.23	465.97	298.61	282.59	305.61
Navy - IFO	+	+	+	+	+	+	4.63	7.07	11.61	5.29	6.39	12.87	15.43
Total	522.37	481.15	491.47	448.27	364.01	333.82	366.85	484.29	517.72	511.00	328.84	317.95	348.19

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

Table 3-56: Aviation and Marine Carbon Contents (Tg Carbon/QBtu) and Fraction Oxidized

Mode (Fuel)	Carbon Content Coefficient	Fraction Oxidized
Aviation (Jet Fuel)	variable	0.99
Marine (Distillate)	19.95	0.99
Marine (Residual)	21.49	0.99

Table 3-57: Annual Variable Carbon Content Coefficient for Jet Fuel (Tg Carbon/QBtu)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33	19.33	19.33	19.33

Table 3-58: Total U.S. DoD CO_2 Emissions from Bunker Fuels (Tg CO_2 Eq.)

Mode	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Aviation	8.2	8.1	6.6	6.4	5.8	5.6	5.2	4.8	4.8	4.7	4.6	5.0	4.5
Marine	5.2	4.8	4.9	4.5	3.7	3.4	3.7	4.9	5.2	5.1	3.3	3.2	3.5
Total	13.4	12.9	11.6	10.9	9.5	8.9	8.9	9.6	10.0	9.8	7.9	8.2	8.0

Note: Totals may not sum due to independent rounding.

3.8. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

The Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. Under the terms of the Montreal Protocol and the United States' Clean Air Act Amendments of 1990, the domestic U.S. production of ODS—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—has been drastically reduced, forcing these industrial sectors to transition to more ozone friendly chemicals. As these industries have moved toward ODS alternatives such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the decline of ODS consumption and emissions.

The Vintaging Model estimates emissions from the five ODS substitute end-use sectors mentioned above. Within these sectors, there are over 40 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, as well as a history of the market transition from ODS to alternatives. As ODS are phased out, a percentage of the market share originally filled by the ODS is allocated to each of its substitutes.

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 and ODS and ODS substitute in each of the end-uses. The simulation is considered to be a "business-as-usual" baseline case, and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. 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.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and conference proceedings from the International Conferences on Ozone Protection Technologies. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy, the Air-Conditioning and Refrigeration Institute, the Association of Home Appliance Manufacturers, the American Automobile Manufacturers Association, and many of their member companies, have provided valuable information over the years. In some instances the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA.

The following sections discuss the forms of the emission estimating equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of the different end-uses. In the majority of these end-uses, more than one ODS substitute chemical is used.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by extrapolating forward in time from the amount of regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives will likely be used, and what fraction of the ODS market in each end-use will be captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

Methodology

The Vintaging Model estimates the use and emissions of ODS alternatives by taking the following steps:

1. *Gather historical emissions data*. The Vintaging Model is populated with information on each end-use, taken from published sources and industry experts.

2. *Simulate the implementation of new, non-ODS technologies*. The Vintaging model uses detailed characterizations of the existing uses of the ODSs, as well as data on how the substitutes are replacing the ODSs, to simulate the implementation of new technologies that ensure compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end-uses over time as needed to comply with the ODS phase-out.

3. *Estimate emissions of the ODS substitutes*. The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions are estimated from the emission profile for each vintage of equipment or product in each end-use. By aggregating the emissions from each vintage, a time profile of emissions from each end-use is developed.

Each set of end uses is discussed in more detail in the following sections.

Refrigeration and Air-Conditioning

For refrigeration and air conditioning products, emission calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. Two separate steps are required to calculate the lifetime emissions from leakage and service, and the emissions resulting from disposal of the equipment. These lifetime emissions and disposal emissions are summed to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates.

Step 1: Calculate lifetime emissions

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \quad \text{for } i=1 \rightarrow k$$

Where:

- Es = Emissions from Equipment Serviced. Emissions in year j from normal leakage and servicing (including recharging) of equipment.
- l_a = Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).
- l_s = Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).
- Qc = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year by weight.
- i = Counter, runs from 1 to lifetime (k).
- j = Year of emission.
- k = Lifetime. The average lifetime of the equipment.

Step 2: Calculate disposal emissions

The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$$

Where:

Ed = Emissions from Equipment Disposed. Emissions in year *j* from the disposal of equipment.

Qc = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year *j-k+1*, by weight.

rm = Chemical Remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge).

rc = Chemical Recovery Rate. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal *(rm)*).

j = Year of emission.

k = Lifetime. The average lifetime of the equipment.

Step 3: Calculate total emissions

Finally, lifetime and disposal emissions are summed to provide an estimate of total emissions.

$$E_j = Es_j + Ed_j$$

Where:

E = Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j*.

Es = Emissions from Equipment Serviced. Emissions in year *j* from normal leakage and servicing (recharging) of equipment.

Ed = Emissions from Equipment Disposed. Emissions in year *j* from the disposal of equipment.

j = Year of emission.

Assumptions

The assumptions used by the Vintaging Model to trace the transition of each type of equipment away from ODS are presented in Table 3-59, below. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. Additionally, the market for each equipment type is assumed to grow independently, according to annual growth rates, presented in Table 3-59.

Table 3-59. Refrigeration and Air-Conditioning Market Transition Assumptions

Initial Market Segment	Primary Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
Mobile Air Conditioners									
CFC-12	HFC-134a	1992	1995	100%	None				1.5%
Chillers									
CFC-11	HCFC-22	1991	1995	16%	HFC-134a	2000	2010	70%	0.5%
					R-407C	2000	2010	30%	
	HFC-134a	1992	1995	39%	None				
	HCFC-123	1993	1995	45%	HFC-134a	2015	2020	75%	
					HFC-245fa	2015	2020	25%	
CFC-12	HCFC-22	1991	1995	16%	HFC-134a	2000	2010	70%	0.5%
					R-407C	2000	2010	30%	
	HFC-134a	1992	1995	53%	None				
	HCFC-123	1993	1995	31%	HFC-134a	2015	2020	75%	
					HFC-245fa	2015	2020	25%	
R-500	HCFC-22	1991	1995	16%	HFC-134a	2000	2010	70%	0.5%
					R-407C	2000	2010	30%	
	HFC-134a	1992	1995	53%	None				
	HCFC-123	1993	1995	31%	HFC-134a	2015	2020	75%	
					HFC-245fa	2015	2020	25%	

HCFC-22	HFC-134a	2000	2010	70%	None				0.5%
	R-407C	2000	2010	30%	R-407C	2009	2020	60%	
					R-410A	2009	2020	40%	
CFC-114	HFC-236fa	1997	1999	100%	HFC-134a	1998	2010	100%	0.2%
Cold Storage									
CFC-12	HCFC-22	1990	1994	65%	R-404A	1996	2010	75%	2.5%
					R-507	1996	2010	25%	
	HFC-134a	1994	1997	35%	None				
HCFC-22	R-404A	1996	2010	75%	None				
	R-507	1996	2010	25%	None				
R-502	HCFC-22	1990	1994	40%	R-404A	1996	2010	38%	2.5%
					R-507	1996	2010	12%	
					999	1996	2010	50%	
	R-404A	1993	1997	45%	None				
	R-507	1994	1997	15%	None				
Commercial Unitary Air Conditioners									
HCFC-22	R-407C	2000	2007	5%	None				2.5%
	R-410A	2000	2007	5%	None				
	HFC-134a	2000	2010	20%	None				
	R-407C	2006	2010	25%	None				
	R-410A	2006	2010	45%	None				
HCFC-22	R-407C	2000	2007	5%	None				2.5%
	R-410A	2000	2007	5%	None				
	HFC-134a	2000	2010	20%	None				
	R-410A	2006	2010	45%	None				
	R-407C	2006	2010	25%	None				
Dehumidifiers									
HCFC-22	HFC-134a	1997	1998	89%	None				0.5%
	R-410A	2007	2010	11%	None				
Ice Makers									
CFC-12	HFC-134a	1993	1996	100%	None				2.5%
Industrial Process Refrigeration									
CFC-11	HCFC-22	1991	1995	15%	HFC-134a	1995	2010	100%	2.5%
	HCFC-123	1992	1995	70%	HFC-134a	2015	2020	100%	
	HFC-134a	1992	1995	15%	None				
CFC-12	HCFC-22	1991	1995	10%	HFC-134a	1995	2010	15%	2.5%
					R-404A	1995	2010	50%	
					R-410A	1999	2010	20%	
					R-507	1995	2010	15%	
	HCFC-123	1992	1995	35%	HFC-134a	2015	2020	100%	
	HFC-134a	1992	1995	50%	None				
	R-401A	1995	1997	5%	HFC-134a	1997	2001	100%	
HCFC-22	HFC-134a	1995	2010	15%	None				2.5%
	R-404A	1995	2010	50%	None				
	R-507	1995	2010	15%	None				
	R-410A	1999	2010	20%	None				
Refrigerated Appliances									
CFC-12	HFC-134a	1994	1996	100%	None				0.5%
Residential Unitary Air Conditioners									
HCFC-22	R-410A	2000	2007	10%	None				1.9%
	R-407C	2006	2010	25%	None				
	R-410A	2006	2010	65%	None				
Retail Food									
CFC-12	HCFC-22	1990	1994	70%	R-404A	1996	2010	75%	1.7%
					R-507	1996	2010	25%	
	HFC-134a	1994	1997	30%	HFC-134a	2005	2006	100%	
HCFC-22	R-404A	1996	2010	60%	None				1.7%
	R-507	1996	2010	15%	None				
	HFC-134a	1999	2010	25%	None				
R-502	HCFC-22	1990	1994	40%	R-404A	2000	2010	75%	1.7%
					R-507	2000	2010	25%	

	R-404A	1993	1997	40%	None				
	R-507	1994	1997	10%	None				
	HFC-134a	1996	1997	10%	None				
Transport Refrigeration									
CFC-12	HFC-134a	1993	1996	98%	None				2.5%
	HCFC-22	1993	1996	2%	HFC-134a	1995	2000	100%	
R-502	HFC-134a	1993	1996	55%	None				2.5%
	R-404A	1993	1996	45%	None				
Water-Source, Ground-Source and Unitary Heat Pumps; Packaged Terminal Air Conditioners and Heat Pumps									
HCFC-22	R-407C	2000	2007	5%	None				2.5%
	R-410A	2000	2007	5%	None				
	HFC-134a	2000	2010	20%	None				
	R-407C	2006	2010	25%	None				
	R-410A	2006	2010	45%	None				
HCFC-22	R-407C	2000	2007	5%	None				2.5%
	R-410A	2000	2007	5%	None				
	HFC-134a	2000	2010	20%	None				
	R-407C	2006	2010	25%	None				
	R-410A	2006	2010	45%	None				
Window Units									
HCFC-22	R-407C	2003	2007	3%	None				0.1%
	R-410A	2003	2007	7%	None				
	R-407C	2006	2010	35%	None				
	R-410A	2006	2010	55%	None				

Table 3-60 presents the average equipment lifetimes for each end use assumed by the Vintaging Model.

Table 3-60. Refrigeration and Air-conditioning Lifetime Assumptions

End Use	Lifetime (Years)
Mobile Air Conditioners	12
Chillers	20 - 27
Retail Food	15 - 20
Cold Storage	20 - 25
Industrial Process Refrigeration	25
Transport Refrigeration	12
Ice Makers and Ice Rinks	20
Refrigerated Appliances	20
Residential Unitary A/C	15
Commercial Unitary A/C	15
Water & Ground Source Heat Pumps	20
PTAC/PTHP	12
Window Units	15

Aerosols

ODSs, HFCs and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. Two types of aerosol products are modeled, including metered dose inhalers and consumer aerosols. In the United States, the use of ODSs in consumer aerosols was banned in 1977, and many products transitioned to "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays.

All HFCs and PFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The following equation describes the emissions from the aerosols sector.

$$E_j = Qc_j$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* from use in aerosol products, by weight.

Qc = Quantity of Chemical. Total quantity of a specific chemical contained in aerosol products sold in year *j*, by weight.

j = Year of emission.

Assumptions

Transition assumptions and growth rates for those items that use ODSs or HFCs as propellants, including vital medical devices and specialty consumer products, are presented in Table 3-61.

Table 3-61. Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute	Start Date	Date of Full Pene-tration in New Products	Maximum Market Pene-tration	Secondary Substitute	Start Date	Date of Full Penetration in New Products	Maximum Market Pene-tration	Growth Rate
MDI Aerosols									
CFC-11	HFC-134a	1997	2005	75%	None				1.5%
	HFC-227ea	1997	2005	25%	None				
CFC-12	HFC-134a	1997	2005	75%	None				1.5%
	HFC-227ea	1997	2005	25%	None				
CFC-114	HFC-134a	1999	2000	75%	None				1.5%
	HFC-227ea	1999	2000	25%	None				
Consumer Aerosols									
NA*	HFC-152a	1990	1992	50%	None				2.0%
	HFC-134a	1995	1996	50%	HFC-152a	1997	1999	44%	
					HFC-134a	1997	1999	56%	

*Consumer Aerosols transitioned away from ODS prior to the beginning of the Vintaging Model, which begins in 1985. The portion of the market that is now using HFC propellants is modeled.

Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent. Generally, most solvents are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered “incomplete,” and are a fixed percentage of the amount of solvent consumed in a year. The remainder of the consumed solvent is assumed to be reused or disposed without being released to the atmosphere. The following equation calculates emissions from solvent applications.

$$E_j = l \times Qc_j$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* from use in solvent applications, by weight.

l = Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere, currently assumed to be 90 percent.

Qc = Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j, by weight.

j = Year of emission.

Assumptions

The transition assumptions and growth rates used within the Vintaging Model for electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks, are presented in Table 3-62.

Table 3-62. Solvent Market Transition Assumptions

Initial Market Segment	Primary Substitute	Start Date	Date of Full Pene-tration in New Uses	Maximum Market Pene-tration	Secondary Substitute	Start Date	Date of Full Pene-tration in New Uses	Maximum Market Pene-tration	Growth Rate
Electronics Cleaning									
CFC-113	Non-ODP/GWP	1992	1997	46.0%	None				2.0%
	Non-ODP/GWP	1994	1996	52.5%	None				
	HCFC-225ca/cb	1994	1996	0.2%	None				
	HFE-7100	1994	1996	0.7%	None				
	HFC-4310mee	1995	1997	0.7%	None				
MCF	Non-ODP/GWP	1996	1998	99.8%	None				2.0%
	PFC/PFPE	1996	1998	0.2%	Non-ODP/GWP	2000	2004	90%	
					Non-ODP/GWP	2005	2025	10%	
Metals Cleaning									
MCF	Non-ODP/GWP	1992	1997	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	1997	100%	None				2.0%
CCl_4	Non-ODP/GWP	1992	1997	100%	None				2.0%
Precision Cleaning									
MCF	Non-ODP/GWP	1995	1997	99.3%	None				2.0%
	HFC-4310mee	1995	1997	0.6%	None				
	PFC/PFPE	1995	1997	0.1%	Non-ODP/GWP	2000	2004	90%	
					Non-ODP/GWP	2005	2025	10%	
CFC-113	Non-ODP/GWP	1995	1997	95.7%	None				2.0%
	HCFC-225ca/cb	1995	1997	1.0%	None				
	HFE-7100	1995	1997	3.3%	None				
Adhesives, Coatings, Inks									
MCF	Non-ODP/GWP	1994	1996	100%	None				

MCF= Methyl Chloroform, also known as TCA or 1,1,1-Trichloroethane
Non-ODP/GWP includes chemicals with 0 ODP and low GWP, such as hydrocarbons and ammonia, as well as not-in-kind alternatives such as "no clean" technologies.

Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire-extinguishing agents, in both hand-held "streaming" applications as well as in built-up "flooding" equipment similar to water sprinkler systems. Although these systems are generally built to be leak-tight, some leaks do occur and of course emissions occur when the agent is released. Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, as shown in the equation below. In streaming systems, emissions are assumed to be 2 percent of all chemical in use in each year, while in flooding systems 1.5 percent of the installed base of chemical is assumed to leak annually. The equation is applied for a single year, accounting for all fire protection equipment in operation in that year. Each fire protection agent is modeled separately. In the Vintaging Model, both streaming applications have a 10-year lifetime and flooding applications have a 20-year lifetime.

$$E_j = \mathrm{r} \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* for streaming fire extinguishing equipment, by weight.

r = Percent Released. The percentage of the total chemical in operation that is released to the atmosphere.

Qc = Quantity of Chemical. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, *j*-*i*+1, by weight.

i = Counter, runs from 1 to lifetime (k).

j = Year of emission.

k = Lifetime. The average lifetime of the equipment.

Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table 3-63.

Table 3-63. Fire Extinguishing Market Transition Assumptions

Initial Market Segment	Primary Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute	Start Date	Date of Full Pene-tration in New Equipment	Maximum Market Pene-tration	Growth Rate
Streaming Agents									
Halon 1211	HFC-236fa	1997	2000	4%	Non-ODP/GWP	2010	2011	50%	3.0%
	Blends	1995	2000	6%	Non-ODP/GWP	2010	2011	50%	
	Non-ODP/GWP	1993	1995	75%	None				
	Non-ODP/GWP	2005	2006	15%	None				
Flooding Agents									
Halon 1301	HFC-23	1994	Varies	1%	None				2.2%
	HFC-227ea	1994	Varies	33%	None				
	Blend	1994	Varies	14%	None				
	Non-ODP/GWP	1994	Varies	52%	None				

Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item. Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC or PFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal.

Step 1: Calculate emissions from open-cell foam

Emissions from open-cell foams are calculated using the following equation.

$$E_j = Qc_j$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* used for open-cell foam blowing, by weight.

Qc = Quantity of Chemical. Total amount of a specific chemical used for open-cell foam blowing in year *j*, by weight.

j = Year of emission.

Step 2: Calculate emissions from closed-cell foam

Emissions from closed-cell foams are calculated using the following equation.

$$E_j = \sum (ef_i \times Qc_{j-i+1}) \quad for\ i=1 \rightarrow k$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* for closed-cell foam blowing, by weight.

ef = Emission Factor. Percent of foam's original charge emitted in each year (for $i=1 \rightarrow k$). This emission factor is generally variable, including a rate for manufacturing emissions (occurs in the first year of foam life), annual emissions (every year throughout the foam lifetime), and disposal emissions (occurs during the final year of foam life).

Qc = Quantity of Chemical. Total amount of a specific chemical used in closed-cell foams in year $j\text{-}I+1$.

i = Counter, runs from 1 to lifetime (k).

j = Year of emission.

k = Lifetime. The average lifetime of the equipment.

Assumptions

The Vintaging Model contains 13 foam types, whose transition assumptions away from ODS and growth rates are presented in Table 3-64. The emission profiles of the foam types estimating in the Vintaging Model are shown in Table 3-65.

Table 3-64. Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
Commercial Refrigeration Foam									
CFC-11	HCFC-141b	1989	1997	40%	HFC-245fa	2002	2004	80%	6.0%
					Non-ODP/GWP	2002	2004	20%	
	HCFC-142b	1989	1997	8%	Non-ODP/GWP	2009	2011	80%	
					HFC-245fa	2009	2011	20%	
	HCFC-22	1989	1997	52%	Non-ODP/GWP	2009	2011	80%	
					HFC-245fa	2009	2011	20%	
Flexible Polyurethane Foam									
CFC-11	Non-ODP/GWP	1992	1993	100%	None				2.0%
One Component Foam									
CFC-12	Blend	1989	1997	70%	Non-ODP/GWP	2009	2011	80%	4.0%
					HFC-134a	2009	2011	10%	
					HFC-152a	2009	2011	10%	
	HCFC-22	1989	1997	30%	Non-ODP/GWP	2009	2011	80%	
					HFC-134a	2009	2011	10%	
					HFC-152a	2009	2011	10%	
Phenolic Foam									
CFC-11	HCFC-141b	1989	1991	100%	Non-ODP/GWP	1992	1993	100%	2.0%
Polyisocyanurate Boardstock Foam									
CFC-11	HCFC-141b	1993	1997	100%	Non-ODP/GWP	2000	2004	95%	6.0%
					Blend	2000	2004	5%	
Polyolefin Foam									
CFC-114	HFC-152a	1989	1994	10%	Non-ODP/GWP	2005	2011	100%	2.0%
	HCFC-142b	1989	1994	90%	Non-ODP/GWP	1994	1997	100%	
Polystyrene Boardstock Foam									
CFC-12	Blend	1989	1995	30%	HFC-134a	2009	2011	70%	4.0%
					HFC-152a	2009	2011	10%	
					CO_2	2009	2011	10%	
					Non-ODP/GWP	2009	2011	10%	
	HCFC-142b	1989	1995	70%	HFC-134a	2009	2011	70%	
					HFC-152a	2009	2011	10%	
					CO_2	2009	2011	10%	
					Non-ODP/GWP	2009	2011	10%	
Polystyrene Sheet/Insulation Board Foam									
CFC-12	CO_2	1989	1995	1%	None				2.0%
	Non-ODP/GWP	1989	1995	99%	CO_2	1995	2000	9%	
					HFC-152a	1995	2000	10%	
Polyurethane Appliance Foam									
CFC-11	HCFC-141b	1993	1997	89%	HFC-134a	1996	2004	10%	3.0%

					HFC-245fa	2002	2004	85%	
					Non-ODP/GWP	2002	2004	5%	
	Blend	1993	1997	1%	HFC-245fa	2009	2011	50%	
					HFC-134a	2009	2011	50%	
	HCFC-22	1993	1997	10%	HFC-134a	2009	2011	100%	
Polyurethane Integral Skin Foam									
CFC-11	HCFC-141b	1989	1991	100%	HFC-134a	1993	1997	25%	2.0%
					HFC-134a	1994	1997	25%	
					CO_2	1993	1997	25%	
					CO_2	1994	1997	25%	
Polyurethane Panel Foam*									
CFC-11	HCFC-141b	1989	1997	82%	Blend	2001	2004	20%	6.0%
					Blend	2002	2005	20%	
					Non-ODP/GWP	2001	2005	40%	
					HFC-134a	2002	2005	20%	
	HCFC-22	1989	1997	18%	Blend	2009	2011	40%	
					Non-ODP/GWP	2009	2011	20%	
					CO_2	2009	2011	20%	
					HFC-134a	2009	2011	20%	
Polyurethane Slabstock and Other Foam**									
CFC-11	HCFC-141b	1989	1997	100%	CO_2	1999	2004	45%	2.0%
					Non-ODP/GWP	2001	2004	45%	
					HCFC-22	2003	2004	10%	
Polyurethane Spray Foam									
CFC-11	HCFC-141b	1989	1997	95%	HFC-245fa	2004	2006	30%	6.0%
					Blend	2004	2006	60%	
					Non-ODP/GWP	2003	2006	10%	
	CO_2	1986	2004	5%	None				

* Polyurethane Panel Foam has a tertiary substitution; the first blend is assumed to contain HCFCs, and is thus substituted out with a 50/50 mixture of another blend an a non-ODP/GWP substitute in 2009, with 100% penetration in new equipment by 2011.

** Polyurethane Slabstock and Other Foam has a tertiary substitution; HCFC-22 is substituted with a non-ODP/GWP substitute in 2009, with 100% penetration in new equipment in 2011.

Table 3-65. Emission profile for the foam end-uses.

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total*
Flexible PU	100	0	0	0	100
Polyisocyanurate Boardstock	6	1	50	44	100
Rigid PU Integral Skin	95	2.5	2	0	100
Rigid PU Appliance	4	0.25	15	92.25	100
Rigid PU Commercial Refrigeration	6	0.25	15	90.25	100
Rigid PU Spray	25	1.5	50	0	100
One Component	100	0	0	0	100
Rigid PU Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic	23	0.875	32	49	100
Polyolefin	95	2.5	2	0	100
XPS Sheet/Insulation Board*	40	2	25	0	90
XPS Boardstock	25	2.5	30	0	100
PU Sandwich Panels	5.5	0.5	50	69.5	100

PU (Polyurethane)
XPS (Extruded Polystyrene)
*In general, total emissions from foam end-uses are assumed to be 100 percent, although work is underway to investigate that assumption. In the XPS Sheet/Insulation Board end-use, the source of emission rates and lifetimes did not yield 100 percent emissions; it is unclear at this time whether that was intentional.

Sterilization

Sterilization is used to control microorganisms and pathogens during the growing, collecting, storing and distribution of flowers as well as various foods including grains, vegetables and fruits. Currently, the Vintaging

Model assumes that the sterilization sector has not transitioned to any HFC or PFC as an ODS substitute, however, the modeling methodology is provided below for completeness.

The sterilization sector is modeled as a single end-use. For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

$$E_j = Qc_j$$

Where:

E = Emissions. Total emissions of a specific chemical in year *j* from use in sterilization equipment, by weight.

Qc = Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year *j*, by weight.

j = Year of emission.

Model Output

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use basis. Values for use and emissions are calculated both in metric tons and in teragrams of carbon dioxide equivalents (Tg CO_2 Eq.). The conversion of metric tons of chemical to Tg CO_2 Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical.

Throughout its development, the Vintaging Model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often altered.

3.9. Methodology for Estimating CH_4 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 3-66.

Table 3-66: 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 bulls[1]) 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 (2003a, 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 2002. 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 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

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

each year (USDA 2003c, 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 2002 are shown in Table 3-67. Table 3-68 provides the target weights used to track average weights of cattle by animal type. Table 3-69 provides a summary of the reported feedlot placement statistics for 2002. Data on feedlot placements were available for 1996 through 2002. 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 **Error! Reference source not found.** of the Manure Management Annex. 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 (2003a, 2003c, 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 States[2] were developed. 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 DE 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 DE as it is essentially the same as the digestible energy value. For forage diets, two separate regional DE values were used to account for the generally lower forage quality in the western US. For non-western grazing animals, the forage DE 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 DE for western grazing animals was 58.5 percent. The supplemental diet DE values were estimated for each specific feed component, as shown in Table 3-70, along with the percent of each feed type in each region. Finally, weighted averages were developed for DE values for each region using both the supplemental diet and the forage diet[3]. For beef cows, the DE 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 DE values for each region are shown in Table 3-71. Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002).

For feedlot animals, DE and Y_m values for 1996 through 2002 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).

Table 3-72 shows the regional DE, the Y_m, and percent of total U.S. cattle population in each region based on 2002 data.

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)

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[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.

- Net Energy for Activity (C_a)[4]
- Standard Reference Weight[5] (Dairy = 1,324 lbs; Beef = 1,195 lbs)
- 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:

$$DayEmit = [GE \times Y_m] / [55.65 \text{ MJ/kg } CH_4]$$

Where:

DayEmit = emission factor (kg CH_4/head/day)

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.

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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.

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 CH_4/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 3-73. 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. **Error! Reference source not found.** of the Manure Management Annex 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 3-74 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 3-75 (Tg CO_2 Eq.) and Table 3-76 (Gg).

Table 3-67: Dairy Lactation by Region (lbs· year/cow)*

Year	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
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	20,890	20,799	17,330	14,827	17,603	17,217	15,304
2002	21,166	21,102	18,037	15,789	17,982	17,515	15,463

Source: USDA (2003d, 2002d, 2001d, 2000d, 1999a, 1995a).

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

Table 3-68: 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 3-69: Feedlot Placements in the United States for 2002 (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	489	351	333	301	382	347	424	573	775	1066	757	504	6,302
600 - 700 lbs	691	476	411	310	471	380	386	504	612	755	559	516	6,071
700 - 800 lbs	654	596	717	577	794	498	592	691	681	531	405	406	7,142
> 800 lbs	382	457	570	519	658	439	505	672	618	477	293	273	5,863
Total	2,216	1,880	2,031	1,707	2,305	1,664	1,907	2,440	2,686	2,829	2,014	1,699	25,378

Source: USDA (2003f, 2002f, 2001f, 2000f, 1999a, 1995a).
Note: Totals may not sum due to independent rounding.

Table 3-70: 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).

Table 3-71: 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 3-72: Regional Digestible Energy (DE), Methane Conversion Rates (Y_m), and population percentages for Cattle in 2002

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]	2%	10%	29%	24%	2%	14%	18%
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.	19%	12%	4%	4%	18%	37%	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%	41%	23%	2%	18%	4%
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%	49%	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%	15%	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%	15%	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.	18%	14%	5%	5%	18%	32%	8%
Steer Step-Up	DE	58	58	49	43	49	48	42
	Y_m	74	74	74	74	74	74	74
Heifer Step-Up	DE	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
	Y_m	74	74	74	74	74	74	74

[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 3-73: CH_4 Emissions from Cattle (Gg)

Cattle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Dairy	1,375	1,378	1,375	1,316	1,314	1,320	1,254	1,255	1,251	1,266	1,284	1,283	1,289
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	1,061
Replacements 7-11 months	49	49	49	49	49	49	48	48	48	48	48	48	49
Replacements 12-23 months	184	181	183	185	183	183	181	179	177	180	177	180	180
Beef	3,961	3,920	4,031	4,070	4,147	4,272	4,227	4,124	4,046	4,035	3,976	3,911	3,912
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	2,471
Replacements 7-11 months	52	54	57	60	62	61	60	56	54	53	53	54	54
Replacements 12-23 months	190	196	203	216	229	232	225	216	206	198	198	200	199
Steer Stockers	430	402	464	482	435	479	455	430	418	393	369	342	350
Heifer Stockers	231	220	233	240	231	249	239	241	236	227	213	200	204
Feedlot Cattle	56	54	53	51	52	54	51	55	48	59	67	69	61
Bulls	70	67	66	61	64	65	66	61	62	67	66	67	65
Total	5,336	5,298	5,406	5,385	5,461	5,591	5,481	5,379	5,297	5,300	5,260	5,194	5,201

Note: Totals may not sum due to independent rounding.

Table 3-74: Emission Factors for Other Livestock (kg CH_4/head/year)

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

Source: IPCC (2000).

Table 3-75: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Beef Cattle	83.2	82.3	84.7	85.5	87.1	89.7	88.8	86.6	85.0	84.7	83.5	82.1	82.1
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	27.1
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	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	1.1
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	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	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	114.3	114.4

Table 3-76: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Beef Cattle	3,961	3,920	4,031	4,070	4,147	4,272	4,227	4,124	4,046	4,035	3,976	3,911	3,912
Dairy Cattle	1,375	1,378	1,375	1,316	1,314	1,320	1,254	1,255	1,251	1,266	1,284	1,283	1,289
Horses	91	92	92	92	92	92	93	93	94	93	94	95	95
Sheep	91	89	86	82	79	72	68	64	63	58	56	56	53
Swine	81	85	88	87	90	88	84	88	93	90	88	88	90
Goats	13	13	13	12	12	11	10	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	5,443	5,450

3.10. Methodology for Estimating CH_4 and N_2O 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 3.11).

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2002 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, 2003 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 2003). 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 3-77.

Dairy Cattle: The total annual dairy cow and heifer state population data for 1990 through 2002 are provided in various USDA National Agricultural Statistics Service reports (1995a, 1999a, 2000a-b, 2001a-b, 2002a-b, 2003a-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/>), 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 2002 are provided in various USDA National Agricultural Statistics Service reports (1995a, 1999a, 2000a-b, 2001a-b, 2002a-b, 2003a-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,” “Calves Less Than 500 Lbs,” “Bulls 500+ Lbs,” and “Steers 500+ Lbs.” Additional information regarding the percent of beef steers and heifers in feedlots was obtained from contacts with the national USDA office (Milton 2000).

For all beef cattle groups (cows, heifers, steers, 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 U.S. 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, 2003c). 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 2002 were obtained from USDA National Agricultural Statistics Service (USDA 1994b, 1999c, 2000f, 2001f, 2002f, 2003f). Population data for lamb and sheep on feed are not available after 1993. The number of lamb and sheep on feed for 1994 through 2002 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 in feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb in feedlots for all years, it was assumed that the percentage of sheep and lamb on feed that are in 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 2002. 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, 2003d-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 2003).

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_o) for U.S. animal waste
- Nitrogen excretion rate (N_{ex})
- Typical animal mass (TAM)

Table 3-78 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 dairy cow population is assumed to be comprised of both lactating and dry cows. Nitrogen excretion rates were collected from the sources indicated in Table 3-78 and are based on measurement data from excreted manure.

The method for calculating volatile solids production from beef and dairy cows, heifers, and steers 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 Annex 3.9 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 value 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:

VS production (kg) = [GE - DE + (0.02 * GE)] / 20.1 (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., 2003).

Table 3-79 presents the state-specific volatile solids production rates used for 2002.

Step 3: Waste Management System Usage Data

Estimates were made of the distribution of waste 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 waste 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 steers and heifers in 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)

Table 3-80 through Table 3-85 summarize 2002 manure distribution data among waste management systems at beef feedlots, dairies, dairy heifer facilities, and swine, layer, broiler, and turkey operations. Manure from beef cattle not on feed, sheep, horses, and goats is managed on pasture, range, or paddocks, on drylot, or with solids storage systems. Additional information on the development of the manure distribution estimates for each animal type is presented below.

Beef Cattle: The beef feedlot and dairy heifer waste management system (WMS) data were developed using information from EPA's Office of Water's engineering cost analyses conducted to support the development of effluent limitations guidelines for Concentrated Animal Feeding Operations (ERG, 2001a). Based on EPA site visits and state contacts supporting this work, beef feedlot manure is almost exclusively managed in drylots. Therefore, for these animal groups, the percent of manure deposited in drylots is assumed to be 100 percent. In addition, there is a small amount of manure contained in runoff, which may or may not be collected in runoff ponds. The runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* (ERG 2003b) and was used to estimate the percentage of manure managed in runoff ponds in addition to drylots; this percentage ranges from 0.003 to 0.010 percent. The percentage of manure generating emissions from beef feedlots is therefore greater than 100 percent. The remaining population categories of beef cattle outside of feedlots are managed through pasture/range/paddock systems, which are utilized for the majority of the population of beef cattle in the country.

Dairy Cows: The WMS data for dairy cows was developed using data from the Census of Agriculture, EPA's Office of Water, USDA, and expert sources. Farm-size distribution data are reported in the 1992 and 1997 Census of Agriculture (USDA 1999e). Due to a 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, 2001, and 2002. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

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 waste 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 (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).

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 waste that are managed using these systems. These percentages were applied to the total annual dairy cow and heifer state population data for 1990 through 2002, which were obtained from the National Agricultural Statistics Service (USDA 1995a, 1999a, 2000a-b, 2001a-b, 2002a-b, 2003a-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: 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. In addition, there is a small amount of manure contained in runoff, which may or may not be collected in runoff ponds. The runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* (ERG 2003b) and was used to estimate the percentage of manure managed in runoff ponds in addition to drylots; this percentage ranges from 0.003 to 0.010 percent. The percentage of manure generating emissions from dairy heifers is therefore greater than 100 percent.

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.

Due to lack of additional data, it was assumed that the swine farm size 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 through 2002. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

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

Goats/Horses: Waste management system data for 1990 to 2002 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that all manure not deposited in pasture, range, or paddock lands were managed in dry systems.

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 through 2002 was equal to that estimated for 1999. It was also assumed that 1 percent of poultry waste are deposited on pasture, range, or paddock lands (EPA 1992).

Poultry - Broilers/Turkeys: The percentage of turkeys and broilers on pasture was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA1992). It was assumed that 1 percent of poultry waste are deposited in pastures, range, and paddocks (EPA 1992). The remainder of waste is assumed to be deposited in operations with bedding management.

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)

IPCC default MCFs were used for all dry systems modeling, while a country-specific methodology was used to develop MCFs for all lagoon and liquid systems. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) published default methane conversion factors for dry systems according to climate classification (cool, temperate, or warm). The IPCC default MCFs for the temperate climate classification were used for all animal waste managed in dry systems as follows:

Pasture/Range/Paddock	1.5%
Daily Spread	0.5%
Solid Storage	1.5%
Dry Lot	1.5%
Poultry Manure with Bedding	1.5%
Poultry Manure without bedding	1.5%

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000) published default methane conversion factors of 0 to 100 percent for anaerobic lagoon systems, which reflects the wide range in performance that may be achieved with these systems, depending on temperature and retention time. Therefore, a climate-based approach was developed to estimate MCFs for anaerobic lagoons and other liquid systems that reflects the seasonal changes in temperatures, and also accounts for long term retention time.

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 = 303.16K

T_2 = ambient temperature (K) for climate zone (in this case, a weighted value for each state)

E = activation energy constant (15,175 cal/mol)

R = 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 in 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 calculated from the state-level NASS data and the distribution of county-to-state population calculated from the 1992 and 1997 Census data (USDA 1999e). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1998 through 2001 were assumed to be the same as 1997; and county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

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. Lagoons are also modeled to have a solids clean-out once per year, occurring after the month of September.

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_o).

8) The annual MCF is then calculated as:

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

Where:

$MCF_{(annual)}$	=	Methane conversion factor
$VS \text{ produced}_{(annual)}$	=	Volatile solids excreted annually
B_o	=	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 3-86 by state and waste management system represent the average MCF for 2002 by state for all animal groups located in that state. However, in the actual calculation of methane emissions, specific MCFs for each animal type in the state are used that represent the locations of the particular animal group in each state.

Nitrous Oxide Emission Factors

Nitrous oxide emission factors for all manure management systems were set equal to the default IPCC factors (IPCC 2000) of 0.02 kg N_2O-N/kg N excreted for dry manure systems and 0.001 kg N_2O-N/kg N excreted for wet manure systems.

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 waste 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
$MCF_{system, state}$	=	MCF for that system and state (see Step 4)
$\% Manure_{animal, system, state}$	=	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:

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

Where:

$EF_{animal, state}$	=	Weighted emission factor for that animal group and state
EF_{system}	=	Emission factor for that system (see Step 4)
% $Manure_{animal, system, state}$	=	Percent of manure managed in the system for that animal group in that state (expressed as a decimal)

For each state, the MCFs attributed to each animal group were weight-averaged according to the waste management system distribution in that state for that animal group. A summary of the weighted MCFs used to calculate beef feedlot, dairy cow and heifer, swine, and poultry emissions for 2002 are presented in Table 3-87. For certain animal groups (beef cattle not on feed, horses, sheep, and goats), the emission factors do not vary for the management systems used. In these cases, a weighted emission factor was not necessary.

Step 6: Methane and Nitrous Oxide Emission Calculations

Methane emissions were calculated for each animal group as follows:

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

Where:

$Methane_{animal\ group}$	=	methane emissions for that animal group (kg CH_4/yr)
Population	=	annual average state animal population for that animal group (head)
VS	=	total volatile solids produced annually per animal (kg/yr/head)
B_o	=	maximum methane producing capacity per kilogram of VS (m^3 CH_4/kg VS)
$MCF_{animal, state}$	=	weighted MCF for the animal group and state (see Step 5)
0.662	=	conversion factor of m^3 CH_4 to kilograms CH_4 (kg CH_4 /m^3 CH_4)

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

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

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 N_2O-N/kg N excreted (see Step 5)
44/28	=	conversion factor of N_2O-N to N_2O

Emission estimates are summarized in Table 3-88 and Table 3-89.

Table 3-77: Livestock Population (1,000 Head)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Dairy Cattle	14,143	13,980	13,830	13,767	13,566	13,502	13,305	13,138	12,992	13,026	13,070	12,970	13,011
Dairy Cows	10,007	9,883	9,714	9,679	9,504	9,491	9,410	9,309	9,200	9,142	9,220	9,141	9,131
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	3,880
Swine	53,941	56,478	58,532	58,016	59,951	58,899	56,220	58,728	61,991	60,340	58,892	58,970	59,979
Market <60 lbs.	18,359	19,212	19,851	19,434	20,157	19,656	18,851	19,886	20,691	19,973	19,582	19,657	19,826
Market 60-119 lbs.	11,734	12,374	12,839	12,656	13,017	12,836	12,157	12,754	13,552	13,299	12,933	12,939	13,315
Market 120-179 lbs.	9,440	9,840	10,253	10,334	10,671	10,545	10,110	10,480	11,235	11,035	10,753	10,709	10,995
Market >180 lbs.	7,510	7,822	8,333	8,435	8,824	8,937	8,463	8,768	9,672	9,680	9,390	9,477	9,718
Breeding	6,899	7,231	7,255	7,157	7,282	6,926	6,639	6,840	6,841	6,354	6,233	6,188	6,126
Beef Cattle	86,087	87,267	88,548	90,321	92,571	94,391	94,269	92,290	90,730	90,032	89,215	88,622	87,929
Feedlot Steers	7,338	7,920	7,581	7,984	7,797	7,763	7,380	7,644	7,845	7,782	8,280	8,565	8,324
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	4,806
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	2,172
NOF Calves[2]	23,909	23,853	24,118	24,209	24,586	25,170	25,042	24,363	24,001	23,896	23,508	22,952	22,581
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	9,225	9,253
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	7,359
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	33,649	33,434
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	6,685
Sheep not on Feed	10,178	10,064	9,613	9,009	8,824	8,083	7,595	7,172	6,991	6,430	6,260	6,200	5,963
Sheep on Feed	1,180	1,110	1,183	1,192	1,012	906	870	851	834	785	772	765	722
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	1,990
Poultry	1,537,074	1,594,944	1,649,998	1,707,422	1,769,135	1,826,977	1,882,078	1,926,790	1,963,717	2,007,350	2,027,780	2,050,885	2,083,345
Hens >1 yr.	119,551	117,178	121,103	131,688	135,094	133,841	138,048	140,966	150,778	151,914	153,212	153,357	153,032
Pullets[1]	227,083	239,559	243,267	240,712	243,286	246,599	247,446	261,515	265,634	274,520	272,269	277,290	274,984
Chickens	6,545	6,857	7,113	7,240	7,369	7,637	7,243	7,549	7,682	9,659	8,084	8,121	8,345
Broilers	1,066,209	1,115,845	1,164,089	1,217,147	1,275,916	1,331,940	1,381,229	1,411,673	1,442,596	1,481,093	1,506,182	1,525,290	1,561,850
Turkeys	117,685	115,504	114,426	110,635	107,469	106,960	108,112	105,088	97,026	90,165	88,033	86,827	85,134
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	5,300

Note: Totals may not sum due to independent rounding.

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

[2]NOF = Not on Feed

Table 3-78: Waste Characteristics Data

Animal Group	Average TAM (kg)	Source	Total Kjeldahl Nitrogen, N_{ex} (kg/day per	Source	Maximum Methane Generation Potential, B_o (m^3	Source	Volatile Solids, VS (kg/day per 1,000 kg mass)	Source

			1,000 kg mass)		CH_4/kg VS added)			
Dairy Cows	604	Safley 2000	0.44	USDA 1996a	0.24	Morris 1976	Table 3-79	Peterson et al., 2003
Dairy Heifers	476	Safley 2000	0.31	USDA 1996a	0.17	Bryant et. al. 1976	Table 3-79	Peterson et al., 2003
Feedlot Steers	420	USDA 1996a	0.30	USDA 1996a	0.33	Hashimoto 1981	Table 3-79	Peterson et al., 2003
Feedlot Heifers	420	USDA 1996a	0.30	USDA 1996a	0.33	Hashimoto 1981	Table 3-79	Peterson et al., 2003
NOF Bulls	750	Safley 2000	0.31	USDA 1996a	0.17	Hashimoto 1981	6.04	USDA 1996a
NOF Calves	118	ERG 2003	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 3-79	Peterson et al., 2003
NOF Steers	318	Safley 2000	0.31	USDA 1996a	0.17	Hashimoto 1981	Table 3-79	Peterson et al., 2003
NOF Cows	533	NRC 2000	0.33	USDA 1996a	0.17	Hashimoto 1981	Table 3-79	Peterson et al., 2003
Market Swine <60 lbs.	16	Safley 2000	0.60	USDA 1996a	0.48	Hashimoto 1984	8.80	USDA 1996a
Market Swine 60-119 lbs.	41	Safley 2000	0.42	USDA 1996a	0.48	Hashimoto 1984	5.40	USDA 1996a
Market Swine 120-179 lbs.	68	Safley 2000	0.42	USDA 1996a	0.48	Hashimoto 1984	5.40	USDA 1996a
Market Swine >180 lbs.	91	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
Feedlot Sheep	27	ASAE 1999	0.42	ASAE 1999	0.36	USEPA 1992	9.20	USEPA 1992
NOF Sheep	27	ASAE 1999	0.42	ASAE 1999	0.19	USEPA 1992	9.20	USEPA 1992
Goats	64	ASAE 1999	0.45	ASAE 1999	0.17	USEPA 1992	9.50	USEPA 1992
Horses	450	ASAE 1999	0.30	ASAE 1999	0.33	USEPA 1992	10.0	USEPA 1992
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 3-79: Estimated Volatile Solids Production Rate by State for 2002

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	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Alaska	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Arizona	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Arkansas	8.36	7.57	6.72	7.15	7.57	3.34	3.27
California	9.44	6.82	6.57	6.98	7.39	3.29	3.23
Colorado	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Connecticut	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Delaware	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Florida	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Georgia	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Hawaii	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Idaho	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Illinois	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Indiana	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Iowa	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Kansas	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Kentucky	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Louisiana	8.36	7.57	6.72	7.15	7.57	3.34	3.27
Maine	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Maryland	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Massachusetts	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Michigan	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Minnesota	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Mississippi	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Missouri	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Montana	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Nebraska	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Nevada	10.86	6.82	8.71	9.44	10.04	3.33	3.26
New Hampshire	8.52	6.14	6.62	7.04	7.46	3.33	3.26
New Jersey	8.52	6.14	6.62	7.04	7.46	3.33	3.26
New Mexico	10.86	6.82	8.71	9.44	10.04	3.33	3.26
New York	8.52	6.14	6.62	7.04	7.46	3.33	3.26
North Carolina	8.61	6.82	6.74	7.17	7.60	3.37	3.30
North Dakota	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Ohio	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Oklahoma	8.36	7.57	6.72	7.15	7.57	3.34	3.27
Oregon	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Pennsylvania	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Rhode Island	8.52	6.14	6.62	7.04	7.46	3.33	3.26
South Carolina	8.61	6.82	6.74	7.17	7.60	3.37	3.30
South Dakota	8.53	6.82	6.19	6.55	6.93	3.33	3.26
Tennessee	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Texas	8.36	7.57	6.72	7.15	7.57	3.34	3.27
Utah	10.86	6.82	8.71	9.44	10.04	3.33	3.26
Vermont	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Virginia	8.61	6.82	6.74	7.17	7.60	3.37	3.30
Washington	10.86	6.82	8.71	9.44	10.04	3.33	3.26
West Virginia	8.52	6.14	6.62	7.04	7.46	3.33	3.26
Wisconsin	8.38	6.82	6.63	7.04	7.46	3.35	3.28
Wyoming	8.53	6.82	6.19	6.55	6.93	3.33	3.26

Source: Peterson et al., 2003.

Table 3-80: 2002 Manure Distribution Among Waste Management Systems at Beef Feedlots (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot[a]	Liquid/ Slurry[a]	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding

State	Pasture	Daily Spread	Solid Storage	Dry Lot[a]	Liquid/ Slurry[a]	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	0	0	0	100	1.3	0	0	0	0
Alaska	0	0	0	100	1.3	0	0	0	0
Arizona	0	0	0	100	0.4	0	0	0	0
Arkansas	0	0	0	100	1.3	0	0	0	0
California	0	0	0	100	1.3	0	0	0	0
Colorado	0	0	0	100	0.4	0	0	0	0
Connecticut	0	0	0	100	1.0	0	0	0	0
Delaware	0	0	0	100	1.0	0	0	0	0
Florida	0	0	0	100	1.3	0	0	0	0
Georgia	0	0	0	100	1.3	0	0	0	0
Hawaii	0	0	0	100	1.3	0	0	0	0
Idaho	0	0	0	100	0.4	0	0	0	0
Illinois	0	0	0	100	0.6	0	0	0	0
Indiana	0	0	0	100	0.6	0	0	0	0
Iowa	0	0	0	100	0.6	0	0	0	0
Kansas	0	0	0	100	0.6	0	0	0	0
Kentucky	0	0	0	100	1.0	0	0	0	0
Louisiana	0	0	0	100	1.3	0	0	0	0
Maine	0	0	0	100	1.0	0	0	0	0
Maryland	0	0	0	100	1.0	0	0	0	0
Massachusetts	0	0	0	100	1.0	0	0	0	0
Michigan	0	0	0	100	0.6	0	0	0	0
Minnesota	0	0	0	100	0.6	0	0	0	0
Mississippi	0	0	0	100	1.3	0	0	0	0
Missouri	0	0	0	100	0.6	0	0	0	0
Montana	0	0	0	100	0.4	0	0	0	0
Nebraska	0	0	0	100	0.6	0	0	0	0
Nevada	0	0	0	100	0.4	0	0	0	0
New Hampshire	0	0	0	100	1.0	0	0	0	0
New Jersey	0	0	0	100	1.0	0	0	0	0
New Mexico	0	0	0	100	0.4	0	0	0	0
New York	0	0	0	100	1.0	0	0	0	0
North Carolina	0	0	0	100	1.0	0	0	0	0
North Dakota	0	0	0	100	0.6	0	0	0	0
Ohio	0	0	0	100	0.6	0	0	0	0
Oklahoma	0	0	0	100	0.4	0	0	0	0
Oregon	0	0	0	100	1.3	0	0	0	0
Pennsylvania	0	0	0	100	1.0	0	0	0	0
Rhode Island	0	0	0	100	1.0	0	0	0	0
South Carolina	0	0	0	100	1.3	0	0	0	0
South Dakota	0	0	0	100	0.6	0	0	0	0
Tennessee	0	0	0	100	1.0	0	0	0	0
Texas	0	0	0	100	0.4	0	0	0	0
Utah	0	0	0	100	0.4	0	0	0	0
Vermont	0	0	0	100	1.0	0	0	0	0
Virginia	0	0	0	100	1.0	0	0	0	0
Washington	0	0	0	100	1.3	0	0	0	0
West Virginia	0	0	0	100	1.0	0	0	0	0
Wisconsin	0	0	0	100	0.6	0	0	0	0
Wyoming	0	0	0	100	0.4	0	0	0	0

[a] Because manure at beef feedlots may be managed for long periods of time in multiple systems (i.e., both drylot and runoff collection pond), the percent of manure that generates emissions is greater than 100 percent.

Table 3-81: 2002 Manure Distribution Among Waste Management Systems at Dairies (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	63	14	8	0	7	8	0	0	0
Alaska	10	17	23	0	20	25	6	0	0
Arizona	0	10	9	0	20	61	0	0	0

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Arkansas	63	14	12	0	5	6	1	0	0
California	1	11	9	0	21	57	0	0	0
Colorado	1	2	13	0	27	56	2	0	0
Connecticut	6	44	23	0	17	7	3	0	0
Delaware	8	45	25	0	14	5	3	0	0
Florida	12	23	7	0	15	43	0	0	0
Georgia	53	16	9	0	9	13	0	0	0
Hawaii	12	0	13	0	21	53	2	0	0
Idaho	1	2	15	0	25	56	2	0	0
Illinois	7	12	51	0	19	6	5	0	0
Indiana	11	18	45	0	16	5	4	0	0
Iowa	10	17	47	0	16	6	4	0	0
Kansas	8	14	51	0	17	5	5	0	0
Kentucky	63	14	16	0	5	1	1	0	0
Louisiana	58	15	11	0	6	9	1	0	0
Maine	9	47	26	0	12	4	3	0	0
Maryland	8	46	25	0	13	5	3	0	0
Massachusetts	8	46	26	0	13	5	3	0	0
Michigan	6	10	42	0	26	12	5	0	0
Minnesota	11	19	45	0	16	5	4	0	0
Mississippi	63	14	10	0	6	7	0	0	0
Missouri	10	16	49	0	16	5	5	0	0
Montana	3	4	32	0	23	30	9	0	0
Nebraska	9	16	48	0	17	5	5	0	0
Nevada	2	3	11	0	20	63	0	0	0
New Hampshire	7	45	26	0	13	5	3	0	0
New Jersey	8	46	26	0	13	4	3	0	0
New Mexico	0	10	10	0	19	61	0	0	0
New York	8	46	23	0	14	7	2	0	0
North Carolina	63	14	10	0	8	3	2	0	0
North Dakota	12	20	48	0	12	3	4	0	0
Ohio	10	17	46	0	17	5	5	0	0
Oklahoma	0	5	34	0	23	29	9	0	0
Oregon	31	0	13	0	20	33	3	0	0
Pennsylvania	10	48	27	0	10	3	2	0	0
Rhode Island	12	51	28	0	6	2	2	0	0
South Carolina	63	14	7	0	7	9	0	0	0
South Dakota	10	17	47	0	16	5	4	0	0
Tennessee	63	14	13	0	7	2	2	0	0
Texas	0	7	16	0	26	49	3	0	0
Utah	2	3	22	0	28	41	5	0	0
Vermont	8	46	24	0	14	6	3	0	0
Virginia	63	14	12	0	7	2	2	0	0
Washington	23	0	11	0	22	43	2	0	0
West Virginia	9	47	27	0	11	4	3	0	0
Wisconsin	10	17	46	0	17	6	4	0	0
Wyoming	8	14	23	0	22	28	6	0	0

Table 3-82: 2002 Manure Distribution Among Waste Management Systems at Dairy Heifer Facilities (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot[1]	Liquid/ Slurry[1]	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	0	0	0	100	1.0	0	0	0	0
Alaska	0	0	0	100	1.0	0	0	0	0
Arizona	0	0	0	100	0.3	0	0	0	0
Arkansas	0	0	0	100	1.0	0	0	0	0
California	0	0	0	100	1.0	0	0	0	0
Colorado	0	0	0	100	0.3	0	0	0	0
Connecticut	0	0	0	100	0.8	0	0	0	0

State	Pasture	Daily Spread	Solid Storage	Dry Lot[1]	Liquid/ Slurry[1]	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Delaware	0	0	0	100	0.8	0	0	0	0
Florida	0	0	0	100	1.0	0	0	0	0
Georgia	0	0	0	100	1.0	0	0	0	0
Hawaii	0	0	0	100	1.0	0	0	0	0
Idaho	0	0	0	100	0.3	0	0	0	0
Illinois	0	0	0	100	0.5	0	0	0	0
Indiana	0	0	0	100	0.5	0	0	0	0
Iowa	0	0	0	100	0.5	0	0	0	0
Kansas	0	0	0	100	0.5	0	0	0	0
Kentucky	0	0	0	100	0.8	0	0	0	0
Louisiana	0	0	0	100	1.0	0	0	0	0
Maine	0	0	0	100	0.8	0	0	0	0
Maryland	0	0	0	100	0.8	0	0	0	0
Massachusetts	0	0	0	100	0.8	0	0	0	0
Michigan	0	0	0	100	0.5	0	0	0	0
Minnesota	0	0	0	100	0.5	0	0	0	0
Mississippi	0	0	0	100	1.0	0	0	0	0
Missouri	0	0	0	100	0.5	0	0	0	0
Montana	0	0	0	100	0.3	0	0	0	0
Nebraska	0	0	0	100	0.5	0	0	0	0
Nevada	0	0	0	100	0.3	0	0	0	0
New Hampshire	0	0	0	100	0.8	0	0	0	0
New Jersey	0	0	0	100	0.8	0	0	0	0
New Mexico	0	0	0	100	0.3	0	0	0	0
New York	0	0	0	100	0.8	0	0	0	0
North Carolina	0	0	0	100	0.8	0	0	0	0
North Dakota	0	0	0	100	0.5	0	0	0	0
Ohio	0	0	0	100	0.5	0	0	0	0
Oklahoma	0	0	0	100	0.3	0	0	0	0
Oregon	0	0	0	100	1.0	0	0	0	0
Pennsylvania	0	0	0	100	0.8	0	0	0	0
Rhode Island	0	0	0	100	0.8	0	0	0	0
South Carolina	0	0	0	100	1.0	0	0	0	0
South Dakota	0	0	0	100	0.5	0	0	0	0
Tennessee	0	0	0	100	0.8	0	0	0	0
Texas	0	0	0	100	0.3	0	0	0	0
Utah	0	0	0	100	0.3	0	0	0	0
Vermont	0	0	0	100	0.8	0	0	0	0
Virginia	0	0	0	100	0.8	0	0	0	0
Washington	0	0	0	100	1.0	0	0	0	0
West Virginia	0	0	0	100	0.8	0	0	0	0
Wisconsin	0	0	0	100	0.5	0	0	0	0
Wyoming	0	0	0	100	0.3	0	0	0	0

[1] Because manure from dairy heifers may be managed for long periods of time in multiple systems (i.e., both drylot and runoff collection pond), the percent of manure that generates emissions is greater than 100 percent.

Table 3-83: 2002 Manure Distribution Among Waste Management Systems at Swine Operations (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	10	0	4	0	12	41	33	0	0
Alaska	100	0	0	0	0	0	0	0	0
Arizona	6	0	4	0	12	45	34	0	0
Arkansas	2	0	4	0	10	50	34	0	0
California	10	0	3	0	8	49	30	0	0
Colorado	2	0	5	0	26	17	49	0	0
Connecticut	60	0	2	0	11	8	19	0	0
Delaware	11	0	5	0	24	16	44	0	0
Florida	62	0	2	0	11	8	18	0	0
Georgia	9	0	4	0	13	40	34	0	0

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Hawaii	36	0	3	0	18	14	30	0	0
Idaho	34	0	3	0	18	13	32	0	0
Illinois	4	0	4	0	27	16	48	0	0
Indiana	4	0	4	0	27	16	48	0	0
Iowa	3	0	4	0	16	40	38	0	0
Kansas	6	0	4	0	27	14	49	0	0
Kentucky	7	0	4	0	15	39	36	0	0
Louisiana	61	0	2	0	11	8	18	0	0
Maine	100	0	0	0	0	0	0	0	0
Maryland	19	0	4	0	22	16	39	0	0
Massachusetts	42	0	3	0	16	12	27	0	0
Michigan	7	0	5	0	25	17	46	0	0
Minnesota	3	0	5	0	26	18	48	0	0
Mississippi	4	0	4	0	8	52	32	0	0
Missouri	5	0	4	0	27	14	49	0	0
Montana	8	0	5	0	24	17	46	0	0
Nebraska	5	0	4	0	27	16	47	0	0
Nevada	100	0	0	0	0	0	0	0	0
New Hampshire	63	0	2	0	10	8	17	0	0
New Jersey	49	0	2	0	14	11	24	0	0
New Mexico	100	0	0	0	0	0	0	0	0
New York	32	0	4	0	18	13	34	0	0
North Carolina	0	0	4	0	7	58	32	0	0
North Dakota	14	0	4	0	23	16	42	0	0
Ohio	10	0	4	0	25	16	45	0	0
Oklahoma	2	0	4	0	7	56	31	0	0
Oregon	66	0	1	0	9	7	16	0	0
Pennsylvania	6	0	5	0	25	18	46	0	0
Rhode Island	45	0	2	0	15	12	26	0	0
South Carolina	9	0	4	0	11	44	33	0	0
South Dakota	8	0	5	0	25	17	45	0	0
Tennessee	13	0	4	0	15	33	35	0	0
Texas	12	0	3	0	8	46	30	0	0
Utah	3	0	5	0	26	17	49	0	0
Vermont	100	0	0	0	0	0	0	0	0
Virginia	5	0	4	0	9	51	32	0	0
Washington	30	0	3	0	19	14	34	0	0
West Virginia	42	0	3	0	16	12	27	0	0
Wisconsin	14	0	4	0	23	17	41	0	0
Wyoming	5	0	5	0	25	16	48	0	0

Table 3-84: 2002 Manure Distribution Among Waste Management Systems at Layer Operations (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	0	0	0	0	0	42	0	0	58
Alaska	0	0	0	0	0	25	0	0	75
Arizona	0	0	0	0	0	60	0	0	40
Arkansas	0	0	0	0	0	0	0	0	100
California	0	0	0	0	0	12	0	0	88
Colorado	0	0	0	0	0	60	0	0	40
Connecticut	0	0	0	0	0	5	0	0	95
Delaware	0	0	0	0	0	5	0	0	95
Florida	0	0	0	0	0	42	0	0	58
Georgia	0	0	0	0	0	42	0	0	58
Hawaii	0	0	0	0	0	25	0	0	75
Idaho	0	0	0	0	0	60	0	0	40
Illinois	0	0	0	0	0	2	0	0	98
Indiana	0	0	0	0	0	0	0	0	100

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Iowa	0	0	0	0	0	0	0	0	100
Kansas	0	0	0	0	0	2	0	0	98
Kentucky	0	0	0	0	0	5	0	0	95
Louisiana	0	0	0	0	0	60	0	0	40
Maine	0	0	0	0	0	5	0	0	95
Maryland	0	0	0	0	0	5	0	0	95
Massachusetts	0	0	0	0	0	5	0	0	95
Michigan	0	0	0	0	0	2	0	0	98
Minnesota	0	0	0	0	0	0	0	0	100
Mississippi	0	0	0	0	0	60	0	0	40
Missouri	0	0	0	0	0	0	0	0	100
Montana	0	0	0	0	0	60	0	0	40
Nebraska	0	0	0	0	0	2	0	0	98
Nevada	0	0	0	0	0	0	0	0	100
New Hampshire	0	0	0	0	0	5	0	0	95
New Jersey	0	0	0	0	0	5	0	0	95
New Mexico	0	0	0	0	0	60	0	0	40
New York	0	0	0	0	0	5	0	0	95
North Carolina	0	0	0	0	0	42	0	0	58
North Dakota	0	0	0	0	0	2	0	0	98
Ohio	0	0	0	0	0	0	0	0	100
Oklahoma	0	0	0	0	0	60	0	0	40
Oregon	0	0	0	0	0	25	0	0	75
Pennsylvania	0	0	0	0	0	0	0	0	100
Rhode Island	0	0	0	0	0	5	0	0	95
South Carolina	0	0	0	0	0	60	0	0	40
South Dakota	0	0	0	0	0	2	0	0	98
Tennessee	0	0	0	0	0	5	0	0	95
Texas	0	0	0	0	0	12	0	0	88
Utah	0	0	0	0	0	60	0	0	40
Vermont	0	0	0	0	0	5	0	0	95
Virginia	0	0	0	0	0	5	0	0	95
Washington	0	0	0	0	0	12	0	0	88
West Virginia	0	0	0	0	0	5	0	0	95
Wisconsin	0	0	0	0	0	2	0	0	98
Wyoming	0	0	0	0	0	60	0	0	40

Table 3-85: 2002 Manure Distribution Among Waste Management Systems at Broiler and Turkey Operations (Percent)

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Alabama	1	0	0	0	0	0	0	0	99
Alaska	1	0	0	0	0	0	0	0	99
Arizona	1	0	0	0	0	0	0	0	99
Arkansas	1	0	0	0	0	0	0	0	99
California	1	0	0	0	0	0	0	0	99
Colorado	1	0	0	0	0	0	0	0	99
Connecticut	1	0	0	0	0	0	0	0	99
Delaware	1	0	0	0	0	0	0	0	99
Florida	1	0	0	0	0	0	0	0	99
Georgia	1	0	0	0	0	0	0	0	99
Hawaii	1	0	0	0	0	0	0	0	99
Idaho	1	0	0	0	0	0	0	0	99
Illinois	1	0	0	0	0	0	0	0	99
Indiana	1	0	0	0	0	0	0	0	99
Iowa	1	0	0	0	0	0	0	0	99
Kansas	1	0	0	0	0	0	0	0	99
Kentucky	1	0	0	0	0	0	0	0	99

State	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry with Bedding	Poultry without Bedding
Louisiana	1	0	0	0	0	0	0	0	99
Maine	1	0	0	0	0	0	0	0	99
Maryland	1	0	0	0	0	0	0	0	99
Massachusetts	1	0	0	0	0	0	0	0	99
Michigan	1	0	0	0	0	0	0	0	99
Minnesota	1	0	0	0	0	0	0	0	99
Mississippi	1	0	0	0	0	0	0	0	99
Missouri	1	0	0	0	0	0	0	0	99
Montana	1	0	0	0	0	0	0	0	99
Nebraska	1	0	0	0	0	0	0	0	99
Nevada	1	0	0	0	0	0	0	0	99
New Hampshire	1	0	0	0	0	0	0	0	99
New Jersey	1	0	0	0	0	0	0	0	99
New Mexico	1	0	0	0	0	0	0	0	99
New York	1	0	0	0	0	0	0	0	99
North Carolina	1	0	0	0	0	0	0	0	99
North Dakota	1	0	0	0	0	0	0	0	99
Ohio	1	0	0	0	0	0	0	0	99
Oklahoma	1	0	0	0	0	0	0	0	99
Oregon	1	0	0	0	0	0	0	0	99
Pennsylvania	1	0	0	0	0	0	0	0	99
Rhode Island	1	0	0	0	0	0	0	0	99
South Carolina	1	0	0	0	0	0	0	0	99
South Dakota	1	0	0	0	0	0	0	0	99
Tennessee	1	0	0	0	0	0	0	0	99
Texas	1	0	0	0	0	0	0	0	99
Utah	1	0	0	0	0	0	0	0	99
Vermont	1	0	0	0	0	0	0	0	99
Virginia	1	0	0	0	0	0	0	0	99
Washington	1	0	0	0	0	0	0	0	99
West Virginia	1	0	0	0	0	0	0	0	99
Wisconsin	1	0	0	0	0	0	0	0	99
Wyoming	1	0	0	0	0	0	0	0	99

Table 3-86: Methane Conversion Factors By State for Liquid Systems[1] for 2002 (percent)

State	Liquid/Slurry and Deep Pit	Anaerobic Lagoon
Alabama	41.0	76.2
Alaska	15.2	49.4
Arizona	46.8	77.6
Arkansas	36.3	75.2
California	34.8	74.6
Colorado	23.1	66.4
Connecticut	25.9	68.0
Delaware	32.7	73.6
Florida	53.8	76.7
Georgia	40.4	75.2
Hawaii	59.2	76.7
Idaho	22.1	65.5
Illinois	30.2	72.6
Indiana	29.4	72.3
Iowa	26.5	70.0
Kansas	33.3	63.4
Kentucky	33.6	74.4
Louisiana	46.3	76.7
Maine	20.5	63.5

[1] As defined by IPCC (IPCC 2000). MCFs represent weighted average of multiple animal types.

Maryland	30.4	72.6
Massachusetts	24.3	68.6
Michigan	24.6	68.9
Minnesota	24.2	68.0
Mississippi	41.6	76.3
Missouri	32.2	73.6
Montana	20.0	61.9
Nebraska	28.8	71.7
Nevada	24.8	68.4
New Hampshire	22.1	66.2
New Jersey	28.7	71.9
New Mexico	32.2	72.8
New York	23.6	67.8
North Carolina	35.8	73.9
North Dakota	22.2	65.7
Ohio	28.4	71.8
Oklahoma	36.5	75.1
Oregon	21.2	63.8
Pennsylvania	27.5	71.1
Rhode Island	24.1	65.4
South Carolina	40.2	75.0
South Dakota	25.9	70.0
Tennessee	34.9	74.6
Texas	43.0	76.0
Utah	26.1	69.8
Vermont	21.1	64.6
Virginia	30.3	72.4
Washington	21.5	64.4
West Virginia	27.9	71.2
Wisconsin	23.8	67.9
Wyoming	21.6	64.5

Table 3-87: Weighted Methane Conversion Factors for 2002[a] (Percent)

State	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine – Market	Swine – Breeding	Layer	Broiler	Turkey
Alabama	2.0	2.0	10.4	1.9	49.8	50.1	32.6	1.5	1.5
Alaska	1.7	1.7	16.8	1.6	1.5	1.5	13.5	1.5	1.5
Arizona	1.7	1.7	60.6	1.6	52.4	52.4	47.4	1.5	1.5
Arkansas	2.0	2.0	7.4	1.9	53.9	54.4	1.5	1.5	1.5
California	1.9	2.0	50.8	1.8	49.5	49.2	10.5	1.5	1.5
Colorado	1.6	1.6	43.3	1.6	28.6	28.6	40.0	1.5	1.5
Connecticut	1.8	1.8	10.9	1.7	14.6	13.3	4.9	1.5	1.5
Delaware	1.8	1.8	10.0	1.8	34.6	34.6	5.1	1.5	1.5
Florida	2.2	2.2	41.8	2.1	21.9	21.9	33.0	1.5	1.5
Georgia	2.0	2.0	14.6	1.9	50.2	49.9	32.1	1.5	1.5
Hawaii	2.3	2.3	54.3	2.1	39.3	39.3	20.3	1.5	1.5
Idaho	1.6	1.6	43.7	1.6	20.3	20.2	39.2	1.5	1.5
Illinois	1.7	1.7	12.4	1.6	34.2	34.2	2.9	1.5	1.5
Indiana	1.7	1.7	10.4	1.6	33.5	33.7	1.5	1.5	1.5
Iowa	1.7	1.7	10.1	1.6	42.2	42.2	1.5	1.5	1.5
Kansas	1.7	1.7	12.1	1.7	35.8	35.8	1.5	1.5	1.5
Kentucky	1.8	1.8	4.3	1.8	46.4	46.3	5.1	1.5	1.5
Louisiana	2.1	2.1	11.1	2.0	20.5	20.4	46.6	1.5	1.5
Maine	1.7	1.7	6.3	1.7	1.5	01.5	4.6	1.5	1.5
Maryland	1.8	1.8	9.4	1.7	30.9	30.9	5.1	1.5	1.5
Massachusetts	1.7	1.7	7.7	1.7	19.6	19.6	4.8	1.5	1.5
Michigan	1.6	1.6	16.2	1.6	30.1	30.0	2.9	1.5	1.5
Minnesota	1.6	1.6	09.2	1.6	30.7	30.7	1.5	1.5	1.5
Mississippi	2.0	2.0	09.4	1.9	56.2	56.2	46.4	1.5	1.5
Missouri	1.7	1.7	10.9	1.7	35.4	35.4	1.5	1.5	1.5

Montana	1.6	1.6	24.7	1.6	24.4	24.4	37.6	1.5	1.5
Nebraska	1.7	1.7	10.8	1.6	33.3	33.3	2.9	1.5	1.5
Nevada	1.6	1.6	50.3	1.6	1.5	01.5	1.5	1.5	1.5
New Hampshire	1.7	1.7	7.39	1.7	12.5	12.4	4.8	1.5	1.5
New Jersey	1.8	1.8	8.47	1.7	19.3	19.5	5.0	1.5	1.5
New Mexico	1.6	1.6	52.1	1.6	1.5	01.5	45.3	1.5	1.5
New York	1.7	1.7	9.3	1.7	21.7	21.6	4.8	1.5	1.5
North Carolina	1.8	1.8	6.8	1.8	58.4	58.3	31.8	1.5	1.5
North Dakota	1.6	1.6	6.7	1.6	26.0	26.0	2.7	1.5	1.5
Ohio	1.7	1.7	10.7	1.6	32.0	32.0	1.5	1.5	1.5
Oklahoma	1.6	1.6	34.4	1.6	55.6	56.0	45.8	1.5	1.5
Oregon	1.8	1.8	26.3	1.7	11.0	11.0	16.8	1.5	1.5
Pennsylvania	1.8	1.8	6.2	1.7	33.2	33.1	1.5	1.5	1.5
Rhode Island	1.8	1.8	3.9	1.7	19.4	19.4	3.3	1.5	1.5
South Carolina	2.0	2.0	10.5	1.9	51.7	51.5	45.7	1.5	1.5
South Dakota	1.6	1.6	9.6	1.6	30.9	31.0	2.9	1.5	1.5
Tennessee	1.8	1.8	5.7	1.8	43.2	43.1	5.7	1.5	1.5
Texas	1.7	1.7	50.7	1.6	51.9	51.9	10.5	1.5	1.5
Utah	1.6	1.6	37.3	1.6	32.0	31.9	42.8	1.5	1.5
Vermont	1.7	1.7	08.3	1.8	01.5	01.5	4.6	1.5	1.5
Virginia	1.8	1.8	05.5	1.7	50.2	50.2	5.0	1.5	1.5
Washington	1.8	1.8	32.1	1.7	21.1	20.8	8.9	1.5	1.5
West Virginia	1.8	1.8	07.2	1.7	21.5	21.5	5.0	1.5	1.5
Wisconsin	1.6	1.6	10.1	1.6	27.9	27.9	2.8	1.5	1.5
Wyoming	1.6	1.6	23.2	1.6	27.7	27.5	38.9	1.5	1.5

[a] MCFs are weighted by the distribution of waste management systems for each animal type.

Table 3-88: CH_4 Emissions from Livestock Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Dairy Cattle	545	585	573	565	623	640	611	639	661	700	694	719	735
Dairy Cows	535	575	564	556	614	631	602	631	653	691	685	710	727
Dairy Heifer	9	9	9	9	9	9	9	8	8	9	9	9	9
Swine	623	675	638	679	740	762	729	781	876	839	813	826	844
Market Swine	484	524	500	534	584	608	581	626	716	684	665	677	696
Market <60 lbs.	102	110	103	108	119	121	116	125	140	131	128	131	133
Market 60-119 lbs.	101	111	104	110	119	123	117	127	143	136	132	134	139
Market 120-179 lbs.	136	147	140	151	165	170	164	175	200	191	185	187	193
Market >180 lbs.	145	156	152	165	182	193	185	198	233	226	220	225	231
Breeding Swine	139	151	138	146	156	155	148	156	160	155	148	150	149
Beef Cattle	149	148	149	149	152	152	152	149	146	146	145	144	143
Feedlot Steers	21	19	19	17	16	14	14	15	15	15	16	16	15
Feedlot Heifers	10	11	9	10	9	8	8	8	9	9	9	9	9
NOF Bulls	6	6	6	6	6	7	7	6	6	6	6	6	6
NOF Calves	11	11	11	11	11	12	12	11	11	11	11	11	11
NOF Heifers	16	17	18	18	19	20	20	19	18	18	17	17	17
NOF Steers	11	11	12	11	12	12	13	12	12	12	11	10	11
NOF Cows	73	73	74	76	78	79	79	77	76	75	75	74	74
Sheep	3	3	3	3	3	2	2	2	2	2	2	2	2
Goats	1	1	1	1	1	1	1	1	1	1	1	1	1
Poultry	128	129	125	129	129	127	124	127	130	123	124	127	124
Hens >1 yr.	33	31	33	34	34	33	32	31	33	30	30	31	29
Total Pullets	63	65	59	60	60	58	56	58	60	56	57	59	57
Chickens	4	4	4	4	4	4	3	3	4	3	3	3	4
Broilers	19	20	21	21	22	23	24	25	25	26	27	27	28
Turkeys	10	10	10	10	9	9	9	9	8	8	8	7	7
Horses	29	29	29	29	29	29	29	29	30	29	30	30	30

Table 3-89: N_2O Emissions from Livestock Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
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	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	7.9
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	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	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	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	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	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	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	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	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	19.0
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	12.0
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	6.9
Sheep	0.2	0.1	0.2	0.2	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	0.1
Poultry	20.5	20.9	21.3	21.6	22.1	22.6	23.2	23.3	23.2	23.2	23.3	23.5	23.8
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	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	0.8
Chickens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Broilers	12.0	12.5	13.1	13.7	14.3	15.0	15.5	15.9	16.2	16.7	16.9	17.1	17.6
Turkeys	6.7	6.6	6.5	6.3	6.1	6.1	6.2	6.0	5.5	5.2	5.0	5.0	4.9
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	0.7

+ Emission estimate is less than 0.1 Gg

3.11. Methodology for Estimating N_2O Emissions from Agricultural Soil Management

Nitrous oxide (N_2O) emissions from agricultural soil management result from activities that add nitrogen to soils, and thereby enhance natural emissions of N_2O. The IPCC methodology (IPCC/UNEP/OECD/IEA 1997, IPCC 2000), which is used here, divides this source category into three components: (1) direct N_2O emissions from managed soils; (2) direct N_2O emissions from pasture, range, and paddock livestock manure; and (3) indirect N_2O emissions from soils induced by applications of nitrogen.

There are five steps in estimating N_2O 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, N_2O 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 N_2O 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, 2003) 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 2002). 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 not available for calendar year 2002, so a "least squares line" statistical extrapolation using the previous twelve 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 3-90.

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[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.

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; 2003b-g). Horse population data were obtained from the FAOSTAT database (FAO 2003). 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 nitrogen[3] 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 3-91).

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). For 2001 and 2002, sludge generation was extrapolated based on wastewater flow rates, while percent land applied was held constant at the year 2000, as no new data were available (Bastian 2002, 2003). Final estimates of annual amounts of sewage sludge nitrogen applied to land are presented in Table 3-90.

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

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, 2002a, 2003a). Annual production statistics for 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 Stützle (1987). The dry matter content for peanuts was obtained through personal communications with Ketzis (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 3-92. The residue to crop product mass ratios and dry matter fractions used in these calculations are presented in Table 3-95.

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, 2002a, 2003a). Production statistics for rice in Florida and Oklahoma, which are not recorded by USDA, were estimated by applying an average rice crop yield for Florida (Schueneman and Deren 2002) to annual Florida and Oklahoma rice areas (Schueneman 1999, 2001, Deren 2002, Kirstein 2003, Lee 2003). Residue to crop product ratios for all crops were obtained from, or derived from, Strehler and Stützle (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 Stützle (1987). Peanut, sorghum, oat, and rye residue dry matter contents were obtained through personal communications with Ketzis (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 Ketzis (1999), and the nitrogen content of millet residue is from Strehler and Stützle (1987). Nitrogen contents of all other beans and pulses were estimated by averaging the values for soybeans and peanuts. Estimates of the amounts of rice

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[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 N_2O 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.

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 3-93. The residue to crop product mass ratios, residue dry matter fractions, and residue nitrogen contents used in these calculations are presented in Table 3-95.

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 region[8] 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 2002 Table 3-94).

Step 1b: Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of N_2O 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 2002, which were obtained from the USDA National Agricultural Statistics Service (USDA 1995a; 1999a; 2000a,b; 2001b,c; 2002b,c, 2003b,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; 2003b,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, 2003d) 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, 2003f). However, population data for lamb and sheep on feed were not available after 1993. The number of lamb and sheep on feed for 1994 through 2002 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" 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

[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.

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 2002. Data for 1993 through 1996 were interpolated 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, 2003f). 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, 2003).

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 3-91).

Step 1c: Indirect N_2O Emissions from Soils Induced by Applications of Nitrogen

This component accounts for N_2O 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 NH_3 and NO_x, and subsequently returns to soils through atmospheric deposition, thereby enhancing N_2O 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 N_2O. 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 3-90). 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 used as a livestock feed supplement, and manure in pasture, range, and paddock) 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 3-91.

Table 3-90: Commercial Fertilizer Consumption & Land Application of Sewage Sludge (Gg N)

Fertilizer Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Synthetic	10,107	10,277	10,354	10,721	11,163	10,800	11,159	11,174	11,196	11,239	10,915	10,596	10,988
Other Organics*	5	9	6	5	8	11	13	15	13	11	10	8	10
Sewage Sludge	78	88	98	109	119	129	133	135	137	142	148	152	156

* Excludes manure and sewage sludge used as commercial fertilizer.

Table 3-91: Livestock Manure Nitrogen (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Applied to Soils	2,675	2,746	2,735	2,792	2,811	2,833	2,814	2,875	2,910	2,908	2,944	2,966	2,964
Used in Cattle Feed	32	32	33	34	35	36	36	37	37	37	38	38	38
Pasture, Range, & Paddock	3,816	3,833	3,918	3,961	4,061	4,116	4,110	3,983	3,901	3,859	3,798	3,767	3,759
Total Manure	6,523	6,612	6,686	6,786	6,907	6,985	6,961	6,896	6,848	6,804	6,779	6,771	6,761

Table 3-92: Aboveground Biomass Nitrogen in Nitrogen-Fixing Crops and Forages (Gg)

Crop Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
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	6,011
Peanuts	84	115	100	79	99	81	86	83	93	90	76	100	78
Dry Edible Beans	98	102	68	66	87	93	84	89	92	100	80	59	90
Dry Edible Peas	7	11	8	10	7	14	8	17	18	14	11	11	13
Austrian Winter Peas	+	+	+	+	+	+	+	+	+	+	+	+	+

Lentils	3	5	5	6	6	7	4	7	6	7	9	9	8
Wrinkled Seed Peas	3	3	2	3	2	3	2	2	2	2	2	2	1
Alfalfa	1,730	1,729	1,642	1,662	1,683	1,746	1,642	1,655	1,708	1,740	1,642	1,647	1,522
Red Clover	513	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	2,735
Birdsfoot Trefoil	99	99	99	99	99	99	99	99	99	99	99	99	99
Arrowleaf Clover	67	67	67	65	63	61	58	56	54	52	50	48	46
Crimson Clover	21	21	21	19	18	17	16	14	13	12	11	9	8
Total	9,600	9,774	10,082	9,375	10,850	10,156	10,488	11,192	11,368	11,207	11,300	11,598	11,124

+ Less than 0.5 Gg N.
Note: Totals may not sum due to independent rounding.

Table 3-93: Nitrogen in Crop Residues Retained on Soils (Gg)

Product Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Corn	957	902	1,143	765	1,213	893	1,114	1,111	1,177	1,138	1,196	1,147	1,087
Wheat	501	364	453	440	426	401	418	456	468	422	410	359	297
Barley	71	78	77	67	63	61	66	61	59	47	54	42	38
Sorghum	180	184	275	168	203	144	250	199	164	187	148	162	116
Oats	39	27	32	23	25	18	17	18	18	16	16	13	13
Rye	2	2	2	2	2	2	1	1	2	2	1	1	1
Millet	3	3	3	3	3	3	3	3	3	3	1	3	0
Rice	51	52	60	52	65	59	57	65	68	74	67	77	78
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	2,810
Peanuts	13	18	16	13	16	13	14	13	15	14	12	16	12
Dry Edible Beans	11	12	8	7	10	10	10	10	10	11	9	7	10
Dry Edible Peas	1	1	1	1	1	2	1	2	2	2	1	1	1
Austrian Winter Peas	+	+	+	+	+	+	+	+	+	+	+	+	+
Lentils	+	1	1	1	1	1	+	1	1	1	1	1	1
Wrinkled Seed Peas	+	+	+	+	+	+	+	+	+	+	+	+	+
Total	3,813	3,688	4,326	3,466	4,616	3,844	4,401	4,708	4,808	4,649	4,756	4,805	4,466

+ Less than 0.5 Gg N.
Note: Totals may not sum due to independent rounding.

Table 3-94: 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	441	197
2000	445	197
2001	447	198
2002	449	198

Table 3-95: 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	0.0168
Dry Edible Peas	1.55	0.87	0.0168
Austrian Winter Peas	1.55	0.87	0.0168
Lentils	1.55	0.87	0.0168
Wrinkled Seed Peas	1.55	0.87	0.0168

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 N_2O Emissions from Managed Soils Due to Nitrogen Additions and Cultivation of Histosols

In this step, N_2O emissions were calculated for each of two parts (direct N_2O emissions due to nitrogen additions and direct N_2O emissions due to histosol cultivation), which were then summed to yield total direct N_2O emissions from managed soils (Table 3-96).

Step 2a: Direct N_2O 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 N_2O-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 NH_3 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 NH_3 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 NH_3 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 N_2O Emissions Due to Cultivation of Histosols

To estimate annual N_2O emissions from histosol cultivation, the temperate histosol area was multiplied by the IPCC default emission factor for temperate soils (8 kg N_2O-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 N_2O-N/ha cultivated; IPCC 2000).

Step 3: Estimate Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

To estimate direct N_2O 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 N_2O-N/kg N excreted) (see Table 3-97).

Step 4: Estimate Indirect N_2O Emissions Induced by Applications of Nitrogen

In this step, N_2O emissions were calculated for each of two parts (indirect N_2O emissions due to volatilization of applied nitrogen and indirect N_2O emissions due to leaching and runoff of applied nitrogen), which were then summed to yield total direct N_2O 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 NH_3 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 N_20-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in Table 3-98.

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 and 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 N_20-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in Table 3-98.

Table 3-96: Direct N_2O Emissions from Managed Soils (Tg CO_2 Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Commercial Fertilizers*	55	56	57	59	61	59	61	61	61	62	60	58	60
Applied Livestock Manure	13	13	13	14	14	14	14	14	14	14	14	14	14
Sewage Sludge	+	+	+	1	1	1	1	1	1	1	1	1	1
Nitrogen Fixation	58	60	61	57	66	62	64	68	69	68	69	71	68
Crop Residue	23	22	26	21	28	23	27	29	29	28	29	29	27
Histosol Cultivation	3	3	3	3	3	3	3	3	3	3	3	3	3
Total	153	155	161	154	172	162	169	176	178	176	176	176	173

+ Less than 0.5 Tg CO_2 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 3-97: Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure (Tg CO_2 Eq.)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Beef Cattle	32	32	33	34	35	35	36	34	34	33	33	32	32
Dairy Cows	2	2	2	2	2	1	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	2
Total	37	37	38	39	40	40	40	39	38	38	37	37	37

+ Less than 0.5 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-98: Indirect N_2O Emissions (Tg CO_2 Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Volatil. & Atm. Deposition	11	12	12	12	12	12	12	12	12	12	12	12	12
Comm. Fertilizers	5	5	5	5	5	5	5	5	5	5	5	5	5
Total Livestock Manure	6	6	7	7	7	7	7	7	7	7	7	7	7
Sewage Sludge	+	+	+	+	+	+	+	+	+	+	+	+	+
Surface Leaching & Runoff	61	62	63	64	66	65	67	66	66	66	65	64	65
Comm. Fertilizers	37	38	38	39	41	39	41	41	41	41	40	39	40

Applied and PRP Livestock Manure	24	24	24	25	25	25	25	25	25	25	25	25	25
Sewage Sludge	+	+	+	+	+	+	+	+	+	1	1	1	1
Total	72	73	74	76	79	78	79	79	79	79	77	76	77

+ Less than 0.5 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Step 5: Estimate Total N_2O 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 3-99).

Table 3-99: Total N_2O Emissions (Tg CO_2 Eq.)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Direct Emissions from Managed Soils	153	155	161	154	172	162	169	176	178	176	176	176	173
Direct Emissions from Pasture, Range, and Paddock Livestock	37	37	38	39	40	40	40	39	38	38	37	37	37
Indirect Emissions	72	73	74	76	79	78	79	79	79	79	77	76	77
Total	263	266	273	269	291	279	288	293	294	292	290	289	287

Note: Totals may not sum due to independent rounding.

3.12. Methodology for Estimating Net Changes in Forest Carbon Stocks

This annex describes 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. The details of carbon conversion factors and procedures for calculating net CO_2 flux for forests are given in four steps. In addition, the USDA Forest Service forest sector modeling system is described briefly. More detailed descriptions of selected topics may be found in the cited references.

Step 1: Estimate Forest Carbon Stocks and Net Changes in Non-Soil Forest Carbon Stocks

Step 1a: Obtain Forest Inventory Data

Forest survey data in the United States were obtained from three USDA Forest Service, Forest Inventory and Analysis (FIA) Resources Planning Act Assessment (RPA) databases. These databases contain data for between 146,302 (1987) and 174,401 (2002) individual forest plots throughout the United States These databases were developed in support of RPA reports of forest condition throughout the United States based on the most recent available data for each state. Summaries of these databases were published for the nominal reporting years of 1987 (Waddell et al. 1989) and 1997 (Smith et al. 2001). Draft summaries for the 2002 reporting year are available at the FIA web site, as are reports for earlier reporting years (<http://fia.fs.fed.us/rpa.htm>). The inventory plot level data are available in a new format called the "FIADB" which is similar to the RPA databases (<http://ncrs2.fs.fed.us/4801/fiadb/fiadb_dump/fiadb_dump.htm>).

As discussed in Chapter 6 of this document, forest data are collected periodically in each state, so the actual survey dates of individual forest inventory plots are always older than the RPA reporting year. For this reason, the phrase "reporting year" is used herein to distinguish between the RPA reporting year and the actual survey year during which data were collected on a plot. Forest inventory data for each state were selected from the three RPA databases for each periodic inventory that occurred between 1991 and 2002, and for the most recent inventory prior to 1991. The average field survey year was calculated from the inventory plot field survey dates for each state for each periodic survey. Because the RPA databases include the most recent data for each state, the same data are included in subsequent RPA databases when no newer data for a state are available. These average survey years for each state are shown in Table 3-100, as is the RPA database from which each state survey was selected. For carbon estimation, key FIA data elements include growing stock volume, forest type (Table 3-101), ownership group, and age of the plot. For more information about using forest inventory data to estimate carbon stock change, see Birdsey and Heath (2001) and Smith and Heath (in press).

Historically, the main purpose of the FIA program has been to estimate areas, volume of growing stock, timber products output, and utilization factors. Growing stock is a classification of timber inventory that includes live trees of commercial species that meet specified standards of quality (Smith et al. 2001). Timber products output refers to the production of industrial roundwood products such as logs and other round timber generated from harvesting trees, and the production of bark and other residue at processing mills. Utilization factors relate inventory volume to the volume cut or destroyed when producing roundwood (May 1998). Growth, harvests, land-use change, and other estimates of temporal change are derived from repeated surveys. Because each state has been surveyed periodically, the most recent data for most states are several years old. Because forest inventory data are not available for 2003, projections of growing stock volume from the forest sector modeling system displayed in Figure 3-4 were used. The ATLAS model within this system projects growing stock volumes for broad forest type groups (e.g., Table 3-101) for each of the 10 regions in the United States shown in Figure 3-5. Projections for the year 2010 were used because projections for most regions of the country are available only in 10-year increments.

Table 3-100: Summary of Average Forest Inventory Survey Years for each State, by RPA Database

State[a]	RPA Region	Data Source[b] 1987 RPA	 1997 RPA Average Survey Year[c]	 2002 RPA
AL	SC		1990.0	1998.7
AR	SC	1978.0		1995.1

AZ	RMS	1984.4	1991.4	1995.8
CA	PSW	1980.4	1992.2	1995.8
CO	RMS			1985.7
CT	NE		1985.0	1997.8
DE	NE		1986.0	1999.0
FL	SE	1987.0		1994.0
GA	SE	1982.1		1996.4
IA	NPS	1987.0		1989.1
ID	RMN	1982.5		1991.9
IL	NPS		1985.0	1997.5
IN	NPS	1987.0		1997.3
KS	NPS	1987.0		1993.8
KY	SC			1986.6
LA	SC	1984.0		1990.9
MA	NE		1985.0	1997.1
MD	NE		1986.0	1999.0
ME	NE	1983.0		1994.7
MI	NLS	1987.0		1992.3
MN	NLS			1988.6
MO	NPS			1987.8
MS	SC	1977.0		1993.3
MT	RMN	1984.3		1993.0
NC	SE			1989.6
ND	NPS	1987.0		1994.0
NE	NPS	1986.9		1993.9
NH	NE		1983.0	1996.5
NJ	NE		1987.0	1998.3
NM	RMS	1982.9	1992.4	1997.2
NV	RMS		1985.1	1994.0
NY	NE	1985.0		1992.4
OH	NPS	1985.0		1991.0
OK	SC	1986.0		1991.2
ORE	PWE	1983.2		1995.5
ORW	PWW	1984.3	1990.7	1995.5
PA	NE			1989.3
RI	NE		1985.0	1998.0
SC	SE	1986.0	1992.3	1999.5
SDE	NPS	1986.7		1994.9
SDW	RMS		1987.2	1997.9
TN	SC		1989.0	1997.7
TX	SC	1985.3		1991.8
UT	RMS	1978.2		1993.0
VA	SE	1986.0		1990.9
VT	NE		1983.0	1996.7
WAE	PWE	1982.7		1993.0
WAW	PWW		1989.9	1991.8
WI	NLS	1987.0		1994.7
WV	NE		1989.0	
WY	RMS		1982.5	1993.3

[a] Three states are divided into Eastern and Western parts for estimation purposes: OR, SD, and WA.
[b] Estimates for each state for the year 2010 are from the forest sector modeling system shown in Figure 3-4.
[c] The nominal RPA reporting year is shown in the column heading, see discussion and citations in text.
The average survey year for each state is shown in the body of the table. The decimal point indicates tenths of a year.

Table 3-101: Forest types for plot-level tree biomass estimates and dead wood ratios[a]

Region[b]	Forest Type Group[c]	Dead Wood Ratio (Mg ha^{-1})[d]
NE	Aspen-Birch	0.078
	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Maple-Beech-Birch	0.071
	Oak-Hickory	0.068
	Oak-Pine	0.061

	Longleaf-Slash Pine, Loblolly-Shortleaf Pine, and pines other than White-Red-Jack	0.065
	Spruce-Fir and other non-pine conifers	0.092
	White-Red-Jack Pine	0.055
NLS	Aspen-Birch	0.081
	Oak-Gum-Cypress and Elm-Ash-Cottonwood	0.061
	Maple-Beech-Birch	0.076
	Oak-Hickory	0.077
	All pine groups and Oak-Pine	0.072
	Spruce-Fir	0.087
NPS	All conifer groups	0.073
	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.069
	Maple-Beech-Birch	0.063
	Oak-Hickory	0.068
	Oak-Pine	0.069
SC	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.063
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, naturally occurring	0.068
	Oak-Pine	0.072
	Other conifer groups	0.068
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, planted	0.077
	Oak-Hickory and Maple-Beech-Birch	0.067
SE	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.064
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, naturally occurring	0.081
	Oak-Pine	0.063
	Other conifer groups	0.081
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, planted	0.075
	Oak-Hickory and Maple-Beech-Birch	0.059
PSW	Douglas-fir and Hemlock-Sitka Spruce	0.091
	Fir-Spruce-Mountain Hemlock	0.109
	Hardwoods	0.042
	Ponderosa Pine, Lodgepole Pine, and other conifer groups	0.100
	Pinyon-Juniper	0.031
	Redwood	0.108
PWE	Douglas-fir, Western Larch, and Redwood	0.103
	Fir-Spruce-Mountain Hemlock and Hemlock-Sitka Spruce	0.106
	Hardwoods	0.027
	Lodgepole Pine	0.093
	Ponderosa Pine and Western White Pine	0.103
	Pinyon-Juniper	0.032
PWW	Douglas-fir and Redwood	0.100
	Fir-Spruce-Mountain Hemlock	0.090
	Ponderosa Pine, Western White Pine, Lodgepole Pine, and other conifer groups	0.073
	Other hardwoods	0.062
	Alder-Maple	0.095
	Hemlock-Sitka Spruce	0.099
RMN	Douglas-fir, Western White Pine, Hemlock-Sitka Spruce, Western Larch, and Redwood	0.062
	Fir-Spruce-Mountain Hemlock	0.100
	Hardwoods	0.112
	Lodgepole Pine	0.058
	Other conifer groups	0.060
	Ponderosa Pine	0.087
	Pinyon-Juniper	0.030
RMS	Douglas-fir, Western White Pine, Hemlock-Sitka Spruce, Western Larch, and Redwood	0.077
	Fir-Spruce-Mountain Hemlock	0.079

Hardwoods	0.064
Lodgepole Pine	0.098
Other conifer groups	0.060
Ponderosa Pine	0.082
Pinyon-Juniper	0.030

[a] Source: Smith et al. 2003
[b] NE=Northeast; NLS=Northern Lake States; NPS=Northern Prairie States; SC=South Central; SE=Southeast; PSW=Pacific Southwest; PWE=Pacific Northwest Eastside; PWW=Pacific Northwest Westside; RMN=Rocky Mountains North; RMS=Rocky Mountains South.
[c] Forest group types taken from the Forest Inventory Assessment Database.
[d] Ratio of the down dead wood to the live tree biomass in the plot.

Step 1b: Estimate Carbon in Living and Standing Dead Trees (Tree Pool)

The tree pool includes aboveground biomass and belowground (coarse root) biomass of both live trees and standing dead trees. Fallen trees are included in the "down dead wood" pool. The minimum sized tree included in FIA data is one-inch diameter (2.54 cm) at diameter breast height (1.3 meter). The biomass of live trees was estimated by applying equations that convert growing stock volume from the plot-level FIA data to total live tree dry biomass for a number of forest types (Table 3-101). In some cases, separate equations are used for different forest ownerships (public or private) and for different regions of the country (Table 3-101, Figure 3-5, see Smith et al. 2003 for details). 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). A similar approach was used to estimate the biomass of standing dead trees using equations specifically developed for standing dead trees (Smith et al. 2003). Estimates of carbon in the tree pool for 2003 were made based on the projected forest inventory volume described in Step 1a by using the same equations described above and implemented in the FORCARB2 model, which is part of the forest sector modeling system shown in Figure 3-4. To estimate forest carbon stocks for individual states, the regionally aggregated model projections were disaggregated into individual states based on the proportion of carbon in forests in each state within its region based on the most recent historical data available.

Tree carbon stocks for each periodic survey year in each state are shown in Table 3-102. Carbon stocks for each non-survey year from 1990 to 2003 for each state were estimated by linear interpolation between survey years. These interpolated estimates of carbon stocks in live and dead trees are shown for each state for each year from 1990 to 2003 in Table 3-103.

Table 3-102: Estimates of Live and Dead Tree Carbon Stocks (Tg) for Survey Years[a] by RPA Database

		Carbon Stock by Data Source			
State[b]	RPA Region	1987 RPA[c]	1997 RPA	2002 RPA	2010 Model Projection[d]
AL	SC		517	567	526
AR	SC	439		492	478
AZ	RMS	323	315	289	383
CA	PSW	1,313	1,445	1,440	1,588
CO	RMS			592	494
CT	NE		62	71	63
DE	NE		13	14	11
FL	SE	320		304	455
GA	SE	568		581	663
IA	NPS	37		50	52
ID	RMN	731		803	844
IL	NPS		129	147	118
IN	NPS	132		160	133
KS	NPS	27		36	40
KY	SC			401	341
LA	SC	379		384	385
MA	NE		107	122	120
MD	NE		98	103	87
ME	NE	519		488	703
MI	NLS	520		612	674

MN	NLS			398	619
MO	NPS			296	295
MS	SC	430		455	465
MT	RMN	629		733	794
NC	SE			583	556
ND	NPS	8		11	18
NE	NPS	14		22	26
NH	NE		183	186	202
NJ	NE		55	66	59
NM	RMS	275	283	314	346
NV	RMS		133	137	215
NY	NE	496		506	667
OH	NPS	199		247	207
OK	SC	104		136	183
OR(E)	PWE	307		355	403
OR(W)	PWW	880	884	884	914
PA	NE			569	565
RI	NE		10	12	11
SC	SE	310	300	309	335
SD(E)	NPS	4		5	9
SD(W)	RMS		26	30	15
TN	SC		403	473	361
TX	SC	405		346	486
UT	RMS	284		299	323
VA	SE	490		506	451
VT	NE		176	179	189
WA(E)	PWE	298		312	321
WA(W)	PWW		746	746	903
WI	NLS	415		452	510
WV	NE		440		359
WY	RMS		312	359	332

[a] Average survey years for each carbon stock estimate are shown in Table 3-100.
[b] Three states are divided into Eastern and Western parts for estimation purposes: OR, SD, and WA.
[c] The nominal RPA reporting year is shown in the column heading, see discussion and citations in text.
[d] Estimates are from the FORCARB2 model for the year 2010.

Table 3-103: Interpolated[a] Estimates of Live and Dead Tree Carbon Stocks (Tg) by State 1990 to 2003

State	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
AL	517	523	529	534	540	546	551	557	563	567	562	558	555	551
AR	476	479	483	486	489	492	491	490	489	488	487	487	486	485
AZ	316	315	311	305	300	294	289	297	304	310	317	324	330	337
CA	1,421	1,432	1,445	1,444	1,443	1,441	1,440	1,452	1,462	1,473	1,483	1,494	1,504	1,515
CO	575	571	567	563	559	554	550	546	542	538	534	530	526	522
CT	65	66	67	68	68	69	70	70	71	70	69	69	68	67
DE	13	13	13	13	14	14	14	14	14	14	14	13	13	13
FL	313	311	309	306	304	313	323	332	341	351	360	370	379	389
GA	575	576	577	578	579	580	581	585	591	597	603	609	615	621
IA	50	50	50	50	50	50	50	50	51	51	51	51	51	51
ID	788	796	803	805	807	810	812	814	816	819	821	823	826	828
IL	136	138	139	141	142	144	145	147	146	144	142	139	137	135
IN	140	143	146	148	151	154	156	160	159	157	154	152	150	148
KS	31	32	33	35	36	36	36	36	37	37	37	37	38	38
KY	393	390	387	385	382	380	377	375	372	369	367	364	362	359
LA	384	384	384	384	384	384	384	384	384	384	384	384	384	384
MA	113	114	116	117	118	119	120	122	122	122	122	121	121	121
MD	100	100	100	101	101	102	102	103	103	103	102	100	99	97
ME	500	498	495	492	489	488	506	520	534	549	563	577	591	605
MI	572	589	612	614	618	621	625	629	632	636	639	643	646	650
MN	412	423	433	443	454	464	474	485	495	505	515	526	536	546

MO	296	296	296	296	296	296	296	296	295	295	295	295	295	295
MS	450	452	453	455	456	456	457	457	458	458	459	460	460	461
MT	697	709	721	733	737	740	744	747	751	755	758	762	765	769
NC	583	581	580	579	577	576	575	573	572	571	569	568	566	565
ND	9	10	10	11	11	12	12	13	13	13	14	14	15	15
NE	17	19	20	21	22	22	22	23	23	23	23	24	24	24
NH	185	185	185	185	186	186	186	187	188	189	190	191	193	194
NJ	58	59	60	61	62	62	63	64	66	65	65	64	64	63
NM	281	282	283	287	293	300	306	314	316	319	321	324	326	329
NV	135	136	136	137	137	142	147	152	157	161	166	171	176	181
NY	503	504	506	512	521	530	539	548	557	566	576	585	594	603
OH	239	247	245	243	241	239	237	234	232	230	228	226	224	222
OK	129	136	138	140	143	145	148	150	153	155	158	160	163	165
OR	1,217	1,221	1,225	1,229	1,233	1,239	1,242	1,247	1,253	1,258	1,263	1,269	1,274	1,279
PA	568	568	568	568	568	568	568	567	567	567	567	567	567	566
RI	11	11	11	11	12	12	12	12	12	12	12	12	12	12
SC	303	302	300	301	302	303	305	306	307	309	309	313	315	318
SD	31	32	32	33	33	33	34	35	35	34	33	32	32	31
TN	411	419	427	435	443	451	459	467	473	461	452	443	434	425
TX	362	353	346	355	363	370	378	386	393	401	409	417	424	432
UT	296	297	298	299	300	302	303	304	306	307	309	310	312	313
VA	503	506	503	500	497	494	491	489	486	483	480	477	474	471
VT	178	178	178	178	178	178	179	179	180	181	181	182	183	184
WA	1,053	1,055	1,057	1,069	1,078	1,087	1,096	1,105	1,115	1,124	1,133	1,142	1,151	1,160
WI	429	434	439	444	448	452	457	460	464	468	472	476	480	484
WV	437	433	429	425	421	417	413	410	406	402	398	394	390	386
WY	345	349	353	359	358	356	355	353	352	350	348	347	345	344
TOTAL	17,618	17,714	17,797	17,877	17,942	18,023	18,122	18,248	18,358	18,442	18,517	18,596	18,674	18,751

[a] Carbon stock values in this table are interpolated among survey years. See Table 3-100 for a list of survey years for each state, and see Table 3-102 for carbon stock estimates for each survey year. Values from Table 3-102 were interpolated to produce the stock estimates above.

Step 1c: Estimate Carbon in Understory Vegetation Pool

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. To estimate the carbon density ($t\text{-}ha^{-1}$) in understory vegetation for each average survey year in each state, equations based on Birdsey (1996) were applied to the FIA data at the plot level. These equations use the estimated tree carbon density, the region, and the forest type to predict the amount of carbon in the understory. The maximum understory carbon density is predicted to occur when the plot contains no trees greater than 2.54 cm in diameter, and this maximum value ranges from 1.8 $t\text{-}ha^{-1}$ to 4.8 $t\text{-}ha^{-1}$, depending on forest type. The minimum understory carbon density value is 0.5 percent of the tree carbon density, which occurs in mature stands with high values of tree carbon density. Carbon density values for each plot were converted to total carbon by multiplying by the forest area represented by the plot. The understory carbon estimates from all plots were then summed to form a total for each inventory year for each state. For the year 2010, a similar procedure was followed, except that estimates were made at the management unit scale as defined in the ATLAS and FORCARB2 models, which are part of the forest sector modeling system shown in Figure 3-4. Management units are defined by region, forest type, ownership group, productivity, management intensity, and age class (Mills and Kincaid 1992). Regional results from the FORCARB2 model were disaggregated for each state as described in Step 1b. Carbon stocks for each non-survey year from 1990 to 2003 for each state were estimated by linear interpolation between survey years.

Step 1d: Estimate Carbon in Forest Floor Pool

Forest floor carbon is the pool of organic carbon (litter, duff, humus, and fine 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 for each average survey year in each state, equations developed by Smith and Heath (2002) were applied to the FIA data from the RPA databases, described in Step 1a. These equations are based on stand age, and consist of two equations for each of a number of forest types. The first equation represents accumulation and the second represents decay (Table 3-104). Columns A and B of Table 3-104 define net accumulation with age through the equation

(A*age)/(B+age). Columns C and D of Table 3-104 describe the decay curve ($C*e_{-(age/D)}$). Regrowth is the sum of accumulation and decay (Source: Smith and Heath 2002). Both equations are used together to estimate forest floor mass in stands regrowing after a harvest. As for the understory carbon estimates, a similar procedure was followed for the year 2010, except that estimates were made at the regional scale for each forest type using the FORCARB2 model, and then disaggregated for each state as described in Step 1b. Carbon stocks for each non-survey year from 1990 to 2003 for each state were estimated by linear interpolation between survey years.

Table 3-104: Coefficients for predicting forest floor mass from stand age (Mg/ha)[a]

Region[b]	Forest Type	A	B	C	D
North					
	Pine	19.1	25.6	13.8	8.4
	Spruce, fir, hemlock	62.9	57.8	33.7	8.4
	Mixed conifer-hardwood	65.0	79.5	29.7	8.4
	Aspen-birch	18.4	53.7	10.2	9.2
	Maple-beech-birch	50.4	54.7	27.7	9.2
	Mixed hardwood, oak	24.9	134.2	8.2	9.2
South					
	Pine	20.4	27.1	12.2	3.8
	Mixed conifer-hardwood	15.4	20.1	10.3	3.8
	Mixed hardwood, oak-hickory	15.3	61.8	6.0	3.2
Pacific Northwest					
	Douglas-fir, Western Hemlock	87.5	116.7	27.5	16.0
	Fir-hemlock, higher elevation	53.9	44.3	29.5	16.0
	Hardwood	16.5	41.1	9.3	3.4
West					
	Pine	43.9	87.3	24.1	24.1
	Redwood, sequoia	92.6	52.1	62.2	24.1
	Pinyon, juniper[c]			21.1	
	Mixed conifer	53.6	47.0	37.2	24.1
	Hardwood	50.1	62.0	31.7	19.8

[a] Columns A and B define net accumulation with age through the equation (A*age)/(B+age). Columns C and D describe the decay curve (C*e-(age/D)). Regrowth is the sum of accumulation and decay (Source: Smith and Heath 2002).

[b] North is defined as the Northern Prairie States, Lakes States, and Northeast regions (Figure 3-5). South is the Southern and Southeastern regions. Pacific Northwest corresponds to the Pacific Northwest, Westside. West is the Pacific Northwest, Eastside, the Rocky Mountains, both North and South, and the Pacific Southwest.

[c] For the pinyon-juniper forest type, insufficient data were available to estimate the rate of change in forest floor C with stand age. Instead, a single mean value of forest floor mass (variable C) is used for all stands.

Step 1e: Estimate Carbon in Down Dead Wood Pool

Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter that are not attached to living trees. Down dead wood includes stumps and roots of harvested trees. To estimate the carbon density ($t \cdot ha^{-1}$) in down dead wood for each average survey year in each state, estimates were made at the plot level based on the forest inventory data from the RPA databases described in Step 1a. Down dead wood is estimated by multiplying the ratio for the forest type and region shown in Table 3-101 by the live tree carbon density for the plot. Then down dead wood carbon density values for each plot were converted to total carbon by multiplying by the forest area represented by the plot. Estimates from all plots were summed to form a total for each inventory year for each state. For the year 2010, a similar procedure was followed, except that estimates were made at the regional scale based on the area in each forest type in each region using the FORCARB2 model, and then disaggregated for each state as described in Step 1b. Carbon stocks for each non-survey year from 1990 to 2003 for each state were estimated by linear interpolation between survey years.

Step 1f: Calculate Annual Net Stock Changes for all Non-Soil Forest Pools

After estimation of all non-soil forest carbon stocks, the final step was to estimate the annual net carbon stock change for each forest carbon pool in each state, and then nationally, for the years from 1990 through 2002. Annual carbon stock changes for each state and for each year from 1990 to 2002 were calculated by subtracting carbon stocks in the subsequent year from those in the current year. Annual carbon stock changes for each non-soil pool were then summed over all states to derive a national carbon stock change for each year.

Step 2: Estimate Forest Soil Carbon Pool

To estimate soil carbon stocks, two kinds of data were used: (1) average soil carbon density ($t \cdot ha^{-1}$) for each forest type, and (2) area of each forest type in the conterminous United States. Data on soil carbon density down to 1 m in depth were obtained from the national STATSGO spatial soils database (USDA 1991). These data were combined with FIA data on the location and area of different forest types to estimate soil carbon density for all forest types (Johnson and Kern 2003). The area of each forest type in 1987 and 1997 was derived from the corresponding RPA database for those nominal reporting years[1], and the area of each forest type for 2002 was derived from model projections as described in Step 1a. Soil carbon stocks for each year (1987, 1997, and 2002) were estimated for each forest type in each region by multiplying the carbon density of each forest type by the area of that forest type, and then summing across all forest types and all regions. Regions are shown in Figure 3-5.

The average annual soil stock change for 1990 through 1996 was derived by subtracting the 1997 stock from the 1987 stock, and dividing by the number of years between estimates (10). (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 net annual stock change for 2002 was extrapolated from 2001 (i.e., the same estimate was used for 2002 as for 2001). Soil carbon stock estimates were based solely on forest area and a constant soil carbon density for forest type. Thus, any estimated changes in soil carbon stocks over time were due to changes in total forest area and/or changes in forest type. Further information on soil carbon estimates is presented by Heath et al. (2003), and Johnson and Kern (2003).

Step 3: Estimate Harvested Wood Carbon Fluxes

Estimates of carbon stock changes in wood products and wood discarded in landfills were based on the methods described by Skog and Nicholson (1998) which were based in turn on earlier efforts using similar approaches (Heath et al. 1996, Row and Phelps, 1996). Carbon stocks in wood products in use and wood products stored in landfills were estimated from 1910 onward based on several sets of historical data from the USDA Forest Service. These data include estimates of wood product demand, trade, and consumption (USDA 1964, Ulrich 1989, Howard 2001). In addition to the historical data, projections from the forest sector modeling system described below were used (Figure 3-4). Annual historical estimates and model projections of the production of wood products were used to divide consumed roundwood into wood product, wood mill residue, and pulp mill residue. To estimate the amount of time that products remain in use before disposal, wood and paper products were divided into 21 categories, each with an estimated product half-life (Skog and Nicholson 1998). After disposal, an estimate of the amount of waste that is burned was made. For products entering dumps or landfills, the proportion of carbon emitted as CO_2 or CH_4 was estimated, where half-life estimates of wood products were used to estimate removals from pools. By following the fate of carbon from the wood harvested in each year from 1910 onward, the change in carbon stocks in wood products, the change in carbon stocks in landfills, and the amount of carbon emitted to the atmosphere with and without energy recovery were estimated for each year through 2002. To account for imports and exports, the production approach was used, meaning that carbon in exported wood was counted as if it remained in the United States, and carbon in imported wood was not counted. From 1990 through 2002, the amount of carbon in exported wood averaged 6 Tg C per year, with little variation from year to year. For comparison, imports (which were not included in the harvested wood net flux estimates) increased from 7.2 Tg C per year in 1990 to 13 Tg C per year in 2002. Further description of this methodology is presented by Skog and Nicholson (1998).

Step 4: Sum the Results from Step 1 through Step 3 for the Total Net Flux from U.S. Forests

In the final step, national annual net changes in forest carbon stocks were added to national annual net changes in harvested wood carbon stocks, to obtain estimates of total national annual net forest flux.

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[1] Unlike other forest carbon pools, the nominal reporting years of these databases were used, as was done in previous U.S. inventories, rather than using the average survey years by State. In principal, estimates of soil carbon stocks could be developed using a procedure similar to that for other forest carbon pools described above. However, this approach has not been used for soil carbon stocks because an improved methodology is currently under development (see "Planned Improvements" in Chapter 6).

Forest Sector Modeling System

The forest sector modeling system is a set of models that has been used for the USDA Forest Service, Resource Planning Act Assessment since the late 1980s (Figure 3-4) and is currently still in use (Haynes 2003). 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 modeling system include growing stock volume, forest areas, harvests, and primary product production. For a description of the assumptions and results of the modeling system, see Haynes (2003).

The FORCARB model (Plantinga and Birdsey 1993, Heath and Birdsey 1993, Heath et al. 1996, Heath et al. 1997) uses data on growing stock volume, forest areas, and harvests from the ATLAS model to estimate carbon in live and dead trees using biometrical relationships between carbon and live tree growing stock volume. Similarly, FORCARB estimates carbon in all other forest storage pools. The most recent version of FORCARB is FORCARB2 (Birdsey and Heath 1995, Heath et al. 2003). The model WOODCARB (Skog and Nicholson 1998) uses data and methods reviewed above to estimate carbon in harvested wood. Current estimates of carbon in harvested wood pools are based on Howard (2001 and 2004).

Figure 3-4 illustrates the connections between the various models, data inputs, and data outputs that comprise the forest sector modeling 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 3-4: Forest Sector Modeling Projection System

Figure 3-5: Forest Regions used in Soil C Estimations

3.13. 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* (USDA-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 CO_2 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 3-105). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table 3-105: 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 3-6). Each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).

Figure 3-6: 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 3-106). 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 3-106: 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	Reference Carbon Stock in 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. The 'n' values refer to sample size.

Step 1b: Land Use and Management Activity Data

Land use and management data for 1982, 1992, and 1997 were obtained from the *1997 National Resources Inventory* (USDA-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 3-107). Each National Resources Inventory point was assigned to a system based upon the land use data collected in 1982, 1992, and 1997 (USDA-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 (USDA-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 3-107: Land Use and Management Systems

General Land Use Systems	Specific Management Related Systems	IPCC Category: Mineral Soils	IPCC Category: 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[a]	Undrained
	Rice in Rotation with other crops	Improved Land[a]	Undrained
	Continuous Perennial or Horticultural Crops	Improved Land[a]	Pasture/Forest
	Continuous Hay	Uncultivated Land (General)	Pasture/Forest
	Continuous Hay with Legumes or Irrigation	Improved Land[a]	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[a]	Pasture/Forest
	Aquaculture[b]	Not Estimated	Not Estimated
Non-Agricultural[c]			
	Forest	Uncultivated Land (General)	Pasture/Forest
	Federal	Uncultivated Land (General)	Undrained
	Water[b]	Not Estimated	Not Estimated
	Urban Land[b]	Not Estimated	Not Estimated
	Miscellaneous[b,d]	Not Estimated	Not Estimated

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

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

[b] Assumes 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.

[c] Some non-agricultural land is included in the inventory because it was in agricultural land use in 1992 or 1997.

[d] 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, climate, 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 3-108). 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 3-108: Management Factors for the United States and the IPCC Default Values

		U.S. Factor			
	IPCC default	Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land Use Change					

Cultivated[a]	1	1	1	1	1
General Uncult.[a,b] (n=251)	1.4	1.42±0.06	1.37±0.05	1.24±0.06	1.20±0.06
Set-Aside[a] (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Lands[c]	1.1	1.1	1.1	1.1	1.1
Wetland Rice Production[c]	1.1	1.1	1.1	1.1	1.1
Tillage					
Conv. Till	1	1	1	1	1
Red. Till (n=93)	1.05	1.08±0.03	1.01±0.03	1.08±0.03	1.01±0.03
No-till (n=212)	1.1	1.13±0.02	1.05±0.03	1.13±0.02	1.05±0.03
Input					
Low (n=85)	0.9	0.94±0.01	0.94±0.01	0.94±0.01	0.94±0.01
Medium	1	1	1	1	1
High (n=22)	1.1	1.07±0.02	1.07±0.02	1.07±0.02	1.07±0.02

[a] 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.
[b] Default factor was higher for aquic soils at 1.7, but the U.S. analysis showed no significant differences between aquic and non-aquic soils and so a single U.S. factor was estimated for all soil types.
[c] 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.
Note: The "n" values refer to sample size.

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 3-109). 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 3-109).

Table 3-109: 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

Variable	Value
Factor (Initial Increase—First 10 Years)	1.22±0.18
Mass Accumulation (After Initial 10 Years)	0.79±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 3-110). Probability density functions were constructed as normal densities based on the mean carbon loss rates and associated variances.

Table 3-110: Carbon Loss Rates from Organic Soils Under Agricultural Management in the United States, and the IPCC Default Rates (Metric Ton C/ha-yr)

	Cropland		Pasture / Forest	
Region	IPCC	U.S. Revised	IPCC	U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2±2.5	0.25	2.8±0.5[a]
Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8[a]
Sub-Tropical, Dry & Sub-Tropical, Moist	20	14.0±3.3	5	3.5±0.8[a]

[a] 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 3-107). 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 3-111). Between 1997 and 2002, 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 3-111: 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)

	Land Areas		
IPCC Land Use/Management Categories	1982	1992	1997
Medium Input Cropping	87.49	77.17	78.27
High Input Cropping[a]	22.21	22.02	21.74
Low Input Cropping[b]	30.96	28.92	25.13
Rice[c]	2.71	2.13	2.22
Uncultivated Land[d]	210.04	207.77	210.26
Improved Land[e]	31.19	33.65	31.43
Conservation Reserve Program[f]	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 (USDA-NRCS 2000).
[a] Includes hay or legumes in rotation, winter cover crop, and irrigated cropland.
[b] Includes fallow and low residue cropland.
[c] 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.
[d] Includes hayland, rangeland, pasture, forest, and federal land-use.
[e] Includes pasture or hayland with legumes or irrigation and continuous perennial crops.
[f] 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 3-112). 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 3-112: Tillage Percentages for each Management System in U.S. Climate Zones, with Adjustments for Long-term Adoption of No-till Agriculture (Percent)

	1982			1992			1997		
System	No Till[a]	Reduced Till[b]	Conventional Till[c]	No Till[a]	Reduced Till[b]	Conventional Till[c]	No Till[a]	Reduced Till[b]	Conventional Till[c]
Sub-Tropical, Dry									

Continuous Cropping Rotations[d]	0	3	97	0	4	96	0	15	85
Rotations with Fallow[e]	0	0	100	0	2	98	0	5	95
Low Residue Agriculture[f]	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

[a] No-till includes CTIC survey data designated as no-tillage.
[b] Reduced-till includes CTIC survey data designated as ridge tillage, mulch tillage, and reduced tillage.
[d] Conventional till includes CTIC survey data designated as intensive tillage and conventional tillage.
[d] Medium and high input rotations (based on the IPCC categories) found in Table 3-107. CTIC survey data for corn, soybeans, and sorghum were used in this category.
[e] Rotations with fallow found in Table 3-107. CTIC survey data on fallow and small grain cropland were used in this category.
[f] Low input rotations found in Table 3-107, 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 3-113).

Table 3-113: Land Areas for Each Organic Land Use Category (For All U.S. Land Area Categorized as Agricultural in 1992 or 1997) (Million Hectares)

	Land Areas								
	1982			1992			1997		
IPCC Land Use Category for Organic Soils[a]	Warm Temperate	Cool Temperate	Sub-Tropical	Warm Temperate	Cool Temperate	Sub-Tropical	Warm Temperate	Cool Temperate	Sub-Tropical
Undrained	0.0005	0.0337	0.1344	0.0022	0.0651	0.1241	0.0021	0.0576	0.0964
Managed Pasture and Forest (Low Drainage)	0.04541	0.3811	0.0681	0.0397	0.3913	0.0715	0.0381	0.3989	0.0819
Cultivated Cropland (High Drainage)	0.1371	0.3103	0.1852	0.1437	0.2850	0.1940	0.1447	0.2942	0.1961
Other Land Uses[2]	0.0043	0.0360	0.0050	0.0018	0.0197	0.0030	0.0024	0.0104	0.0183
Total	1.34			1.34			1.34		

* Based on Analysis of 1997 National Resources Inventory Data.
[a] Table 3-108 provides information how the IPCC land use systems are classified in the land management categories for organic soils.
[b] 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 25.5 million hectares between 1990 and 2002 (see Table 3-115 for calculations). Of this total area, manure and sewage sludge applications were estimated to range from 6.7 to 9.3 million hectares of cropland and 15 to 16 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 CO_2 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 CO_2 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 2002 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 CO_2 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 3-110). The results for 1992 were applied to the years 1990 through 1992, and the results for 1997 were applied to the years 1993 through 2002. On average, mineral soils under agricultural management were sequestering about 49.1 to 40.8 Tg CO_2 Eq. annually and organic soils lost about 34.1 to 34.7 Tg CO_2 Eq. annually (see Table 3-114). Overall, U.S. agricultural soils appear to be currently sequestering approximately 6.1 Tg CO_2 Eq. annually, although the uncertainties are rather large, ranging from emissions of about 15.8 Tg CO_2 Eq. annually to sequestration of about 27.9 Tg CO_2 Eq. annually.

Table 3-114: Annual Change in Soil Organic Carbon for U.S. Agricultural Soils Based on the Monte Carlo Uncertainty Analysis with U.S. Factor Values, Reference Carbon Stocks, and Carbon Loss Rates (Tg CO_2 Eq.)

Soil Type	1990-1992	1993-2002
Mineral Soils		
Estimate*	(49.1)	(40.81)
Uncertainties	(25.3) to (75.5)	(23.8) to (59.0)

Organic Soils		
Estimate	34.1	34.7
Uncertainties	23.1 to 48.4	23.5 to 49.1
Total		
Estimate	(14.8)	(6.1)
Uncertainties	12.8 to (43.3)	15.8 to (27.9)

*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 2002, manure and sewage sludge applications in agricultural lands increased soil organic carbon storage in mineral soils by about 5.79 to 6.25 Tg C annually (21.3 to 22.9 Tg CO_2 Eq.) (see Table 3-115).

Table 3-115: 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	2002
Total N (Tg)[a]	2.76	2.83	2.83	2.90	2.92	2.90	2.94	3.00	3.04	3.04	3.08	3.10	3.11
Manure N[a]	2.70	2.78	2.77	2.82	2.85	2.82	2.85	2.91	2.95	2.95	2.98	3.01	3.00
Sewage Sludge N[a]	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10
Assimilative Capacity (metric ton N / ha)[b]	0.120	0.120	0.120	0.122	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 10^6)[c,d]	22.97	23.62	23.60	23.74	23.96	23.77	24.07	24.59	24.89	24.92	25.23	25.45	25.46
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	9.34
Grazing Land Receiving Manure	15.18	15.05	15.56	15.32	15.46	17.09	15.42	15.32	15.59	15.75	15.89	16.11	16.12
Contribution to Agricultural Land Soil C (Tg C)[e]	5.79	5.82	5.94	5.90	5.95	6.31	5.95	5.98	6.07	6.11	6.18	6.25	6.25
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	0.93
Contribution to Grazing Land Soil C[e]	5.01	4.97	5.13	5.06	5.10	5.64	5.09	5.06	5.14	5.20	5.24	5.32	5.32

[a] Total N available to be applied to soils (this volume).
[b] 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).
[c] 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.
[d] 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
[e] 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 and 2002, leading to an additional enrollment of 514,377 ha over the five 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 and 2002, agricultural lands sequestered an additional 0.7 and 0.9 Tg CO_2 Eq. in 2001 and 2002, respectively, relative to the baseline inventory (see Table 3-116).

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 2002) are presented in Table 3-116. Agricultural soils were estimated to sequester from 26.4 to 36.6 Tg CO_2 Eq. annually between 1990 and 2002, based on the change in soil organic carbon storage.

Table 3-116: Annual Net Flux of CO_2 from U.S. Agricultural Soils for the Baseline Inventory (Uncertainty Analysis) Plus the Additional Land Use/Management Considerations (Tg CO_2 Eq.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Net emissions based on uncertainty analysis	**(14.79)**	**(14.79)**	**(14.79)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**	**(6.10)**
Mineral Soils	(49.10)	(49.10)	(49.10)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)	(40.82)
Organic Soils	34.31	34.31	34.31	34.72	34.72	34.72	34.72	34.72	34.72	34.72	34.72	34.72	34.72
Additional changes in net emissions from mineral soils	**(21.22)**	**(21.35)**	**(21.77)**	**(21.62)**	**(21.82)**	**(23.13)**	**(21.83)**	**(21.94)**	**(20.36)**	**(20.29)**	**(21.71)**	**(23.58)**	**(23.87)**
Application of manure and sewage sludge N to crop and grazing lands	(21.22)	(21.35)	(21.77)	(21.62)	(21.82)	(23.13)	(21.83)	(21.94)	(22.27)	(22.42)	(22.65)	(22.92)	(22.93)
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)	(0.9)
Total net emissions	**(36.0)**	**(36.1)**	**(36.6)**	**(27.7)**	**(27.9)**	**(29.2)**	**(27.9)**	**(28.0)**	**(26.5)**	**(26.4)**	**(27.8)**	**(29.7)**	**(30.0)**

3.14. Methodology for Estimating CH_4 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 (CO_2). If the methane is extracted and either flared or utilized for energy, then that portion of the methane generated will also be oxidized to CO_2 during combustion. In general, landfill-related CO_2 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 2002 are discussed in greater detail below.

Figure 3-7 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 2002, 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 centralized facilities. The analysis updated the landfill characteristics each year, calculating the profile of waste disposal over time.

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[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 3-3 in the Energy chapter for additional background on how biogenic emissions of landfill CO_2 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 2002a).

Table 3-117 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 and 2002, 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 2002.[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:

$$waste\ in\ place\ (tons) = \sum_{t=1973}^{2002} waste\ landfilled\ (tons)$$

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): CH_4 (m3/min) = 7.43 WIP (10^6 MT)

Large landfills (> 2 MMT WIP): CH_4 (m3/min) = 8.22 + 5.27 WIP (10^6 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):

8.6 MMT organic waste in industrial landfills	÷	65% organic content of MSW	=	13.2 MMT of equivalent total MSW

13.2 MMT ÷ 190 MMT total MSW in MSW landfills = 7%

Estimates of methane generation from industrial landfills are shown in Table 3-118.

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[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.

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, RTI 2003). 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 2003). 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 on a state-by-state basis. This step likely results in an underestimate of methane avoided due to flaring. This approach was taken 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 3-118.

Table 3-117: 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	2002
Total MSW Generated[a]	269	258	268	281	296	299	300	312	343	350	374	370	380
Percent of MSW Landfilled[a]	77%	76%	72%	71%	67%	63%	62%	61%	61%	60%	61%	61%	61%
Total MSW Landfilled	207	196	193	200	198	189	186	190	209	210	228	228	232
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	6,385

[a] Source: *BioCycle* (2001), adjusted for missing U.S. territories using U.S. Census Bureau (2000), and EPA (2002a). 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 and 2002 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 3-118: Methane Emissions from Landfills (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
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	15,221
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	6,640
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	7,075
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	1,506
Industrial Generation	812	829	852	876	900	927	946	966	983	1,007	1,026	1,047	1,065
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	16,287
Emissions Avoided	(1,302)	(1,563)	(1,776)	(2,029)	(2,399)	(2,869)	(3,419)	(4,007)	(4,631)	(4,927)	(5,140)	(5,776)	(6,074)
Landfill Gas-to-Energy	(824)	(860)	(927)	(1,005)	(1,129)	(1,164)	(1,360)	(1,618)	(1,938)	(2,177)	(2,376)	(2,630)	(2,748)
Flare	(478)	(703)	(849)	(1,024)	(1,270)	(1,705)	(2,059)	(2,390)	(2,692)	(2,750)	(2,764)	(3,146)	(3,325)
Oxidation at MSW Landfills	(1,030)	(1,027)	(1,040)	(1,048)	(1,046)	(1,037)	(1010)	(979)	(942)	(946)	(952)	(918)	(915)
Oxidation at Industrial Landfills	(81)	(83)	(85)	(88)	(90)	(93)	(95)	(97)	(98)	(101)	(103)	(105)	(107)
Net Emissions	9,998	9,992	10,126	10,220	10,228	10,166	9,942	9,685	9,360	9,419	9,491	9,202	9,192

Note: Totals may not sum due to independent rounding.

Note: MSW generation in Table 3-118 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.

( ) denotes a negative value

Figure 3-7: 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 2002 based on BioCycle

[c] EPA 1993

[d] ICF Consulting 2002 and RTI International (2003)

[e] EPA 2003

[f] Liptay et al. 1998

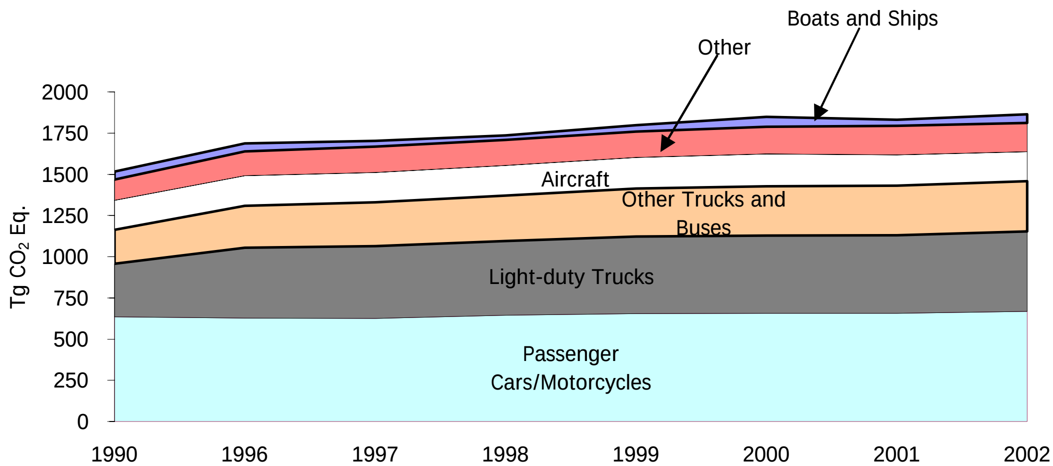


Figure 3-1: 2002 Domestic Greenhouse Gas Emissions by Mode and Vehicle Type

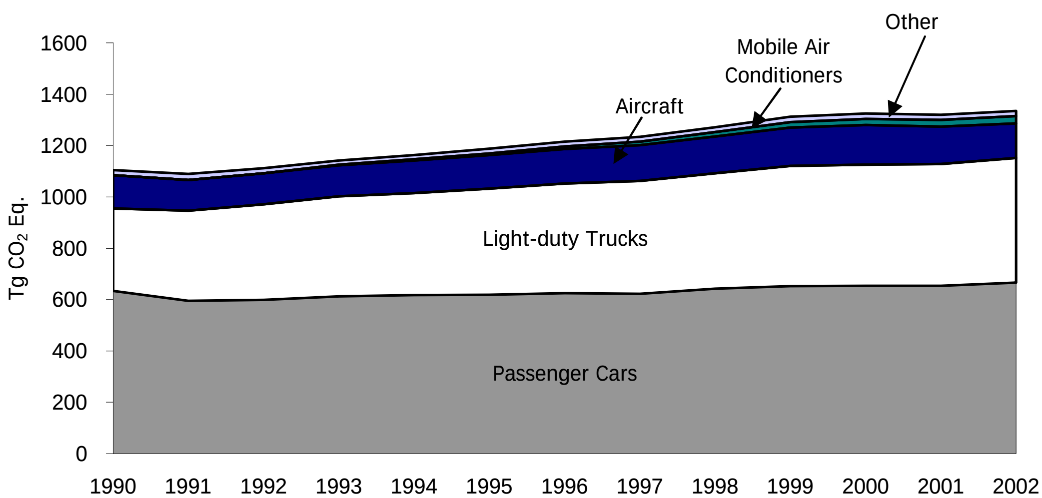


Figure 3-2: Greenhouse Gas Emissions from Passenger Transportation by Mode

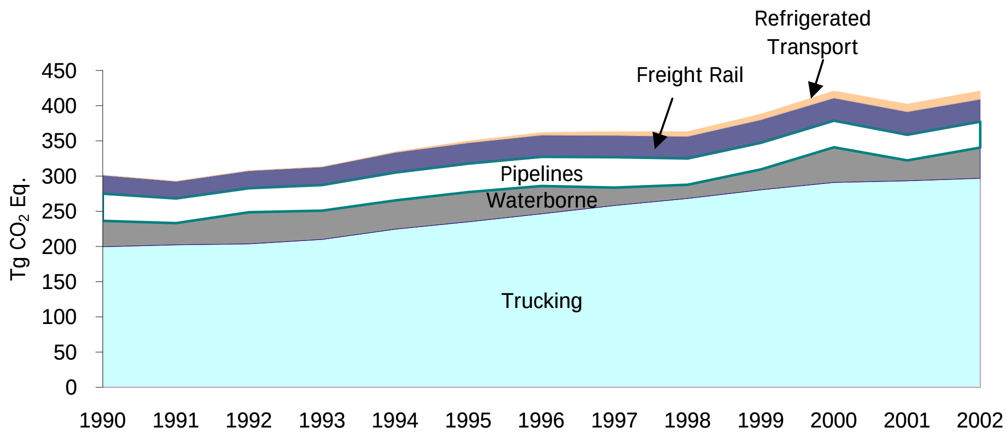


Figure 3-3: Greenhouse Gas Emissions from Domestic Freight Transportation by Mode

Figure 3-4: Forest Sector Modeling Projection System

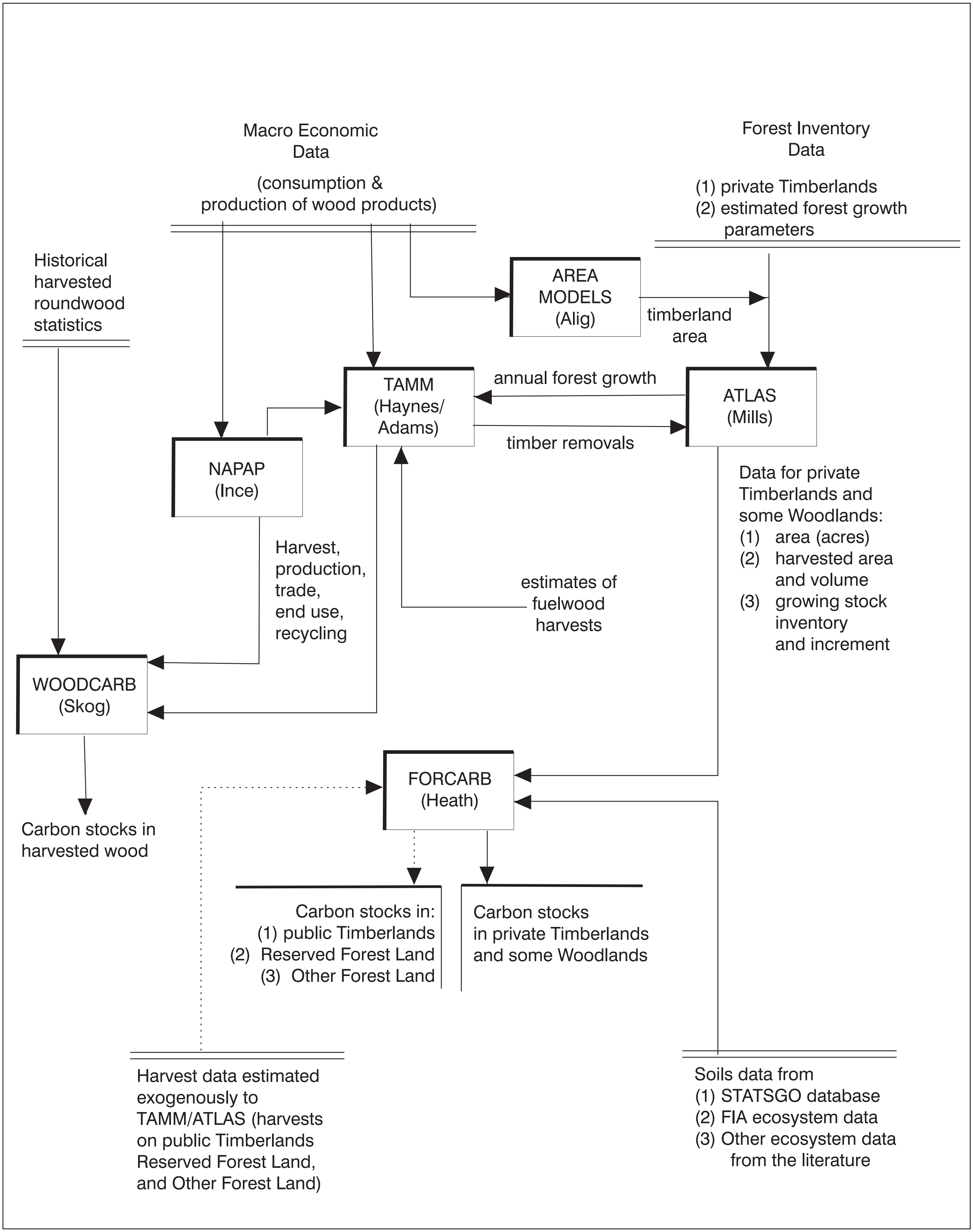


Figure 3-5

Forest Regions Used in Soil C Estimations

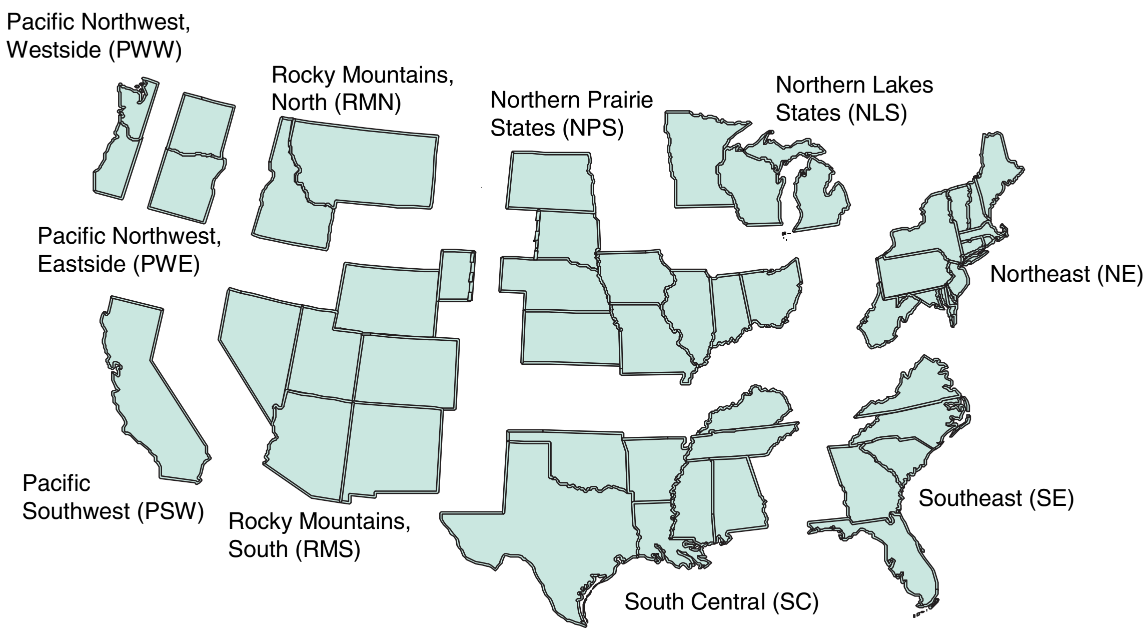
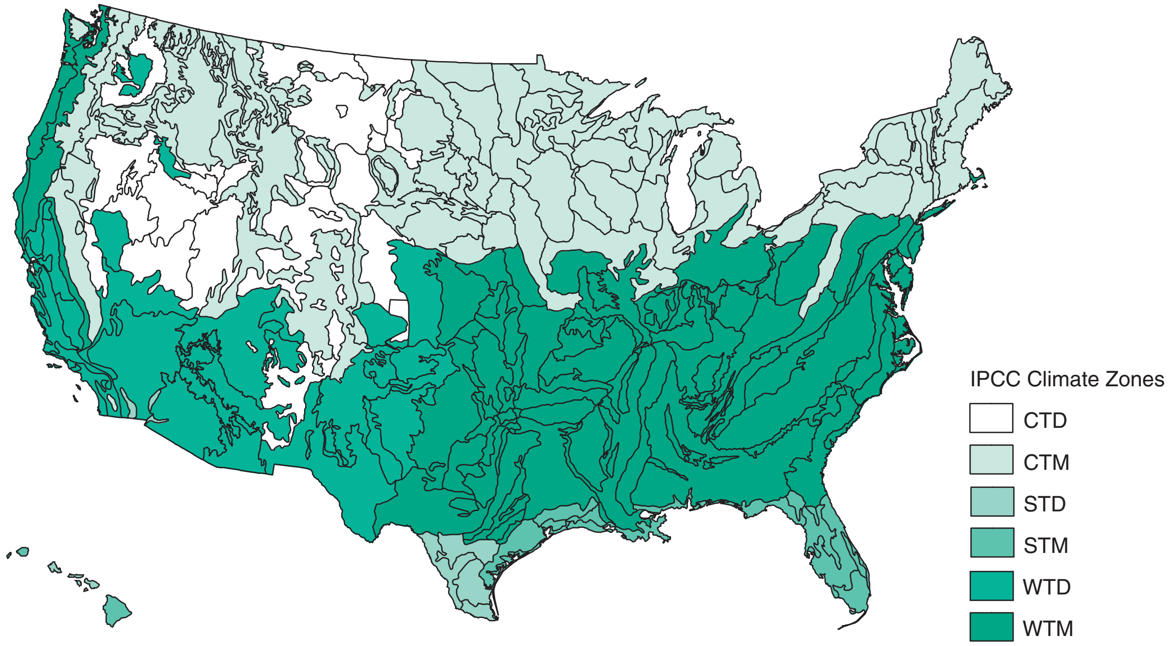


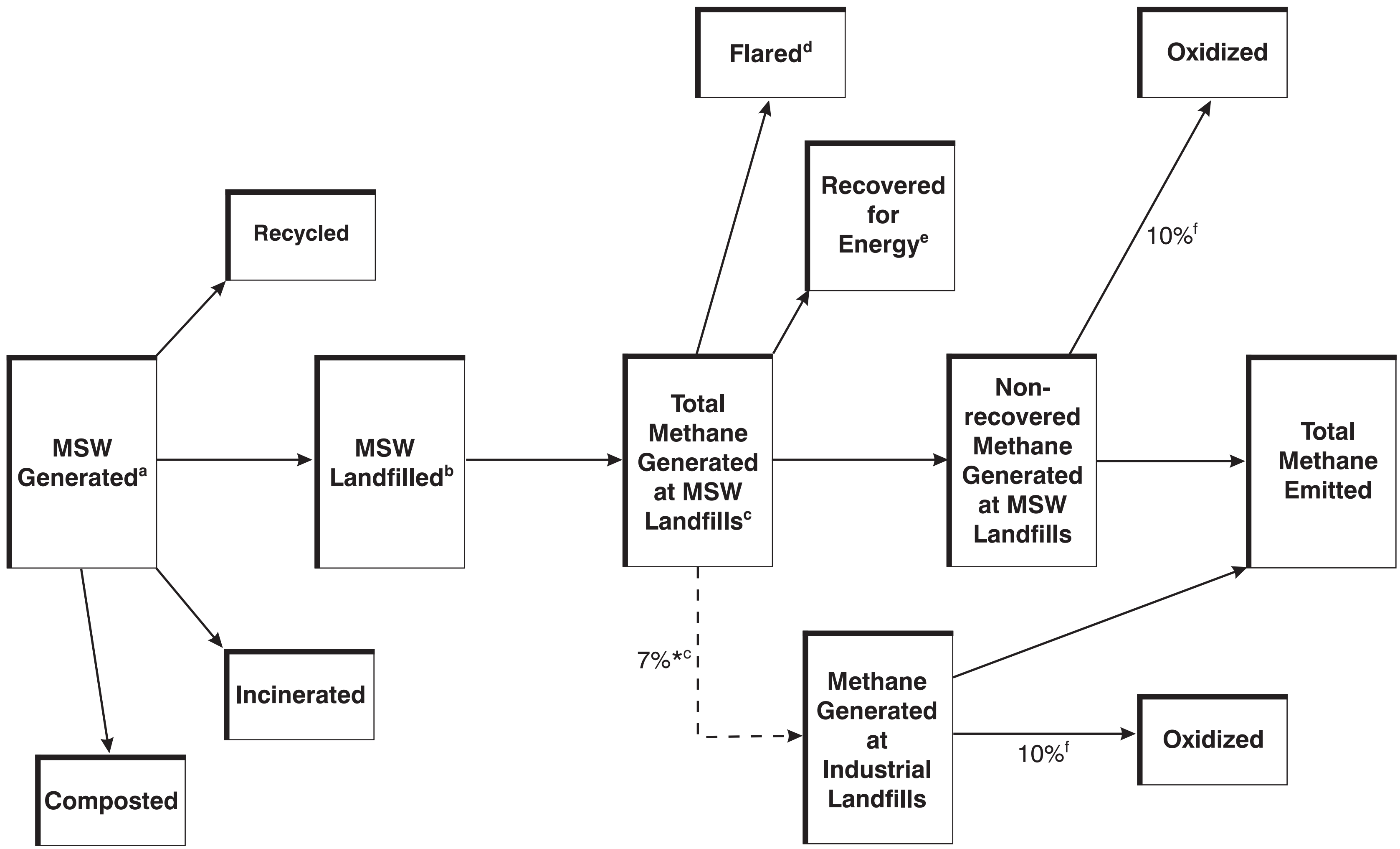
Figure 3-6

Major Land Resource Areas by IPCC Climate Zone



This figure shows the IPCC climate zone assigned to each of the 180 Major Land Resource Areas (MLRAs) in the United States, based on PRISM climate data averaged for each MRLA.

Figure 3-7: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



Descriptions of Figures: Annex 3

Figure 3-1 presents estimates of emissions from transportation and other mobile sources for all of the primary GHGs combined, in CO_2 equivalent. Passenger cars and motorcycles account for the largest share, followed by light-duty trucks, other trucks and buses, aircraft, "other" sources, and boats and ships.

Figure 3-2 presents GHG estimates from transportation for each passenger category. Passenger cars account for the largest share, followed by light-duty trucks, aircraft, mobile air conditioners, and other sources.

Figure 3-3 presents GHG estimates from transportation for each freight category. Trucking accounts for the largest share, followed by waterborne vehicles, pipelines, freight rail, and refrigerated transport.

Figure 3-4 shows the relationships between the various models used to develop projections of forest stock volume.

Figure 3-5 is a map of the U.S. showing the 10 forest regions used in soil carbon estimation.

Figure 3-6 is a map of the U.S. showing the IPCC climate zones assigned to each Major Land Resource Area (see Figure 3-6). Each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses.

Figure 3-7 presents the process of methane emissions resulting landfilling municipal and industrial waste—from waste generation to emissions—in graphical format.