ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

3.1. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion

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. Beginning in this inventory, the electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The differences in the methodology applied are described within each of the steps below. Data are presented in Table A-82 through Table A-87.

Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electric power, and U.S. territories. For CH_4 and N_2O from industrial, commercial, residential, and U.S. territories, 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, February 2012* and Published Supplemental Tables on Petroleum Product detail (EIA 2012). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2011). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were collected separately from the EIA from Jacobs (2010).[36] Data for 2010 were proxied to 2009 since fuel consumption data by U.S. Territories for 2010 were unavailable at the time of publication. Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[37] Construction and agricultural fuel use was obtained from EPA (2011). 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 A-82 provides annual energy consumption data for the years 1990 through 2010.

In this inventory, the emission estimation methodology for the electric power sector was revised from Tier 1 to Tier 2 as fuel consumption by technology-type for the electricity generation sector was obtained from the Acid Rain Program Dataset (EPA 2011). This combustion technology- and fuel-use data was available by facility from 1996 to 2010. Since there was a difference between the EPA (2011) and EIA (2011a) total energy consumption estimates, the remainder between total energy consumption using EPA (2011) and EIA (2011a) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2010.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2011) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2011a) and the ratio of combustion technology and fuel types from EPA 2011. The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995.

Lastly, there were significant differences between wood biomass consumption in the electric power sector between the EPA (2011) and EIA (2011a) datasets. The difference in wood biomass consumption in the electric power sector was distributed to the residential, commercial, and industrial sectors according to their percent share of wood biomass energy consumption calculated from EIA (2011a).

Step 2: Determine the Amount of CH_4 and N_2O Emitted

Activity data for industrial, commercial, residential, and U.S. territories and fuel type for each of these sectors were then multiplied by default Tier 1 emission factors to obtain emission estimates. Emission factors for the residential,

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

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

commercial, and industrial sectors were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). 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 A-83 provides emission factors used for each sector and fuel type. For the electric power sector, emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors shown in Table A-84.

Estimates of NOx, CO, and NMVOC Emissions

Emissions estimates for NO_x, CO, and NMVOCs were obtained from preliminary data (EPA 2010b, EPA 2009) and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site.

For indirect greenhouse gases, the major source categories included 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. EPA 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.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2009) 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 A-82: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Coal	**19,610**	**20,888**	**21,328**	**21,879**	**22,224**	**22,159**	**23,080**	**22,391**	**22,343**	**22,576**	**22,636**	**22,949**	**22,458**	**22,720**	**22,222**	**19,682**	**20,758**
Residential	31	17	17	16	12	14	11	12	12	12	11	8	6	8	8	8	7
Commercial	124	117	122	129	93	103	92	97	90	82	103	97	65	70	69	63	58
Industrial	1,640	1,527	1,455	1,458	1,471	1,373	1,349	1,358	1,244	1,249	1,262	1,219	1,189	1,131	1,084	880	1,016
Electric Power	17,807	19,217	19,724	20,266	20,637	20,659	21,618	20,920	20,987	21,199	21,228	21,591	21,161	21,465	21,026	18,692	19,639
U.S. Territories	7	10	10	10	11	10	10	4	11	34	32	33	37	47	36	38	38
Petroleum	**6,225**	**5,677**	**6,127**	**6,195**	**5,927**	**6,049**	**6,011**	**6,554**	**5,935**	**6,303**	**6,502**	**6,438**	**6,153**	**6,029**	**5,331**	**4,688**	**5,019**
Residential	1,375	1,261	1,397	1,334	1,207	1,342	1,427	1,463	1,359	1,466	1,475	1,369	1,205	1,225	1,215	1,165	1,188
Commercial	891	694	718	655	609	614	694	719	645	762	767	716	678	681	669	697	716
Industrial	2,787	2,400	2,695	2,661	2,262	2,173	2,149	2,461	2,299	2,409	2,600	2,725	3,060	2,954	2,481	1,939	2,199
Electric Power	797	860	883	1,100	1,403	1,459	1,269	1,279	1,074	1,043	1,007	1,004	590	618	488	383	412
U.S. Territories	375	462	435	445	445	461	472	632	557	622	654	623	621	552	479	504	504
Natural Gas	**17,285**	**19,351**	**20,261**	**20,151**	**19,840**	**19,755**	**20,884**	**20,209**	**20,908**	**20,855**	**21,059**	**20,805**	**20,626**	**22,019**	**22,281**	**21,950**	**22,670**
Residential	4,491	4,954	5,354	5,093	4,646	4,835	5,105	4,889	4,995	5,209	4,981	4,946	4,476	4,835	5,010	4,883	4,883
Commercial	2,682	3,096	3,226	3,285	3,083	3,115	3,252	3,097	3,212	3,261	3,201	3,073	2,902	3,085	3,228	3,187	3,164
Industrial	7,736	8,736	9,049	9,052	8,826	8,402	8,621	7,934	8,086	7,806	7,821	7,197	7,323	7,521	7,566	7,119	7,438
Electric Power	2,376	2,564	2,632	2,720	3,285	3,403	3,894	4,266	4,591	4,551	5,032	5,565	5,899	6,550	6,447	6,733	7,159
U.S. Territories	0	0	0	0	0	0	13	23	23	27	25	24	26	27	29	27	27
Wood	**2,216**	**2,370**	**2,437**	**2,371**	**2,184**	**2,214**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,136**	**2,109**	**2,098**	**2,044**	**1,881**	**1,986**
Residential	614	547	571	455	404	414	444	393	409	434	442	468	423	467	486	470	458
Commercial	70	76	80	78	68	71	76	71	74	78	76	76	70	75	79	79	77
Industrial	1,526	1,739	1,779	1,831	1,704	1,720	1,731	1,533	1,503	1,480	1,592	1,581	1,598	1,533	1,452	1,309	1,426
Electric Power	7	8	8	8	8	9	11	9	9	10	11	11	17	23	27	23	25
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table A-83: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[38]

Fuel/End-Use Sector	CH_4	N_2O
Coal		
Residential	300	1.5
Commercial	10	1.5
Industrial	10	1.5
Electric Power	1	1.5
U.S. Territories	1	1.5
Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	3	0.6
Electric Power	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	1	0.1
Electric Power	1	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	30	4.0
Electric Power	30	4.0
U.S. Territories	NA	NA

NA (Not Applicable)

Table A-84: CH_4 and N_2O Emission Factors by Technology Type and Fuel Type for the Electric Power Sector(g/GJ)[39]

Technology	Configuration	CH_4	N_2O
Liquid Fuels			
Residual Fuel Oil/Shale Oil Boilers	Normal Firing	0.8	0.3
	Tangential Firing	0.8	0.3
Gas/Diesel Oil Boilers	Normal Firing	0.9	0.4
	Tangential Firing	0.9	0.4
Large Diesel Oil Engines >600 hp (447kW)		4	NA
Solid Fuels			
Pulverized Bituminous Combination Boilers	Dry Bottom, wall fired	0.7	0.5
	Dry Bottom, tangentially fired	0.7	1.4
	Wet bottom	0.9	1.4
Bituminous Spreader Stoker Boilers	With and without re-injection	1	0.7
Bituminous Fluidized Bed Combustor	Circulating Bed	1	61
	Bubbling Bed	1	61
Bituminous Cyclone Furnace		0.2	0.6
Lignite Atmospheric Fluidized Bed		NA	71
Natural Gas			
Boilers		1	1
Gas-Fired Gas Turbines >3MW		4	1
Large Duel-Fuel Engines		258	NA
Combined Cycle		1	3
Peat			
Peat Fluidized Bed Combustion	Circulating Bed	3	7
	Bubbling Bed	3	3
Biomass			
Wood/Wood Waste Boilers		11	7
Wood Recovery Boilers		1	1

Source: IPCC (2006)

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

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

Table A-85: NOx Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Electric Power	**6,045**	**5,792**	**5,581**	**5,683**	**5,637**	**5,183**	**4,829**	**4,453**	**4,265**	**3,988**	**3,711**	**3,434**	**3,121**	**3,007**	**2,722**	**1,766**	**1,766**
Coal	5,119	5,061	5,079	5,118	4,932	4,437	4,130	3,802	3,634	3,398	3,162	2,926	2,659	2,562	2,319	1,505	1,505
Fuel Oil	200	87	107	131	202	179	147	149	142	133	124	114	104	100	91	59	59
Natural gas	513	510	248	277	329	393	376	325	310	290	270	250	227	219	198	128	128
Wood	NA	NA	5	6	24	33	36	37	36	33	31	29	26	25	23	15	15
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	142	150	149	141	140	140	143	134	124	115	105	101	91	59	59
Industrial	**2,559**	**2,650**	**2,666**	**2,614**	**2,570**	**2,283**	**2,278**	**2,296**	**1,699**	**1,638**	**1,577**	**1,515**	**1,520**	**1,525**	**1,530**	**1,478**	**1,478**
Coal	530	541	490	487	475	475	484	518	384	370	356	342	343	344	345	334	334
Fuel Oil	240	224	203	196	190	190	166	153	114	110	105	101	102	102	102	99	99
Natural gas	877	999	900	880	869	706	710	711	526	507	488	469	471	472	474	458	458
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	103	104	100	109	116	86	82	79	76	77	77	77	74	74
Internal Combustion	792	774	965	948	932	813	809	798	591	569	548	527	528	530	532	514	514
Commercial	**671**	**607**	**734**	**539**	**510**	**483**	**507**	**428**	**438**	**456**	**473**	**490**	**486**	**483**	**479**	**501**	**501**
Coal	36	35	30	32	34	23	21	21	19	19	19	19	19	19	19	19	19
Fuel Oil	88	94	86	88	73	54	52	52	50	49	49	49	49	49	49	49	49
Natural gas	181	210	224	229	220	156	161	165	157	156	156	155	155	155	154	154	154
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	394	191	183	249	273	189	213	231	249	267	263	261	257	280	280
Residential	**749**	**813**	**726**	**699**	**651**	**441**	**439**	**446**	**423**	**421**	**420**	**418**	**417**	**417**	**416**	**414**	**414**
Coal[b]	NA	NA	NA	NA	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	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	27	27	27	25	21	22	21	21	21	20	20	20	20	20	20
Other Fuels[a]	707	769	699	671	624	416	417	424	402	400	399	397	397	396	396	394	394
Total	**10,023**	**9,862**	**9,707**	**9,534**	**9,369**	**8,390**	**8,053**	**7,623**	**6,825**	**6,503**	**6,181**	**5,858**	**5,545**	**5,432**	**5,148**	**4,159**	**4,159**

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

Table A-86: CO Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Electric Power	**329**	**337**	**369**	**385**	**410**	**450**	**439**	**439**	**595**	**590**	**586**	**582**	**598**	**616**	**633**	**631**	**631**
Coal	213	227	228	233	220	187	221	220	298	296	293	292	300	308	317	316	316
Fuel Oil	18	9	11	13	17	36	27	28	38	37	37	37	38	39	40	40	40
Natural gas	46	49	72	76	88	150	96	92	125	124	123	122	126	129	133	132	132
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	7	8	30	24	31	32	44	43	43	43	44	45	46	46	46
Internal Combustion	52	52	52	54	55	52	63	67	91	90	89	89	91	94	97	96	96
Industrial	**797**	**958**	**1,078**	**1,054**	**1,044**	**1,100**	**1,106**	**1,137**	**1,149**	**1,115**	**1,080**	**1,045**	**1,064**	**1,084**	**1,103**	**1,030**	**1,030**
Coal	95	88	100	99	96	114	118	125	127	123	119	115	117	119	121	113	113
Fuel Oil	67	64	49	47	46	54	48	45	46	44	43	42	42	43	44	41	41
Natural gas	205	313	307	307	305	350	355	366	370	359	347	336	342	349	355	331	331
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	316	302	303	286	300	321	325	315	305	296	301	307	312	291	291
Internal Combustion	177	222	305	299	294	296	285	279	282	274	265	257	261	266	271	253	253
Commercial	**205**	**211**	**122**	**126**	**122**	**151**	**151**	**154**	**177**	**173**	**169**	**166**	**166**	**167**	**168**	**158**	**158**
Coal	13	14	13	13	14	16	14	13	15	15	15	14	15	15	15	14	14
Fuel Oil	16	17	17	18	15	17	17	17	20	19	19	19	19	19	19	18	18
Natural gas	40	49	58	59	57	81	83	84	97	95	93	91	91	92	92	87	87
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	34	36	36	36	36	38	44	43	42	41	42	42	42	40	40
Residential	**3,668**	**3,877**	**2,364**	**2,361**	**2,352**	**3,323**	**2,644**	**2,648**	**3,044**	**2,981**	**2,919**	**2,856**	**2,867**	**2,878**	**2,889**	**2,725**	**2,725**
Coal[b]	NA	NA	NA	NA	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	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,133	2,133	2,133	3,094	2,416	2,424	2,787	2,730	2,672	2,615	2,624	2,635	2,645	2,495	2,495
Other Fuels[a]	238	248	231	229	220	229	228	224	257	252	246	241	242	243	244	230	230
Total	**5,000**	**5,383**	**3,934**	**3,926**	**3,928**	**5,024**	**4,340**	**4,377**	**4,965**	**4,860**	**4,753**	**4,649**	**4,695**	**4,744**	**4,792**	**4,543**	**4,543**

NA (Not Applicable)

[a] “Other Fuels” include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the “Other Fuels” category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

Table A-87: NMVOC Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Electric Power	**43**	**40**	**44**	**47**	**51**	**49**	**56**	**55**	**44**	**44**	**44**	**44**	**44**	**45**	**45**	**46**	**46**
Coal	24	26	25	26	26	25	27	26	21	21	21	21	21	22	22	22	22
Fuel Oil	5	2	3	4	5	4	4	4	4	4	4	3	4	4	4	4	4
Natural gas	2	2	7	7	9	9	12	12	10	10	10	10	10	10	10	10	10
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	+	+	1	2	2	2	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	9	10	10	10	11	11	8	8	8	8	8	9	9	9	9
Industrial	**165**	**187**	**163**	**160**	**159**	**156**	**157**	**160**	**138**	**132**	**126**	**121**	**120**	**119**	**118**	**110**	**110**
Coal	7	5	6	6	6	9	9	10	9	9	8	8	8	8	8	7	7
Fuel Oil	11	11	8	7	7	10	9	9	7	7	7	6	6	6	6	6	6
Natural gas	52	66	54	54	54	52	53	54	47	45	43	41	41	40	40	37	37
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	33	31	31	26	27	29	25	24	23	22	22	22	22	20	20
Internal Combustion	49	60	63	62	61	60	58	57	49	47	45	43	43	42	42	39	39
Commercial	**18**	**21**	**22**	**22**	**21**	**25**	**28**	**29**	**61**	**53**	**45**	**33**	**36**	**38**	**40**	**23**	**23**
Coal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	+	+
Fuel Oil	3	3	3	3	3	3	4	4	6	5	3	2	3	4	5	1	1
Natural gas	7	10	13	13	12	11	14	14	23	18	14	9	12	16	19	4	4
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	8	5	5	5	10	9	10	31	29	27	22	19	17	15	18	18
Residential	**686**	**725**	**788**	**788**	**786**	**815**	**837**	**837**	**1,341**	**1,066**	**792**	**519**	**719**	**918**	**1,117**	**244**	**244**
Coal[b]	NA	NA	NA	NA	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	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	756	757	756	794	809	809	1,298	1,032	767	502	695	888	1,081	236	236
Other Fuels[a]	35	37	33	32	30	21	27	27	43	35	26	17	23	30	36	8	8
Total	**912**	**973**	**1,018**	**1,017**	**1,016**	**1,045**	**1,077**	**1,081**	**1,585**	**1,296**	**1,008**	**716**	**918**	**1,120**	**1,321**	**424**	**424**

NA (Not Applicable)

+ Does not exceed 1 Gg.

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions

Estimating CO_2 Emissions by Transportation Mode

Transportation-related CO_2 emissions, as presented in the Carbon Dioxide Emissions from Fossil Fuel Combustion section of the Energy chapter, were calculated using the methodology described in Annex 2.1. This section provides additional information on the data sources and approach used for each transportation fuel type. As noted in Annex 2.1, CO_2 emissions estimates for the transportation sector were calculated directly for on-road diesel fuel and motor gasoline based on data sources for individual modes of transportation (considered a "bottom up" approach). For most other fuel and energy types (i.e., jet fuel, aviation gasoline, residual fuel oil, natural gas, LPG, and electricity), CO_2 emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2012 and EIA 2011a) and apportioned to individual modes (considered a "top down" approach).

Based on interagency discussions between EPA, EIA, and FHWA beginning in 2005, it was agreed that use of "bottom up" data would be more accurate for diesel fuel and motor gasoline, based on the availability of reliable transportation-specific data sources. A "bottom up" diesel calculation was implemented in the 1990-2005 Inventory, and a bottom-up gasoline calculation was introduced in the 1990-2006 Inventory for the calculation of emissions from on-road vehicles. Motor gasoline and diesel consumption data for on-road vehicles come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2012)[40], and are based on federal and state fuel tax records. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book (DOE 1993 through 2011) to develop an estimate of fuel consumption for each vehicle type (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). The on-road gas and diesel fuel consumption estimates by vehicle type were then adjusted for each year so that the sum of gasoline and diesel fuel consumption across all vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Tables MF-21 and MF-27 (FHWA 1996 through 2012). Table MF-21 provided fuel consumption estimates for the most current Inventory year; Table MF-27 provided fuel consumption estimates for years 1990-2009. This resulted in a final estimate of motor gasoline and diesel fuel use by vehicle type, consistent with the FHWA total for on-road motor gasoline and diesel fuel use.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2011) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2011 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004) and Whorton (2006 through 2012) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2011) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2012).

Since EIA's total fuel consumption estimate for each fuel type is considered to be accurate at the national level, adjustments needed to be made in the estimates for other sectors to equal the EIA total. In the case of motor gasoline, estimates of fuel use by recreational boats come from EPA's NONROAD Model (EPA 2011b), and these estimates along with those from other sectors (e.g., commercial sector, industrial sector) were adjusted. Similarly, to ensure consistency with EIA's total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted downward proportionately.

As noted above, for fuels other than motor gasoline and diesel, EIA's transportation sector total was apportioned to specific transportation sources. For jet fuel, estimates come from: FAA (2012, 2006) for commercial aircraft, FAA (2011)) for general aviation aircraft, and DESC (2011) for military aircraft. Estimates for biofuels, including ethanol and biodiesel were discussed separately and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2011a).

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[40] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

Table A-88 displays estimated fuel consumption by fuel and vehicle type. Table A-89 displays estimated energy consumption by fuel and vehicle type. The values in both of these tables correspond to the figures used to calculate CO_2 emissions from transportation. Except as noted above, they are estimated based on EIA transportation sector energy estimates by fuel type, with activity data used to apportion consumption to the various modes of transport. For motor gasoline, the figures do not include ethanol blended with gasoline; although ethanol is included in FHWA's totals for reported motor gasoline use. Ethanol is a biofuel and in order to be in line with IPCC methodological guidance and UNFCCC reporting obligations, net carbon fluxes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change and Forestry chapter, not in Energy chapter totals. Ethanol and biodiesel consumption estimates are shown separately in Table A-90.

Table A-88. Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007[a]	2008[a]	2009[a]	2010[a]
Motor Gasoline[b]	**110,441**	**118,217**	**120,617**	**122,040**	**125,576**	**128,258**	**129,102**	**130,582**	**133,257**	**133,900**	**135,708**	**134,659**	**132,947**	**132,546**	**127,528**	**127,323**	**126,029**
Passenger Cars	69,763	67,948	68,996	69,034	71,303	73,144	72,860	73,466	74,911	72,623	72,223	74,600	71,646	89,794	86,375	86,019	85,050
Light-Duty Trucks	34,698	44,369	45,954	47,528	48,668	50,901	50,774	51,252	52,442	55,951	58,118	54,274	55,460	35,401	33,723	34,311	34,094
Motorcycles	194	200	197	201	206	213	210	194	191	185	195	184	212	478	496	479	422
Buses	39	42	42	42	42	45	44	39	38	36	50	40	43	83	88	89	84
Medium- and Heavy- Duty Trucks	4,350	4,072	3,976	3,901	3,957	4,018	4,096	3,990	4,038	3,479	3,510	3,962	4,008	5,233	5,322	4,918	4,901
Recreational Boats[c]	1,397	1,585	1,452	1,334	1,400	(62)	1,119	1,641	1,637	1,626	1,612	1,599	1,577	1,557	1,524	1,506	1,477
Distillate Fuel Oil (Diesel Fuel)	**25,631**	**31,605**	**33,160**	**34,625**	**35,728**	**37,863**	**39,241**	**39,058**	**40,348**	**41,177**	**42,668**	**44,659**	**45,848**	**46,432**	**43,236**	**39,284**	**40,839**
Passenger Cars	771	765	657	593	546	427	356	357	364	412	419	414	403	402	362	354	365
Light-Duty Trucks	1,119	1,452	1,529	1,586	1,682	1,847	1,961	2,029	2,133	2,652	2,822	2,518	2,610	1,326	1,182	1,181	1,224
Buses	781	851	884	901	922	1,034	997	905	860	930	1,317	1,029	1,051	1,552	1,482	1,375	1,363
Medium- and Heavy-Duty Trucks	18,574	23,241	24,489	25,929	27,153	28,833	30,180	30,125	31,418	31,539	32,599	35,161	36,076	37,492	35,688	32,383	33,666
Recreational Boats	190	228	236	243	251	258	266	274	282	289	297	305	313	321	88	337	345
Ships and Other Boats	735	1,204	1,432	1,426	1,199	1,342	1,377	1,248	1,202	1,178	807	785	729	800	218	119	67
Rail	3,461	3,864	3,934	3,947	3,975	4,122	4,106	4,119	4,089	4,176	4,407	4,446	4,665	4,539	4,216	3,535	3,807
Jet Fuel[d]	**18,350**	**17,849**	**18,220**	**18,586**	**18,397**	**19,833**	**20,491**	**19,298**	**18,137**	**18,376**	**18,702**	**19,918**	**17,383**	**17,303**	**15,904**	**14,320**	**14,410**
Commercial Aircraft	14,103	14,796	15,230	15,773	15,363	16,735	17,353	16,021	15,088	15,321	15,288	16,533	14,065	14,164	12,534	11,425	11,696
General Aviation Aircraft	663	560	608	642	815	967	972	918	938	932	1,231	1,527	1,643	1,486	1,706	1,447	1,432
Military Aircraft	3,583	2,493	2,383	2,172	2,219	2,131	2,167	2,359	2,111	2,123	2,184	1,859	1,676	1,654	1,664	1,448	1,282
Aviation Gasoline[d]	**374**	**329**	**311**	**330**	**295**	**326**	**302**	**291**	**281**	**251**	**260**	**294**	**278**	**263**	**235**	**221**	**230**
General Aviation Aircraft	374	329	311	330	295	326	302	291	281	251	260	294	278	263	235	221	230
Residual Fuel Oil[d, e]	**2,006**	**2,587**	**2,104**	**912**	**527**	**1,174**	**2,963**	**1,066**	**1,522**	**662**	**1,245**	**1,713**	**2,046**	**2,579**	**1,770**	**1,372**	**2,252**
Ships and Other Boats	2,006	2,587	2,104	912	527	1,174	2,963	1,066	1,522	662	1,245	1,713	2,046	2,579	1,770	1,372	2,252
Natural Gas[d] (million cubic feet)	**0.7**	**0.7**	**0.7**	**0.8**	**0.6**	**0.7**	**0.7**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**
Passenger Cars	-	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
Light-Duty Trucks	-	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
Buses	-	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	0.0	0.0	0.0
Pipelines	0.7	0.7	0.7	0.8	0.6	0.7	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7
LPG[d]	**265**	**206**	**182**	**165**	**205**	**166**	**138**	**159**	**166**	**191**	**222**	**327**	**320**	**257**	**468**	**331**	**340**
Buses	-	1.6	3.4	3.0	3.6	2.4	1.5	0.3	0.6	0.7	0.7	1.0	1.0	-	-	-	-
Light-Duty Trucks	106	98	87	80	100	91	88	108	117	134	167	247	229	185	340	228	234

Medium- and Heavy-Duty Trucks	159		106	91	82	102	72	49	51	49	57	55	79	89	72	128	103	106
Electricity[d]	**4,751**		**4,975**	**4,923**	**4,907**	**4,962**	**5,126**	**5,382**	**5,724**	**5,517**	**6,810**	**7,224**	**7,506**	**7,358**	**8,173**	**7,700**	**7,781**	**7,740**
Rail	4,751		4,975	4,923	4,907	4,962	5,126	5,382	5,724	5,517	6,810	7,224	7,506	7,358	8,173	7,700	7,781	7,740

[a] In 2011, FHWA changed how vehicles are classified, moving form a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in fuel consumption data by vehicle class.

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes.

[e] Fluctuations in reported fuel consumption may reflect data collection problems. The residual fuel oil for ships and other boats data is based on EIA's December 2011 Monthly Energy Review data.

+ Less than 0.05 million gallons or 0.05 million cubic feet

- Unreported or zero

Table A-89: Energy Consumption by Fuel and Vehicle Type (Tbtu)

Fuel/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007[a]	2008[a]	2009[a]	2010[a]
Motor Gasoline[b]	**13,813**	**14,679**	**14,979**	**15,147**	**15,583**	**15,913**	**16,015**	**16,198**	**16,524**	**16,600**	**16,850**	**16,730**	**16,517**	**16,470**	**15,844**	**15,818**	**15,658**
Passenger Cars	8,725	8,437	8,569	8,568	8,848	9,075	9,038	9,113	9,289	9,004	8,968	9,268	8,901	11,158	10,731	10,687	10,566
Light-Duty Trucks	4,340	5,509	5,707	5,899	6,040	6,315	6,298	6,358	6,503	6,937	7,216	6,743	6,890	4,399	4,190	4,263	4,236
Motorcycles	24	25	24	25	26	26	26	24	24	23	24	23	26	59	62	60	52
Buses	5	5	5	5	5	6	5	5	5	4	6	5	5	10	11	11	10
Medium- and Heavy-Duty Trucks	544	506	494	484	491	498	508	495	501	431	436	492	498	650	661	611	609
Recreational Boats[c]	175	197	180	166	174	-8	139	204	203	202	200	199	196	193	189	187	184
Distillate Fuel Oil (Diesel Fuel)	**3,555**	**4,383**	**4,599**	**4,802**	**4,955**	**5,251**	**5,442**	**5,417**	**5,596**	**5,711**	**5,918**	**6,194**	**6,359**	**6,440**	**5,996**	**5,448**	**5,664**
Passenger Cars	107	106	91	82	76	59	49	50	51	57	58	57	56	56	50	49	51
Light-Duty Trucks	155	201	212	220	233	256	272	281	296	368	391	349	362	184	164	164	170
Buses	108	118	123	125	128	143	138	126	119	129	183	143	146	215	206	191	189
Medium- and Heavy-Duty Trucks	2,576	3,223	3,396	3,596	3,766	3,999	4,186	4,178	4,357	4,374	4,521	4,877	5,003	5,200	4,950	4,491	4,669
Recreational Boats	26	32	33	34	35	36	37	38	39	40	41	42	43	45	12	47	48
Ships and Other Boats	102	167	199	198	166	186	191	173	167	163	112	109	101	111	30	16	9
Rail	480	536	546	547	551	572	569	571	567	579	611	617	647	630	585	490	528
Jet Fuel[c]	**2,477**	**2,410**	**2,460**	**2,509**	**2,484**	**2,677**	**2,766**	**2,605**	**2,448**	**2,481**	**2,525**	**2,689**	**2,347**	**2,336**	**2,147**	**1,933**	**1,945**
Commercial Aircraft	1,904	1,997	2,056	2,129	2,074	2,259	2,343	2,163	2,037	2,068	2,064	2,232	1,899	1,912	1,692	1,542	1,579
General Aviation Aircraft	89	76	82	87	110	131	131	124	127	126	166	206	222	201	230	195	193
Military Aircraft	484	337	322	293	300	288	292	319	285	287	295	251	226	223	225	196	173
Aviation Gasoline[d]	**45**	**40**	**37**	**40**	**35**	**39**	**36**	**35**	**34**	**30**	**31**	**35**	**33**	**32**	**28**	**27**	**28**
General Aviation Aircraft	45	40	37	40	35	39	36	35	34	30	31	35	33	32	28	27	28
Residual Fuel Oil[d, e]	**300**	**387**	**315**	**137**	**79**	**176**	**443**	**159**	**228**	**99**	**186**	**256**	**306**	**386**	**265**	**205**	**337**
Ships and Other Boats	300	387	315	137	79	176	443	159	228	99	186	256	306	386	265	205	337
Natural Gas[d]	**680**	**724**	**737**	**780**	**666**	**675**	**672**	**658**	**702**	**627**	**602**	**624**	**625**	**665**	**692**	**715**	**756**
Passenger Cars	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Light-Duty Trucks	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Buses	0	1	2	3	4	6	8	9	12	14	16	16	16	19	21	25	25
Pipelines	680	721	734	776	661	670	664	649	690	614	586	608	609	647	672	690	731
LPG[d]	**23**	**18**	**16**	**14**	**18**	**14**	**12**	**14**	**14**	**17**	**19**	**28**	**27**	**22**	**40**	**28**	**29**
Buses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Light-Duty Trucks	9	8	7	7	9	8	8	9	10	12	14	21	20	16	29	19	20
Medium- and Heavy-Duty Trucks	14	9	8	7	9	6	4	4	4	5	5	7	8	6	11	9	9

Electricity[d]	**16**		**17**	**17**	**17**	**17**	**17**	**18**	**20**	**19**	**23**	**25**	**26**	**25**	**28**	**26**	**26**	**26**
Rail	16		17	17	17	17	17	18	20	19	23	25	26	25	28	26	26	26
Total	**20,909**		**22,657**	**23,160**	**23,446**	**23,837**	**24,764**	**25,405**	**25,106**	**25,562**	**25,589**	**26,156**	**26,582**	**26,240**	**26,377**	**25,039**	**24,201**	**24,443**

[a] In 2011, FHWA changed how vehicles are classified, moving form a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in fuel consumption data by vehicle class.

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes.

[e] Fluctuations in reported fuel consumption may reflect data collection problems. The residual fuel oil for ships and other boats data is based on EIA's December 2011 Monthly Energy Review data.

- Unreported or zero

Table A-90. Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	**1990**		**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Ethanol	712.6		1,327	951	1,203	1,331	1,389	1,591	1,661	1,977	2,690	3,377	3,862	5,210	6,567	9,269	10,543	12,616
Biodiesel	NA		NA	NA	NA	NA	NA	NA	10	16	14	27	91	261	358	316	317	222

Estimates of CH_4 and N_2O Emissions

Mobile source emissions of greenhouse gases other than CO_2 are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of 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 fuel consumption and vehicle miles traveled (VMT). These estimates were then multiplied by emission factors, expressed as grams per unit of fuel consumed or per vehicle mile.

Methodology for On-Road Gasoline and Diesel Vehicles

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

VMT by vehicle type (e.g., passenger cars, light-duty trucks, medium- and heavy-duty trucks,[41] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2012)[42]. As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) so that the appropriate emission factors could be applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2012) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book* (DOE 1993 through 2011). These fuel shares are drawn from various sources, including the Vehicle Inventory and Use Survey, the National Vehicle Population Profile, and the American Public Transportation Association. The fuel shares were first adjusted proportionately so that the gasoline and diesel shares for each vehicle type summed to 100 percent in order to develop an interim estimate of VMT for each vehicle/fuel type category that summed to the total national VMT estimate. VMT for alternative fuel vehicles (AFVs) was calculated separately, and the methodology is explained in the following section on AFVs. Estimates of VMT from AFVs were then subtracted from the appropriate interim VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[43] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A- 91 and Table A- 92, respectively.

Total VMT for each on-road category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, medium- and heavy-duty diesel vehicles, and motorcycles) were distributed across 31 model years shown for 2010 in Table A- 95. Distributions for 1990-2010 are presented in the Inventory Docket. This distribution was derived by weighting the appropriate age distribution of the U.S. vehicle fleet according to vehicle registrations by the average annual age-specific vehicle mileage accumulation of U.S. vehicles. Age distribution values were obtained from EPA's MOBILE6 model for all years before 1999 (EPA 2000) and EPA's MOVES model for years 1999 forward (EPA 2011a).[44] Age-specific vehicle mileage accumulation was 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 was distributed across various control technologies as shown in Table A- 99

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[41] Medium-duty trucks include vehicles with a gross vehicle weight rating (GVWR) of 8,500 to 14,000 lbs. while heavy-duty trucks include those with a GVWR of over 14,000 lbs.

[42] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[43] In Inventories through 2002, gasoline-electric hybrid vehicles were considered part of an "alternative fuel and advanced technology" category. However, vehicles are now only separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now considered within the gasoline vehicle category.

[44] Age distributions were held constant for the period 1990-1998, and reflect a 25-year vehicle age span. EPA (2010) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

through Table A- 102. The categories "EPA Tier 0" and "EPA Tier 1" were used instead of 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, EPA Tier 2, and LEV refer to U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and its predecessors EPA Tier 1 and Tier 0 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).[45] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N_2O emissions compared EPA Tier 1 emissions technology (EPA 1999b).

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 2007 were determined using confidential engine family sales data submitted to EPA (EPA 2007b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2007a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, Tier 2, 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. Tier 2 began initial phase-in by 2004.

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

Emission factors for gasoline and diesel on-road vehicles were developed by ICF (2004). These factors were based on EPA and CARB laboratory test results of different vehicle and control technology types. The EPA and CARB tests were designed following the Federal Test Procedure (FTP), which covers three separate driving segments, since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was later analyzed to determine quantities of gases present. The emission characteristics of segment 2 was used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon MOBILE6.2's ratio of start to running emissions for each vehicle class to approximate average driving characteristics.

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

Emissions of CH_4 and N_2O were then calculated by multiplying total VMT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

Methodology for Alternative Fuel Vehicles (AFVs)

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 on 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.[46] The data obtained include vehicle fuel use and total number of vehicles in use from 1992 through 2007. Because AFVs run on different fuel types, their fuel use characteristics are not directly comparable. Accordingly, fuel economy for each vehicle type is expressed in gasoline equivalent terms, i.e., how much gasoline contains the equivalent amount of energy as the alternative fuel. 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, Kassoy 2001). 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 use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. Note that for AFVs

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

[46] 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.

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). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, heavy-duty vehicles) are shown in Table A- 93, while more detailed estimates of VMT by control technology are shown in Table A- 94.

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

CH_4 and N_2O emission factors for alternative fuel vehicles (AFVs) are calculated according to studies by Argonne National Laboratory (2006) and Lipman & Delucchi (2002), and are reported in ICF (2006a). In these studies, N_2O and CH_4 emissions for AFVs were expressed as a multiplier corresponding to conventional vehicle counterpart emissions. Emission estimates in these studies represent the current AFV fleet and were compared against Tier 1 emissions from light-duty gasoline vehicles to develop new multipliers. Alternative fuel heavy-duty vehicles were compared against gasoline heavy-duty vehicles as most alternative fuel heavy-duty vehicles use catalytic after treatment and perform more like gasoline vehicles than diesel vehicles. These emission factors are shown in Table A- 104.

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-Road Mobile Sources

CH_4 and N_2O emissions from non-road mobile sources were estimated by applying emission factors to the amount of fuel consumed by mode and vehicle type.

Activity data for non-road vehicles include annual fuel consumption statistics by transportation mode and fuel type, as shown in Table A- 98. Consumption data for ships and other boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2012) for distillate fuel, and DHS (2008) and EIA (2011a) for residual fuel; marine transport fuel consumption data for U.S. territories (EIA 2008b, EIA 1991 through 2011) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[47] Gasoline consumption by recreational boats was obtained from EPA's NONROAD model (EPA 2011b). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR) (2008-2011), diesel consumption from commuter rail was obtained from APTA (2007 through 2011) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2012). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2011). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2011), 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. Pipeline fuel consumption was obtained from EIA (2007 through 2011) (note: pipelines are a transportation source but are stationary, not mobile, sources). Data on fuel consumption by all non-transportation mobile sources[48] were obtained from EPA's NONROAD model (EPA 2010b) and from FHWA (1996 through 2012) for gasoline consumption for trucks used off-road.

Emissions of CH_4 and N_2O from non-road 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 A- 105).

Estimates of NO_x, CO, and NMVOC Emissions

The emission estimates of NO_x, CO, and NMVOCs from mobile combustion (transportation) were obtained from preliminary data (EPA 2010, EPA 2009), which, in 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 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.

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

[48] "Non-transportation mobile sources" are defined as any vehicle or equipment not used on the traditional road system, but excluding aircraft, rail and watercraft. This category includes snowmobiles, golf carts, riding lawn mowers, agricultural equipment, and trucks used for off-road purposes, among others.

Table A- 106 through Table A- 108 provides complete emission estimates for 1990 through 2009.

Table A- 91: Vehicle Miles Traveled for Gasoline On-Road Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles	Motorcycles
1990	1,391.2	554.3	25.4	9.6
1991	1,341.7	627.2	25.0	9.2
1992	1,354.8	682.9	24.8	9.6
1993	1,356.5	720.5	24.5	9.9
1994	1,387.5	738.8	25.0	10.2
1995	1,420.6	762.5	24.7	9.8
1996	1,454.7	788.0	24.0	9.9
1997	1,488.5	820.8	23.6	10.1
1998	1,536.6	836.8	23.6	10.3
1999	1,559.1	867.4	23.8	10.6
2000	1,591.5	886.7	23.6	10.5
2001	1,619.3	904.9	23.2	9.6
2002	1,649.2	925.8	23.1	9.6
2003	1,662.6	943.0	23.5	9.6
2004	1,690.2	984.2	23.9	10.1
2005	1,698.8	997.8	24.0	10.5
2006	1,681.0	1,037.5	24.3	12.0
2007[a]	2,092.8	561.6	33.6	21.4
2008[a]	2,013.6	579.6	34.4	20.8
2009[a]	2,004.6	591.2	32.0	20.8
2010[a]	2,014.3	595.6	31.8	18.5

Source: Derived from FHWA (1996 through 2012).

[a] In 2011, FHWA changed how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class,

Table A- 92: Vehicle Miles Traveled for Diesel On-Road Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	16.9	19.7	125.5
1991	16.3	21.6	129.3
1992	16.5	23.4	133.5
1993	17.9	24.7	140.3
1994	18.3	25.3	150.5
1995	17.3	26.9	158.7
1996	14.7	27.8	164.3
1997	13.5	29.0	173.4
1998	12.4	30.5	178.4
1999	9.4	32.6	185.3
2000	8.0	35.2	188.0
2001	8.1	37.0	191.1
2002	8.3	38.9	196.4
2003	8.3	39.7	199.1
2004	8.4	41.3	201.6
2005	8.4	41.9	201.6
2006	8.3	43.5	200.1
2007[a]	10.3	23.4	279.2
2008[a]	9.9	24.2	285.4
2009[a]	9.8	24.6	264.7
2010[a]	9.9	24.9	263.4

Source: Derived from FHWA (1996 through 2012).

[a] In 2011, FHWA changed how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class,

Table A- 93: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	0.2	0.0	0.1

1991	0.2	0.0	0.1
1992	0.3	0.0	0.1
1993	0.3	0.0	0.1
1994	0.3	0.0	0.1
1995	0.4	0.0	0.1
1996	0.5	0.0	0.1
1997	0.6	0.0	0.1
1998	0.6	0.0	0.1
1999	0.6	0.0	0.1
2000	0.8	0.0	0.1
2001	0.9	0.0	0.1
2002	1.0	0.0	0.1
2003	1.2	0.0	0.1
2004	1.3	0.0	0.1
2005	1.2	0.0	0.1
2006	1.3	0.0	0.1
2007	1.3	0.0	0.1
2008	1.3	0.0	0.1
2009	1.3	0.0	0.1
2010	1.2	0.0	0.1

Source: Derived from Browning (2003).

Table A- 94: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005[a]	2006[a]	2007[a]	2008[a]	2009[a]	2010[a]
Passenger Cars	**206.3**	**400.6**	**462.7**	**558.1**	**567.3**	**571.4**	**788.1**	**922.0**	**1,042.4**	**1,172.9**	**1,273.0**	**1,243.1**	**1,296.4**	**1,295.4**	**1,309.9**	**1,301.2**	**1,227.1**
Methanol-Flex Fuel ICE	-	40.9	36.4	33.2	26.2	23.5	13.2	10.1	7.8	6.4	3.6	0.0	0.0	0.0	0.0	0.0	0.0
Ethanol-Flex Fuel ICE	+	2.2	6.7	12.3	14.7	38.2	120.4	147.9	189.1	271.2	311.5	391.7	412.8	448.6	459.9	488.4	501.0
CNG ICE	10.6	28.0	39.6	46.3	56.7	60.4	68.9	78.1	83.0	85.0	112.1	62.6	62.5	58.4	53.0	47.3	44.5
CNG Bi-fuel	28.2	75.1	107.5	160.7	164.2	181.7	202.9	236.6	267.2	283.5	274.1	187.6	193.8	180.0	170.9	159.7	153.7
LPG ICE	20.6	40.3	43.0	45.2	52.8	37.9	41.9	45.0	48.8	43.1	37.4	40.7	37.3	24.6	25.9	14.2	11.9
LPG Bi-fuel	146.9	201.7	215.0	231.6	211.1	171.8	197.6	224.8	237.9	221.9	199.4	207.1	186.4	121.4	129.7	88.7	71.2
Biodiesel (BD20)	-	0.0	0.0	0.0	0.0	0.0	8.2	8.3	13.4	13.6	62.3	125.1	186.4	246.1	259.3	295.8	237.4
NEVs	-	5.2	6.5	13.0	18.2	28.2	62.4	88.4	98.8	114.4	124.8	104.2	99.2	99.4	99.1	97.1	97.5
Electric Vehicle	-	7.2	8.1	15.8	23.5	29.6	72.6	82.8	96.3	133.8	147.8	124.2	118.1	116.9	112.0	110.0	109.8
Light-Duty Trucks	**660.7**	**606.8**	**721.2**	**920.3**	**999.3**	**1,016.8**	**1,162.0**	**1,235.1**	**1,344.2**	**1,447.5**	**1,567.3**	**1,395.2**	**1,504.6**	**1,560.0**	**1,726.3**	**1,752.8**	**1,795.6**
Ethanol-Flex Fuel ICE	-	1.3	6.1	12.1	18.2	38.3	122.6	150.1	179.1	279.1	353.7	415.0	491.4	613.9	766.6	923.2	1,064.4
CNG ICE	10.9	29.6	42.1	107.8	130.4	143.5	145.9	145.7	153.4	158.0	162.2	65.5	65.5	64.7	63.0	58.2	55.2
CNG Bi-fuel	24.2	71.0	102.9	210.4	234.6	267.1	280.1	280.1	301.2	313.4	330.0	171.4	178.6	175.4	169.6	157.5	157.4
LPG ICE	56.9	48.5	56.5	58.2	60.3	47.8	58.4	64.4	68.2	64.9	61.5	60.1	60.1	43.8	43.8	33.0	27.6
LPG Bi-fuel	568.7	449.4	504.8	520.9	543.1	502.2	511.9	522.9	557.1	541.8	525.6	513.2	486.1	383.7	383.6	259.7	206.6
Biodiesel (BD20)	-	0.0	0.0	0.0	0.0	0.0	8.2	8.4	17.1	16.9	55.9	109.4	163.8	219.2	240.9	263.8	220.6
Electric Vehicle	-	7.1	8.9	10.9	12.7	17.9	35.0	63.4	68.2	73.4	78.3	60.1	58.4	58.0	57.5	55.8	61.9
Medium-Duty Trucks	**508.0**	**458.4**	**515.2**	**551.3**	**568.0**	**548.6**	**629.6**	**862.5**	**977.7**	**899.7**	**856.6**	**802.6**	**628.8**	**693.1**	**676.7**	**607.4**	**452.4**
CNG Bi-fuel	2.3	20.1	57.7	68.9	78.4	95.2	117.0	203.2	228.2	245.3	241.9	146.7	112.5	154.4	188.3	178.8	182.3
LPG ICE	24.3	20.0	20.0	21.1	21.2	20.7	29.7	41.9	48.3	43.9	40.7	40.5	33.8	31.3	30.9	31.0	22.4
LPG Bi-fuel	481.4	418.3	437.5	461.3	468.4	432.7	475.9	609.7	671.8	585.0	535.7	517.2	326.5	298.2	268.7	215.2	123.3
Biodiesel (BD20)	-	0.0	0.0	0.0	0.0	0.0	7.0	7.6	29.4	25.6	38.2	98.2	156.0	209.1	188.8	182.4	124.5
Heavy-Duty Trucks	**523.9**	**627.0**	**628.4**	**686.0**	**717.0**	**616.4**	**712.3**	**820.5**	**845.2**	**1,041.2**	**1,093.9**	**2,766.2**	**3,913.7**	**4,693.2**	**4,594.2**	**4,881.9**	**4,136.6**
Neat Methanol ICE	3.0	7.8	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	0.0	0.0
Neat Ethanol ICE	-	2.0	3.4	3.5	0.2	2.9	0.1	0.0	0.0	0.0	0.0	1.7	12.1	26.1	27.9	28.2	28.5
CNG ICE	12.7	32.2	34.1	44.8	56.1	54.2	83.7	149.0	146.3	183.6	187.7	408.0	491.8	557.2	761.9	843.7	883.2
LPG ICE	36.3	46.3	47.7	50.1	52.5	39.2	48.3	57.1	60.9	73.4	70.8	69.0	81.9	78.4	76.9	74.7	74.4
LPG Bi-fuel	471.9	531.9	534.9	577.4	595.1	507.1	529.7	558.0	548.5	650.2	626.7	499.2	530.0	522.5	518.1	513.4	515.2
LNG	-	6.9	8.2	10.2	13.1	13.1	22.2	26.9	28.6	56.8	108.1	1,236.1	1,210.5	1,247.0	1,266.4	1,277.2	1,330.9
Biodiesel (BD20)	-	0.0	0.0	0.0	0.0	0.0	28.3	29.5	60.9	77.1	100.6	552.2	1,587.4	2,262.1	1,942.9	2,144.7	1,304.4
Buses	**41.4**	**80.5**	**87.7**	**90.0**	**95.5**	**103.0**	**111.9**	**133.1**	**140.3**	**139.0**	**229.3**	**261.2**	**418.7**	**483.6**	**514.8**	**533.5**	**531.1**
Neat Methanol ICE	1.9	3.7	1.3	1.4	1.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Neat Ethanol ICE	0.1	2.2	7.4	1.9	0.1	0.5	0.0	0.0	0.0	0.0	0.0	0.2	1.0	2.4	3.2	3.2	3.3
CNG ICE	11.2	37.5	39.9	44.1	46.4	52.6	53.4	65.0	65.5	64.3	145.2	160.0	165.1	179.8	202.5	220.2	238.0
LPG ICE	28.2	30.9	31.4	33.4	34.0	32.6	35.6	36.9	36.4	34.1	38.9	30.3	28.9	28.9	28.7	28.4	28.4
LNG	-	4.3	5.1	6.3	10.1	11.9	13.3	21.0	22.3	23.6	25.7	38.9	41.3	46.0	50.6	50.8	55.3
Biodiesel (BD20)	-	0.0	0.0	0.0	0.0	0.0	4.5	4.7	9.9	10.5	13.1	15.6	165.1	209.1	210.9	211.8	186.1
Electric	-	2.0	2.6	2.9	3.1	3.6	5.1	5.6	6.3	6.6	6.4	16.2	17.3	17.1	18.4	18.5	19.3

Total VMT	**1,940.3**		**2,173.4**	**2,415.2**	**2,805.7**	**2,947.1**	**2,856.1**	**3,403.9**	**3,973.1**	**4,349.9**	**4,700.4**	**5,020.2**	**6,468.3**	**7,762.2**	**8,725.2**	**8,821.9**	**9,076.9**	**8,142.9**

Source: Derived from Browning (2003).

Note: Throughout the rest of this Inventory, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types.

[a] In 2011, EIA changed its reporting methodology for 2005-2010. EIA provided more detail on alternative fuel vehicle use by vehicle class. The fuel use breakdown by vehicle class had previously been based on estimates of the distribution of fuel use by vehicle class. The new data from EIA allowed actual data to be used for fuel use, and resulted in greater share of heavy-duty AFV VMT estimated for 2005-2010. The source of this data is the U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics and the DOE/GSA Federal Automotive Statistical Tool (FAST).

+ Less than 0.05 million vehicle miles traveled

- Unreported or zero

Table A- 95: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2010

Vehicle Age	LDGV	LDGT	HDGV	LDDV[b]	LDDT	HDDV	MC
0	6.2%	5.6%	5.4%	9.2%	5.8%	5.7%	8.1%
1	5.2%	3.9%	5.2%	7.7%	4.0%	5.5%	5.9%
2	5.8%	4.9%	5.7%	8.6%	5.0%	6.1%	11.2%
3	6.5%	7.3%	5.9%	9.5%	6.6%	6.4%	10.1%
4	6.6%	7.3%	5.9%	9.7%	6.3%	7.7%	9.6%
5	6.4%	7.6%	5.9%	9.4%	6.6%	7.3%	8.4%
6	6.1%	7.3%	4.6%	9.0%	9.6%	5.8%	7.1%
7	6.0%	6.8%	3.6%	8.9%	6.9%	4.4%	6.0%
8	6.2%	6.3%	3.2%	9.2%	7.3%	4.0%	5.4%
9	6.3%	6.0%	3.8%	9.2%	7.5%	4.4%	4.5%
10	6.3%	5.5%	4.1%	0.0%	6.2%	5.2%	3.6%
11	5.7%	4.7%	4.1%	0.0%	6.6%	5.4%	2.7%
12	4.9%	4.1%	3.3%	0.0%	1.6%	4.2%	2.3%
13	4.3%	3.5%	2.6%	0.0%	3.9%	3.3%	2.2%
14	3.6%	3.1%	2.6%	0.0%	2.7%	3.1%	2.0%
15	3.0%	2.6%	3.0%	0.0%	2.5%	3.4%	1.5%
16	2.5%	2.3%	3.1%	0.0%	2.1%	2.9%	1.7%
17	1.9%	1.9%	2.3%	0.0%	1.6%	2.2%	1.4%
18	1.4%	1.4%	1.7%	0.0%	1.1%	1.5%	1.2%
19	1.1%	1.2%	1.6%	0.0%	0.9%	1.4%	0.9%
20	0.9%	1.1%	2.1%	0.0%	0.8%	1.7%	0.7%
21	0.8%	1.0%	2.9%	0.0%	0.7%	1.8%	0.6%
22	0.6%	0.9%	2.7%	0.0%	0.5%	1.5%	0.5%
23	0.5%	0.8%	2.2%	0.0%	0.4%	1.2%	0.5%
24	0.4%	0.7%	2.9%	0.0%	0.6%	1.2%	0.4%
25	0.3%	0.6%	2.2%	1.2%	0.5%	0.9%	0.3%
26	0.2%	0.4%	1.3%	1.4%	0.5%	0.5%	0.3%
27	0.1%	0.3%	2.0%	1.6%	0.5%	0.5%	0.2%
28	0.1%	0.2%	1.1%	2.0%	0.4%	0.3%	0.2%
29	0.1%	0.2%	1.1%	2.0%	0.1%	0.3%	0.2%

30	0.1%	0.2%	1.7%	1.4%	0.2%	0.3%	0.3%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: EPA (2010).

[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] According to EPA's MOVES model, sales of diesel passenger cars in model years 10-24was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 96: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	14,910	19,906	20,218	14,910	26,371	28,787	4,786
1	14,174	18,707	18,935	14,174	24,137	26,304	4,475
2	13,475	17,559	17,100	13,475	22,095	24,038	4,164
3	12,810	16,462	16,611	12,810	20,228	21,968	3,853
4	12,178	15,413	15,560	12,178	18,521	20,078	3,543
5	11,577	14,411	14,576	11,577	16,960	18,351	3,232
6	11,006	13,454	13,655	11,006	15,533	16,775	2,921
7	10,463	12,541	12,793	10,463	14,227	15,334	2,611
8	9,947	11,671	11,987	9,947	13,032	14,019	2,300
9	9,456	10,843	11,231	9,456	11,939	12,817	1,989
10	8,989	10,055	10,524	8,989	10,939	11,719	1,678
11	8,546	9,306	9,863	8,546	10,024	10,716	1,368
12	8,124	8,597	9,243	8,124	9,186	9,799	1,368
13	7,723	7,925	8,662	7,723	8,420	8,962	1,368
14	7,342	7,290	8,028	7,342	7,718	8,196	1,368
15	6,980	6,690	7,610	6,980	7,075	7,497	1,368
16	6,636	6,127	7,133	6,636	6,487	6,857	1,368
17	6,308	5,598	6,687	6,308	5,948	6,273	1,368
18	5,997	5,103	6,269	5,997	5,454	5,739	1,368
19	5,701	4,642	5,877	5,701	5,002	5,250	1,368
20	5,420	4,214	5,510	5,420	4,588	4,804	1,368
21	5,152	3,818	5,166	5,152	4,209	4,396	1,368
22	4,898	3,455	4,844	4,898	3,861	4,023	1,368
23	4,656	3,123	4,542	4,656	3,542	3,681	1,368
24	4,427	2,822	4,259	4,427	3,250	3,369	1,368
25	4,427	2,822	4,259	4,427	3,250	3,369	1,368
26	4,427	2,822	4,259	4,427	3,250	3,369	1,368
27	4,427	2,822	4,259	4,427	3,250	3,369	1,368
28	4,427	2,822	4,259	4,427	3,250	3,369	1,368
29	4,427	2,822	4,259	4,427	3,250	3,369	1,368
30	4,427	2,822	4,259	4,427	3,250	3,369	1,368

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 presented in aggregate.

Table A- 97: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2010

Vehicle Age	LDGV	LDGT	HDGV	LDDV[b]	LDDT	HDDV	MC
0	9.10%	9.35%	9.84%	12.20%	10.66%	10.94%	12.84%
1	7.23%	6.14%	8.85%	9.69%	6.81%	9.72%	8.77%
2	7.68%	7.22%	8.80%	10.29%	7.81%	9.84%	15.35%
3	8.10%	9.98%	8.84%	10.85%	9.37%	9.39%	12.83%
4	7.82%	9.42%	8.27%	10.48%	8.18%	10.37%	11.18%
5	7.23%	9.18%	7.66%	9.70%	7.82%	8.99%	8.93%
6	6.60%	8.23%	5.68%	8.84%	10.41%	6.52%	6.85%
7	6.17%	7.15%	4.19%	8.27%	6.86%	4.55%	5.18%
8	6.06%	6.17%	3.46%	8.13%	6.69%	3.77%	4.07%
9	5.78%	5.42%	3.79%	7.75%	6.29%	3.77%	2.98%
10	5.56%	4.61%	3.88%	0.00%	4.76%	4.10%	2.01%
11	4.80%	3.64%	3.65%	0.00%	4.63%	3.91%	1.24%
12	3.89%	2.97%	2.78%	0.00%	1.03%	2.75%	1.06%
13	3.21%	2.30%	2.00%	0.00%	2.32%	1.96%	1.01%
14	2.62%	1.87%	1.89%	0.00%	1.43%	1.69%	0.88%
15	2.05%	1.44%	2.06%	0.00%	1.23%	1.71%	0.67%
16	1.62%	1.19%	2.01%	0.00%	0.96%	1.34%	0.77%
17	1.15%	0.87%	1.39%	0.00%	0.67%	0.91%	0.62%
18	0.82%	0.61%	0.94%	0.00%	0.42%	0.58%	0.52%
19	0.60%	0.44%	0.86%	0.00%	0.30%	0.50%	0.41%
20	0.50%	0.40%	1.04%	0.00%	0.26%	0.53%	0.34%
21	0.38%	0.32%	1.34%	0.00%	0.20%	0.54%	0.25%
22	0.30%	0.27%	1.15%	0.00%	0.13%	0.42%	0.21%
23	0.21%	0.21%	0.91%	0.00%	0.10%	0.30%	0.21%
24	0.17%	0.16%	1.10%	0.00%	0.13%	0.27%	0.17%
25	0.12%	0.14%	0.84%	0.49%	0.12%	0.20%	0.15%
26	0.08%	0.10%	0.50%	0.56%	0.11%	0.12%	0.13%
27	0.06%	0.07%	0.78%	0.61%	0.11%	0.11%	0.10%
28	0.04%	0.05%	0.43%	0.79%	0.10%	0.06%	0.07%
29	0.03%	0.04%	0.42%	0.80%	0.03%	0.06%	0.08%
30	0.03%	0.05%	0.64%	0.55%	0.04%	0.08%	0.13%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Note: Estimated by weighting data in Table A- 95 by data in Table A- 96.

[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] According to EPA's MOVES model, sales of diesel passenger cars in model years 10-24was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 98: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

Vehicle Type/Year	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aircraft[a]	**18,724**	**18,178**	**18,530**	**18,916**	**18,692**	**20,159**	**20,793**	**19,588**	**18,417**	**18,627**	**18,962**	**20,212**	**17,661**	**17,566**	**16,139**	**14,541**	**14,640**
Aviation Gasoline	374	329	311	330	295	326	302	291	281	251	260	294	278	263	235	221	230
Jet Fuel	18,349	17,848	18,220	18,586	18,396	19,833	20,491	19,298	18,136	18,376	18,702	19,918	17,383	17,303	15,903	14,320	14,410

Ships and Other Boats	**4,507**		**5,789**	**5,608**	**4,418**	**3,807**	**4,603**	**6,431**	**4,416**	**4,834**	**4,089**	**4,300**	**4,881**	**5,143**	**5,746**	**4,112**	**3,855**	**4,680**
Diesel	1,043		1,546	1,786	1,784	1,557	1,707	1,750	1,630	1,592	1,711	1,347	1,470	1,409	1,489	674	824	781
Gasoline	1,403		1,597	1,654	1,658	1,659	1,657	1,653	1,655	1,654	1,648	1,640	1,630	1,620	1,610	1,600	1,591	1,578
Residual	2,061		2,646	2,168	976	591	1,238	3,028	1,131	1,588	730	1,313	1,781	2,115	2,647	1,838	1,440	2,320
Construction/ Mining Equipment[b]	**3,842**		**4,555**	**4,693**	**4,830**	**4,969**	**5,108**	**5,248**	**5,390**	**5,534**	**5,678**	**5,820**	**5,962**	**6,104**	**6,246**	**6,390**	**6,534**	**6,679**
Diesel	3,674		4,387	4,529	4,672	4,814	4,955	5,095	5,241	5,386	5,532	5,678	5,823	5,968	6,113	6,258	6,403	6,547
Gasoline	168		168	164	158	155	153	153	150	148	146	142	139	136	133	132	132	132
Agricultural Equipment[c]	**2,383**		**2,840**	**2,931**	**3,022**	**3,113**	**3,204**	**3,295**	**3,379**	**3,463**	**3,546**	**3,629**	**3,712**	**3,794**	**3,876**	**3,958**	**4,041**	**4,123**
Diesel	2,321		2,772	2,862	2,952	3,042	3,132	3,222	3,305	3,388	3,471	3,554	3,637	3,719	3,801	3,883	3,965	4,046
Gasoline	62		68	69	70	71	72	73	73	74	75	75	75	75	76	76	76	76
Rail	**3,461**		**3,864**	**3,934**	**3,947**	**3,975**	**4,122**	**4,106**	**4,119**	**4,089**	**4,176**	**4,407**	**4,446**	**4,665**	**4,539**	**4,216**	**3,535**	**3,807**
Diesel	3,461		3,864	3,934	3,947	3,975	4,122	4,106	4,119	4,089	4,176	4,407	4,446	4,665	4,539	4,216	3,535	3,807
Other[d]	**5,916**		**6,525**	**6,598**	**6,624**	**6,710**	**6,677**	**6,826**	**7,657**	**7,840**	**8,049**	**8,263**	**8,281**	**8,396**	**8,256**	**8,387**	**8,482**	**8,830**
Diesel	1,423		1,720	1,779	1,839	1,898	1,957	2,016	2,079	2,144	2,210	2,275	2,340	2,405	2,471	2,536	2,601	2,666
Gasoline	4,493		4,805	4,819	4,785	4,812	4,720	4,810	5,578	5,696	5,840	5,988	5,941	5,991	5,785	5,851	5,881	6,164
Total	**38,833**		**41,750**	**42,295**	**41,756**	**41,266**	**43,871**	**46,698**	**44,550**	**44,176**	**44,166**	**45,381**	**47,495**	**45,763**	**46,229**	**43,202**	**40,987**	**42,759**

Sources: AAR (2008 through 2011), APTA (2007 through 2011), BEA (1991 through 2005), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2011), DESC (2011), DOE (1993 through 2011), DOT (1991 through 2011), EIA (2002), EIA (2007b), EIA (2008), EIA (2007 through 11), EIA (1991 through 2012), EPA (2007b), FAA (2012), FAA (2011), FAA (2006), Gaffney (2007), and Whorton (2006 through 2012).

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

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] “Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A- 99: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV	EPA Tier 2
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	-	-	<1%	87%	13%	-
1999	-	-	<1%	67%	33%	-
2000	-	-	-	44%	56%	-
2001	-	-	-	3%	97%	-
2002	-	-	-	1%	99%	-
2003	-	-	-	<1%	87%	13%
2004	-	-	-	<1%	41%	59%
2005	-	-	-	-	38%	62%
2006	-	-	-	-	18%	82%
2007	-	-	-	-	4%	96%
2008	-	-	-	-	2%	98%
2009	-	-	-	-	-	100%
2010	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).

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

- Not applicable.

Table A- 100: 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]	EPA Tier 2
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%	-
2003	-	-	-	<1%	53%	47%
2004	-	-	-	-	72%	28%
2005	-	-	-	-	38%	62%
2006	-	-	-	-	25%	75%
2007	-	-	-	-	14%	86%
2008	-	-	-	-	-	100%
2009	-	-	-	-	-	100%
2010	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).

[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 A- 101: 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]	EPA Tier 2
≤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%	-
2003	-	-	-	-	65%	30%	5%
2004	-	-	-	-	5%	37%	59%
2005	-	-	-	-	-	23%	77%
2006	-	-	-	-	-	20%	80%
2007	-	-	-	-	-	10%	90%
2008	-	-	-	-	-	0%	100%
2009	-	-	-	-	-	0%	100%
2010	-	-	-	-	-	0%	100%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
[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 manufacturer 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 A- 102: Control Technology Assignments for Diesel On-Road Vehicles and Motorcycles

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1960-1982
Moderate control	1983-1995
Advanced control	1996-2010
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960-1990
Moderate control	1991-2003
Advanced control	2004-2006
Aftertreatment	2007-2010
Motorcycles	
Uncontrolled	1960-1995
Non-catalyst controls	1996-2010

Source: EPA (1998) and Browning (2005)
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.

Table A- 103: Emission Factors for CH_4 and N_2O for On-Road Vehicles

Vehicle Type/Control Technology	N_2O (g/mi)	CH_4 (g/mi)
Gasoline Passenger Cars		
EPA Tier 2	0.0036	0.0173
Low Emission Vehicles	0.0150	0.0105
EPA Tier 1[a]	0.0429	0.0271
EPA Tier 0 [a]	0.0647	0.0704
Oxidation Catalyst	0.0504	0.1355
Non-Catalyst Control	0.0197	0.1696
Uncontrolled	0.0197	0.1780
Gasoline Light-Duty Trucks		
EPA Tier 2	0.0066	0.0163
Low Emission Vehicles	0.0157	0.0148

EPA Tier 1[a]	0.0871	0.0452
EPA Tier 0[a]	0.1056	0.0776
Oxidation Catalyst	0.0639	0.1516
Non-Catalyst Control	0.0218	0.1908
Uncontrolled	0.0220	0.2024
Gasoline Heavy-Duty Vehicles		
EPA Tier 2	0.0134	0.0333
Low Emission Vehicles	0.0320	0.0303
EPA Tier 1[a]	0.1750	0.0655
EPA Tier 0[a]	0.2135	0.2630
Oxidation Catalyst	0.1317	0.2356
Non-Catalyst Control	0.0473	0.4181
Uncontrolled	0.0497	0.4604
Diesel Passenger Cars		
Advanced	0.0010	0.0005
Moderate	0.0010	0.0005
Uncontrolled	0.0012	0.0006
Diesel Light-Duty Trucks		
Advanced	0.0015	0.0010
Moderate	0.0014	0.0009
Uncontrolled	0.0017	0.0011
Diesel Medium- and Heavy-Duty Trucks and Buses		
Aftertreatment	0.0048	0.0051
Advanced	0.0048	0.0051
Moderate	0.0048	0.0051
Uncontrolled	0.0048	0.0051
Motorcycles		
Non-Catalyst Control	0.0069	0.0672
Uncontrolled	0.0087	0.0899

Source: ICF (2006b and 2004).

[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.

Table A- 104: Emission Factors for CH_4 and N_2O for Alternative Fuel Vehicles (g/mi)

	N_2O	CH_4
Light Duty Vehicles		
Methanol	0.067	0.018
CNG	0.050	0.737
LPG	0.067	0.037
Ethanol	0.067	0.055
Biodiesel (BD20)	0.001	0.0005
Medium- and Heavy-Duty Trucks		
Methanol	0.175	0.066
CNG	0.175	1.966
LNG	0.175	1.966
LPG	0.175	0.066
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005
Buses		
Methanol	0.175	0.066
CNG	0.175	1.966
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005

Source: Developed by ICF (2006a) using ANL (2006) and Lipman and Delucchi (2002).

Table A- 105: Emission Factors for CH_4 and N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

Vehicle Type/Fuel Type	N_2O	CH_4
Ships and Boats		
Residual	0.16	0.03
Gasoline	0.08	0.23
Diesel	0.14	0.02
Rail		
Diesel	0.08	0.25
Agricultural Equipment[a]		
Gasoline	0.08	0.45
Diesel	0.08	0.45
Construction/Mining Equipment[c]		
Gasoline	0.08	0.18
Diesel	0.08	0.18
Other Non-Road		
All “Other” Categories[c]	0.08	0.18
Aircraft		
Jet Fuel	0.10	0.087
Aviation Gasoline	0.04	2.64

Source: IPCC/UNEP/OECD/IEA (1997) and ICF (2009).

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] “Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A- 106: NO_x Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010[e]
Gasoline On-Road	**5,746**	**4,560**	**4,322**	**4,268**	**4,090**	**3,924**	**3,812**	**3,715**	**3,761**	**3,541**	**3,322**	**3,102**	**2,897**	**2,693**	**2,488**	**2,212**	**2,212**
Passenger Cars	3,847	2,752	2,533	2,447	2,316	2,158	2,084	2,027	2,052	1,932	1,812	1,692	1,581	1,469	1,357	1,207	1,207
Light-Duty Trucks	1,364	1,325	1,318	1,334	1,294	1,267	1,303	1,285	1,301	1,225	1,149	1,073	1,002	931	860	765	765
Medium- and Heavy-Duty Trucks and Buses	515	469	459	475	467	485	411	390	395	372	349	326	304	283	261	232	232
Motorcycles	20	14	13	13	13	13	13	14	14	13	12	11	11	10	9	8	8
Diesel On-Road	**2,956**	**3,493**	**3,600**	**3,708**	**3,729**	**3,671**	**3,803**	**3,338**	**3,379**	**3,182**	**2,984**	**2,787**	**2,603**	**2,419**	**2,235**	**1,987**	**1,987**
Passenger Cars	39	19	15	13	11	10	7	6	6	6	5	5	5	4	4	3	3
Light-Duty Trucks	20	12	11	10	9	8	6	5	6	5	5	5	4	4	4	3	3
Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,575	3,685	3,709	3,653	3,791	3,326	3,367	3,171	2,974	2,778	2,594	2,411	2,228	1,981	1,981
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,483**	**2,553**	**2,552**	**2,565**	**2,588**	**2,584**	**2,643**	**2,879**	**2,960**	**3,041**	**3,122**	**2,988**	**2,853**	**2,718**	**2,007**	**2,007**
Ships and Boats	402	488	507	483	469	428	506	544	595	612	629	646	618	590	562	415	415
Rail	338	433	455	457	469	444	451	485	531	546	561	576	551	527	502	371	371
Aircraft[b]	25	31	32	36	40	41	40	39	43	44	45	47	45	43	41	30	30
Agricultural Equipment[c]	437	478	486	487	487	497	484	480	521	535	550	565	540	516	491	363	363
Construction/Mining Equipment[d]	641	697	708	707	705	765	697	690	748	769	790	811	776	741	706	521	521
Other[e]	318	357	364	382	394	413	407	406	441	453	465	478	457	437	416	307	307
Total	**10,862**	**10,536**	**10,475**	**10,528**	**10,384**	**10,182**	**10,199**	**9,696**	**10,019**	**9,683**	**9,347**	**9,012**	**8,488**	**7,965**	**7,441**	**6,206**	**6,206**

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

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

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

[e] Criteria Air Pollutant emissions for 2010 were unavailable. Values from 2009 are used as proxy estimates.

Note: Totals may not sum due to independent rounding.

IE = Included Elsewhere

Table A- 107: CO Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010[e]
Gasoline On-Road	**98,328**	**74,673**	**69,941**	**67,509**	**65,245**	**61,210**	**60,657**	**56,716**	**54,143**	**50,554**	**46,965**	**43,374**	**40,492**	**37,610**	**34,727**	**34,199**	**34,199**
Passenger Cars	60,757	42,065	38,327	36,825	35,686	32,921	32,867	31,600	30,166	28,166	26,166	24,166	22,560	20,954	19,348	19,054	19,054
Light-Duty Trucks	29,237	27,048	26,610	25,748	24,754	23,343	24,532	22,574	21,550	20,121	18,693	17,264	16,117	14,969	13,822	13,612	13,612
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	4,867	4,787	4,642	4,782	3,104	2,411	2,302	2,149	1,997	1,844	1,721	1,599	1,476	1,454	1,454
Motorcycles	240	155	138	150	163	164	154	131	125	117	109	100	94	87	80	79	79
Diesel On-Road	**1,696**	**1,424**	**1,370**	**1,301**	**1,202**	**1,122**	**1,088**	**869**	**830**	**775**	**720**	**665**	**621**	**576**	**532**	**524**	**524**
Passenger Cars	35	18	15	13	10	10	7	6	6	5	5	4	4	4	4	4	4
Light-Duty Trucks	22	16	14	13	12	9	6	5	5	5	4	4	4	3	3	3	3
Medium- and Heavy-	1,639	1,391	1,341	1,276	1,179	1,103	1,075	858	819	765	711	656	613	569	525	517	517

Duty Trucks and Buses																	
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,533**	**21,971**	**21,351**	**21,375**	**21,050**	**21,814**	**22,266**	**20,448**	**19,850**	**19,252**	**18,652**	**17,859**	**17,067**	**16,274**	**8,633**	**8,633**
Ships and Boats	1,559	1,781	1,825	1,828	1,828	2,019	1,825	1,832	1,682	1,633	1,584	1,534	1,469	1,404	1,339	710	710
Rail	85	93	94	89	83	98	90	90	82	80	78	75	72	69	66	35	35
Aircraft[b]	217	224	225	250	274	285	245	233	214	208	202	196	187	179	171	91	91
Agricultural Equipment[c]	581	628	638	636	633	630	626	621	570	554	537	520	498	476	454	241	241
Construction/Mining Equipment[d]	1,090	1,132	1,140	1,097	1,081	1,074	1,047	1,041	956	928	900	872	835	798	761	404	404
Other[e]	15,805	17,676	18,049	17,452	17,476	16,943	17,981	18,449	16,943	16,447	15,951	15,455	14,798	14,141	13,484	7,153	7,153
Total	**119,360**	**97,630**	**93,283**	**90,161**	**87,822**	**83,382**	**83,559**	**79,852**	**75,421**	**71,178**	**66,936**	**62,692**	**58,972**	**55,253**	**51,533**	**43,355**	**43,355**

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

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

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

[e] Criteria Air Pollutant emissions for 2010 were unavailable. Values from 2009 are used as proxy estimates.

IE = Included Elsewhere

Table A-108: NMVOCs Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010[e]**
Gasoline On-Road	**8,110**	**5,819**	**5,361**	**5,167**	**5,066**	**4,924**	**4,615**	**4,285**	**4,255**	**4,023**	**3,791**	**3,558**	**3,358**	**3,158**	**2,958**	**2,878**	**2,878**
Passenger Cars	5,120	3,394	3,049	2,928	2,894	2,811	2,610	2,393	2,376	2,247	2,117	1,987	1,875	1,764	1,652	1,607	1,607
Light-Duty Trucks	2,374	2,019	1,947	1,881	1,812	1,734	1,750	1,664	1,652	1,562	1,472	1,382	1,304	1,226	1,149	1,118	1,118
Medium- and Heavy-Duty Trucks and Buses	575	382	343	336	335	351	232	206	205	193	182	171	162	152	142	138	138
Motorcycles	42	24	21	22	25	28	23	22	22	21	19	18	17	16	15	15	15
Diesel On-Road	**406**	**304**	**283**	**263**	**249**	**230**	**216**	**207**	**206**	**195**	**183**	**172**	**163**	**153**	**143**	**139**	**139**
Passenger Cars	16	8	7	6	5	5	3	3	3	3	3	3	2	2	2	2	2
Light-Duty Trucks	14	9	9	8	7	6	4	4	4	3	3	3	3	3	3	2	2
Medium- and Heavy-Duty Trucks and Buses	377	286	268	249	237	219	209	201	199	188	178	167	157	148	139	135	135
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,622**	**2,663**	**2,497**	**2,425**	**2,432**	**2,399**	**2,379**	**2,773**	**2,716**	**2,658**	**2,600**	**2,516**	**2,430**	**2,346**	**1,134**	**1,134**
Ships and Boats	608	739	765	765	762	769	744	730	851	833	816	798	772	746	720	348	348
Rail	33	36	37	35	33	38	35	35	41	40	39	39	37	36	35	17	17
Aircraft[b]	28	28	28	32	35	38	24	19	22	22	21	21	20	20	19	9	9

Agricultural Equipment[c]	85	86	86	83	81	81	76	72	84	83	81	79	77	74	71	35	35
Construction/Mining Equipment[d]	149	152	153	142	137	141	130	125	146	143	140	137	132	128	123	60	60
Other[e]	1,512	1,580	1,593	1,440	1,377	1,366	1,390	1,397	1,629	1,595	1,561	1,527	1,477	1,427	1,378	666	666
Total	**10,932**	**8,745**	**8,306**	**7,926**	**7,740**	**7,586**	**7,229**	**6,871**	**7,234**	**6,934**	**6,633**	**6,330**	**6,037**	**5,742**	**5,447**	**4,151**	**4,151**

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

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

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] “Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

[e] Criteria Air Pollutants emissions for 2010 were unavailable. Values from 2009 are used as proxy estimates.

Note: Totals may not sum due to independent rounding.

IE = Included Elsewhere

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 A- 99 through Table A- 102 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 passenger cars and light-duty trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to have no 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 respectively amounted to a 60 and 40 percent reduction 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.

EPA Tier 2

This emission standard was specified in the 1990 amendments to the Clean Air Act, limiting passenger car NO_x emissions to 0.07 g/mi on average and aligning emissions standards for passenger cars and light-duty trucks. Manufacturers can meet this average emission level by producing vehicles in 11 emission “Bins”, the three highest of which expire in 2006. These new emission levels represent a 77 to 95% reduction in emissions from the EPA Tier 1 standard set in 1994. Emission reductions were met through the use of more advanced emission control systems and lower sulfur fuels and are applied to vehicles beginning in 2004. These advanced emission control systems include improved combustion, 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 2006.

Aftertreatment

Use of diesel particulate filters (DPFs), oxidation catalysts and NOx absorbers or selective catalytic reduction (SCR) systems are designated as aftertreatment control. These technologies provide diesel vehicles with a level of emission control necessary to comply with standards in place from 2007 on.

Supplemental Information on GHG Emissions from Transportation and Other Mobile Sources

This section of this Annex includes supplemental information on the contribution of transportation and other mobile sources to U.S. greenhouse gas emissions. In the main body of the Inventory report, emission estimates are generally presented by greenhouse gas, with separate discussions of the methodologies used to estimate CO_2, N_2O, CH_4, and HFC emissions. 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 emission sources. The purpose of this sub-annex, within the annex that details the calculation methods and data used for non- CO_2 calculations, is to provide all transportation estimates presented throughout the repot in one place.

This section of this Annex reports total greenhouse gas emissions from transportation and other (non-transportation) mobile sources in CO_2 equivalents, with information on the contribution by greenhouse gas and by mode, vehicle type, and fuel type. In order to calculate these figures, additional analyses were conducted to develop estimates of CO_2 from non-transportation mobile sources (e.g., agricultural equipment, construction/mining equipment, recreational vehicles), and to provide more detailed breakdowns of emissions by source.

Estimation of CO_2 from Non-Transportation Mobile Sources

The estimates of N_2O and CH_4 from fuel combustion presented in the Energy chapter of the inventory include both transportation sources and other mobile sources. Other mobile sources include construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources that have utility associated with their movement but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, riding lawnmowers, etc.). Estimates of CO_2 from non-transportation mobile sources, based on EIA fuel consumption estimates, are included in the agricultural, industrial, and commercial sectors. In order to provide comparable information on transportation and mobile sources,

Table A- 109 provides estimates of CO_2 from these other mobile sources, developed from EPA's NONROAD model and FHWA's *Highway Statistics*. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the N_2O and CH_4 estimates.

Table A- 109: CO_2 Emissions from Non-Transportation Mobile Sources (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Agricultural Equipment[a]	31.0	36.6	37.4	38.9	39.2	38.3	38.8	41.0	42.1	43.1	46.1	46.8	49.0	48.4	45.4	46.7	47.6
Construction/Mining Equipment[b]	42.0	48.9	50.4	52.0	52.8	53.7	55.3	59.5	61.2	63.0	64.9	65.9	67.3	67.8	69.3	70.6	73.0
Other Sources[c]	54.5	59.8	60.6	60.9	61.7	61.4	62.8	70.2	72.0	73.9	76.0	76.2	77.6	76.7	77.7	78.6	81.8
Total	**127.6**	**145.4**	**148.4**	**151.8**	**153.7**	**153.4**	**156.9**	**170.7**	**175.3**	**180.0**	**187.0**	**188.9**	**193.9**	**193.0**	**192.4**	**195.9**	**202.4**

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Estimation of HFC Emissions from Transportation Sources

In addition to CO_2, N_2O and CH_4 emissions, transportation sources also result in emissions of HFCs. HFCs are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events. There are three categories of transportation-related HFC emissions; Mobile AC represents the emissions from air conditioning units in passenger cars and light-duty trucks, Comfort Cooling represents the emissions from air conditioning units in passenger trains and buses, and Refrigerated Transport represents the emissions from units used to cool freight during transportation.

Table A- 110 below presents these HFC emissions. Table A- 111 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A- 110: HFC Emissions from Transportation Sources

Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Mobile AC	-	**59.4**	**58.3**	**54.7**	**50.7**	**45.9**	**59.4**	**58.3**	**54.7**	**50.7**	**45.9**	**59.4**	**58.3**	**54.7**	**50.7**	**45.9**	**44.1**
Passenger Cars	-	28.4	27.1	24.6	22.1	19.3	28.4	27.1	24.6	22.1	19.3	28.4	27.1	24.6	22.1	19.3	18.6
Light-Duty Trucks	-	31.0	31.2	30.1	28.6	26.6	31.0	31.2	30.1	28.6	26.6	31.0	31.2	30.1	28.6	26.6	25.4
Comfort Cooling for Trains and Buses	-	**0.2**	**0.3**	**0.3**	**0.4**	**0.4**	**0.2**	**0.3**	**0.3**	**0.4**	**0.4**	**0.2**	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**
School and Tour Buses	-	0.2	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.4
Transit Buses	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Rail	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	-	**13.2**	**13.6**	**13.8**	**13.8**	**13.9**	**13.2**	**13.6**	**13.8**	**13.8**	**13.9**	**13.2**	**13.6**	**13.8**	**13.8**	**13.9**	**13.9**
Medium- and Heavy-Duty Trucks	-	11.1	11.4	11.5	11.6	11.6	11.1	11.4	11.5	11.6	11.6	11.1	11.4	11.5	11.6	11.6	11.6
Rail	-	2.1	2.2	2.2	2.2	2.2	2.1	2.2	2.2	2.2	2.2	2.1	2.2	2.2	2.2	2.2	2.3
Ships and Other Boats	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Total	-	**72.9**	**72.2**	**68.8**	**64.9**	**60.2**	**72.9**	**72.2**	**68.8**	**64.9**	**60.2**	**72.9**	**72.2**	**68.8**	**64.9**	**60.2**	**58.4**

Note: Totals may not sum due to independent rounding.

+ Less than 0.05 Tg CO_2 Eq.

- Unreported or zero

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type

Table A- 111 presents estimates of greenhouse gas emissions from an expanded analysis including all transportation and additional mobile sources, as well as emissions from electricity generation by the consuming category, in CO_2 equivalents. In total, transportation and non-transportation mobile sources emitted 2,042.9 Tg CO_2 Eq. in 2010, an increase of 22 percent from 1990. Transportation sources account for 1,838 Tg CO_2 Eq. while non-transportation mobile sources account for 204.3 Tg CO_2 Eq. These estimates include HFC emissions for mobile AC, comfort cooling for trains and buses, and refrigerated transport. These estimates were generated using the estimates of CO_2 emissions from transportation sources reported in the Carbon Dioxide Emissions from Fossil Fuel Combustion section, and CH_4 emissions and N_2O emissions reported in the Mobile Combustion section of the Energy chapter; information on HFCs from mobile air conditioners, comfort cooling for trains and buses, and refrigerated transportation from Chapter 4; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A- 107 above.

Although all emissions reported here are based on estimates reported throughout this inventory, some additional calculations were performed in order to provide a detailed breakdown of emissions by mode and vehicle category. 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., medium- and 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) by the portion of fuel used by each aircraft type (from FAA 2012, 2011, and 2006). Similarly, N_2O and CH_4 estimates were developed for medium- and heavy-duty trucks and buses by multiplying the emission estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from the Mobile Combustion section in the Energy chapter, by the portion of fuel used by each vehicle type (from DOE 1993 through 2011). 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).

Transportation sources include on-road vehicles, aircraft, boats and ships, rail, and pipelines (note: pipelines are a transportation source but are stationary, not mobile sources). In addition, transportation-related greenhouse gas emissions also include HFC released from mobile air conditioners and refrigerated transportation, and the release of CO_2 from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,838.6 Tg CO_2 Eq. in 2010.

On-road vehicles were responsible for about 76 percent of all transportation and non-transportation mobile GHG emissions in 2010. Although passenger cars make up the largest component of on-road vehicle greenhouse gas emissions, light-duty and medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Between 1990 and 2010, greenhouse gas emissions from passenger cars increased by 20 percent, while emissions from light-duty trucks decreased 3 percent[49]. Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks increased 74 percent, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 21 percent between 1990 and 2010. Emissions from military aircraft decreased 64 percent and commercial aircraft emissions rose 2 percent between 1990 and 2007 then dropped 17 percent from 2007 to 2010.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 204.3Tg CO_2 Eq. in 2010. Together, these sources emitted more greenhouse gases than ships and boats, rail, and pipelines combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 59 percent between 1990 and 2010. CH_4 and N_2O emissions from these sources are included in the "Mobile Combustion" section and CO_2 emissions are included in the relevant economic sectors.

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[49] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A- 112 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, CO_2 accounts for the vast majority of transportation greenhouse gas emissions (approximately 96 percent in 2010). Emissions of CO_2 from transportation and mobile sources increased by 333.5 Tg CO_2 Eq. between 1990 and 2010. In contrast, the combined emissions of CH_4 and N_2O decreased by 26.1 Tg CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[50] Meanwhile, HFC emissions from mobile air conditioners and refrigerated transport increased from virtually no emissions in 1990 to 58.4 Tg CO_2 Eq. in 2010 as these chemicals were phased in as substitutes for ozone depleting substances. It should be noted, however, that the ozone depleting substances that HFCs replaced are also powerful greenhouse gases, but are not included in national greenhouse gas inventories due to their mandated phase out.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A- 113 and Table A- 114present greenhouse gas estimates from transportation, broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general aviation and commercial aircraft), recreational boats, and mobile air conditioners, and are illustrated in Table A- 113. Freight modes include medium- and heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, pipelines, and commercial aircraft and are illustrated in Table A- 114. Commercial aircraft do carry some freight, in addition to passengers, and for this Inventory, the emissions have been split between passenger and freight transportation. (In previous Inventories, all commercial aircraft emissions were considered passenger transportation.) The amount of commercial aircraft emissions to allocate to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned. Each passenger was considered to weigh an average of 150 pounds, with a luggage weight of 50 pounds. The total freight weight and total passenger weight carried were used to determine percent shares which were used to split the total commercial aircraft emissions estimates. The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction/mining and agricultural equipment, lubricants).

The estimates in these tables are derived from the estimates presented in Table A- 111. In addition, estimates of fuel consumption from DOE (1993 through 2010) were used to allocate rail emissions between passenger and freight categories.

In 2010, passenger transportation modes emitted 1,292.3 Tg CO_2 Eq., while freight transportation modes emitted 524.0Tg CO_2 Eq. Between 1990 and 2010, the percentage growth of greenhouse gas emissions from freight sources was 47 percent, while emissions from passenger sources grew by 13 percent. This difference is in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

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[50] The decline in CFC emissions is not captured in the official transportation estimates.

Table A- 111: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (Tg CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Percent Change 1990-2010
Transportation Total[a]	**1,548.3**	**1698.5**	**1746.3**	**1776.0**	**1813.4**	**1883.1**	**1935.8**	**1915.0**	**1948.6**	**1949.7**	**1993.8**	**2022.3**	**1999.1**	**2007.6**	**1894.6**	**1823.9**	**1838.6**	**19%**
On-Road Vehicles	**1,235.2**	**1,371.3**	**1,415.2**	**1,452.4**	**1,503.0**	**1,559.8**	**1,575.1**	**1,585.7**	**1,624.5**	**1,637.1**	**1,673.6**	**1,683.0**	**1,679.8**	**1,680.9**	**1,603.0**	**1,558.4**	**1556.8**	**26%**
Passenger Cars	**657.4**	**646.0**	**657.8**	**660.8**	**682.6**	**697.3**	**695.3**	**701.2**	**714.9**	**693.6**	**691.0**	**709.6**	**682.9**	**847.4**	**807.0**	**798.7**	**787.9**	**20%**
Gasoline	649.4	627.9	636.9	636.7	656.8	670.7	667.3	671.6	683.9	661.3	658.0	676.9	651.6	818.6	781.2	775.7	765.5	18%
Diesel	7.9	7.9	6.7	6.1	5.6	4.4	3.7	3.7	3.7	4.2	4.3	4.2	4.1	4.1	3.7	3.6	3.7	-53%
AFVs	+	0.1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	295%
HFCs from Mobile AC	+	10.1	14.1	18.1	20.2	22.2	24.3	25.9	27.2	28.0	28.7	28.4	27.1	24.6	22.1	19.3	18.6	NA
Light-Duty Trucks	**336.6**	**436.6**	**455.2**	**473.7**	**487.8**	**509.9**	**512.1**	**518.6**	**529.8**	**565.2**	**588.1**	**551.3**	**564.0**	**366.4**	**347.0**	**349.5**	**346.4**	**3%**
Gasoline	324.5	414.6	429.2	443.7	453.8	471.4	469.8	473.2	481.4	509.7	528.9	493.0	504.7	321.7	304.3	309.5	307.1	-5%
Diesel	11.5	14.9	15.7	16.3	17.3	19.0	20.1	20.8	21.9	27.2	29.0	25.9	26.8	13.6	12.1	12.1	12.6	9%
AFVs	0.6	0.5	0.5	0.5	0.6	0.5	0.5	0.6	0.7	0.7	0.9	1.3	1.2	1.0	1.8	1.2	1.3	117%
HFCs from Mobile AC	+	6.5	9.8	13.3	16.2	19.0	21.7	24.0	25.8	27.5	29.4	31.0	31.2	30.1	28.6	26.6	25.4	NA
Medium- and Heavy-Duty Trucks	**231.1**	**277.8**	**290.8**	**306.2**	**320.6**	**339.2**	**354.6**	**353.8**	**368.1**	**365.9**	**377.7**	**408.5**	**418.7**	**444.7**	**427.1**	**389.3**	**402.3**	**74%**
Gasoline	39.5	36.8	36.0	35.3	35.9	36.3	37.0	36.1	36.5	31.6	31.9	35.8	36.3	47.6	48.1	44.3	44.1	12%
Diesel	190.7	238.6	251.4	266.2	278.8	296.0	309.9	309.3	322.6	323.8	334.7	361.0	370.3	385.0	366.5	332.6	345.7	81%
AFVs	0.9	0.6	0.6	0.5	0.6	0.5	0.3	0.4	0.4	0.4	0.4	0.7	0.7	0.6	0.9	0.8	0.8	-9%
HFCs from Refrigerated Transport	+	1.7	2.9	4.1	5.3	6.4	7.4	8.1	8.7	10.0	10.7	11.1	11.4	11.5	11.6	11.6	11.6	NA
Buses	**8.4**	**9.2**	**9.6**	**9.9**	**10.2**	**11.4**	**11.2**	**10.3**	**10.0**	**10.8**	**15.1**	**12.0**	**12.3**	**18.0**	**17.5**	**16.6**	**16.5**	**97%**
Gasoline	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.5	0.4	0.4	0.8	0.8	0.8	0.8	115%
Diesel	8.0	8.7	9.1	9.2	9.5	10.6	10.2	9.3	8.8	9.6	13.5	10.6	10.8	15.9	15.2	14.1	14.0	75%
AFVs	+	0.1	0.1	0.2	0.3	0.3	0.5	0.5	0.6	0.7	0.9	0.9	0.9	1.0	1.1	1.3	1.3	48890%
HFCs from Comfort Cooling	+	+	+	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	NA
Motorcycles	**1.8**	**1.8**	**1.8**	**1.8**	**1.9**	**1.9**	**1.9**	**1.7**	**1.7**	**1.7**	**1.8**	**1.7**	**1.9**	**4.3**	**4.5**	**4.3**	**3.8**	**115%**
Gasoline	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.7	1.7	1.7	1.8	1.7	1.9	4.3	4.5	4.3	3.8	115%
Aircraft	**181.2**	**175.4**	**182.1**	**185.9**	**183.7**	**198.1**	**204.4**	**192.5**	**181.0**	**183.1**	**186.4**	**198.7**	**173.6**	**172.6**	**158.6**	**142.9**	**143.9**	**-21%**
General Aviation Aircraft	**136.8**	**8.2**	**8.6**	**9.1**	**10.5**	**12.3**	**12.1**	**11.5**	**11.6**	**11.3**	**14.3**	**17.5**	**18.5**	**16.9**	**18.8**	**16.1**	**16.1**	**67%**
Jet Fuel	6.4	5.4	6.0	6.3	8.0	9.5	9.6	9.0	9.2	9.2	12.1	15.0	16.2	14.6	16.8	14.3	14.1	119%
Aviation Gasoline	3.2	2.8	2.6	2.8	2.5	2.8	2.6	2.5	2.4	2.1	2.2	2.5	2.4	2.2	2.0	1.9	2.0	-38%
Commercial Aircraft	**136.8**	**143.1**	**150.0**	**155.3**	**151.3**	**164.8**	**170.9**	**157.8**	**148.6**	**150.9**	**150.6**	**162.8**	**138.5**	**139.5**	**123.4**	**112.5**	**115.2**	**-16%**
Jet Fuel	136.8	143.1	150.0	155.3	151.3	164.8	170.9	157.8	148.6	150.9	150.6	162.8	138.5	139.5	123.4	112.5	115.2	-16%
Military Aircraft	**34.8**	**24.1**	**23.5**	**21.4**	**21.9**	**21.0**	**21.3**	**23.2**	**20.8**	**20.9**	**21.5**	**18.3**	**16.5**	**16.3**	**16.4**	**14.3**	**12.6**	**-64%**
Jet Fuel	34.8	24.1	23.5	21.4	21.9	21.0	21.3	23.2	20.8	20.9	21.5	18.3	16.5	16.3	16.4	14.3	12.6	-64%
Ships and Boats[b]	**45.1**	**58.6**	**54.4**	**39.8**	**33.7**	**29.8**	**61.0**	**42.7**	**47.6**	**37.3**	**40.1**	**45.2**	**48.4**	**55.2**	**37.1**	**34.0**	**43.3**	**-4%**
Gasoline	12.6	14.1	12.9	11.9	12.5	+	10.0	14.6	14.6	14.4	14.4	14.2	14.1	14.0	13.6	13.5	13.2	5%
Distillate Fuel	9.6	14.9	17.4	17.4	15.1	16.7	17.1	15.8	15.4	15.3	11.5	11.4	10.9	11.7	3.2	4.8	4.3	-55%
Residual Fuel	22.9	29.5	24.0	10.4	6.0	13.4	33.8	12.2	17.4	7.6	14.2	19.6	23.4	29.5	20.2	15.7	25.7	12%

HFCs from Refrigerated Transport	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.2	+	+	+	+	+	+	+	+	NA
Rail	**39.0**	**43.7**	**44.7**	**45.3**	**45.8**	**47.7**	**48.1**	**48.6**	**48.2**	**49.5**	**52.3**	**53.0**	**55.1**	**54.4**	**50.7**	**43.4**	**46.3**	**19%**
Distillate Fuel	35.8	40.0	40.7	40.9	41.1	42.7	42.5	42.6	42.3	43.2	45.6	46.0	48.3	47.0	43.6	36.6	39.4	10%
Electricity	3.1	3.1	3.1	3.1	3.2	3.2	3.5	3.7	3.5	4.3	4.6	4.8	4.6	5.1	4.7	4.5	4.5	48%
Other Emissions from Rail Electricity Use	0.1	0.1	0.1	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-8%
HFCs from Comfort Cooling	+	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	0.0	0.0	0.0	NA
HFCs from Refrigerated Transport	+	0.5	0.9	1.3	1.5	1.8	2.0	2.2	2.4	1.9	2.1	2.1	2.2	2.2	2.2	2.2	2.3	NA
Pipelines[c]	**36.0**	**38.2**	**38.9**	**41.2**	**35.0**	**35.5**	**35.2**	**34.4**	**36.4**	**32.5**	**31.1**	**32.2**	**32.3**	**34.2**	**35.6**	**36.6**	**38.8**	**8%**
Natural Gas	36.0	38.2	38.9	41.2	35.0	35.5	35.2	34.4	36.4	32.5	31.1	32.2	32.3	34.2	35.6	36.6	38.8	8%
Other Transportation	**11.8**	**11.3**	**11.0**	**11.6**	**12.1**	**12.2**	**12.1**	**11.1**	**10.9**	**10.1**	**10.2**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**9.5**	**-20%**
Lubricants	11.8	11.3	11.0	11.6	12.1	12.2	12.1	11.1	10.9	10.1	10.2	10.2	9.9	10.2	9.5	8.5	9.5	-20%
Non-Transportation Mobile Total	**128.8**	**146.8**	**149.8**	**153.2**	**155.2**	**154.9**	**158.3**	**172.3**	**177.0**	**181.7**	**188.7**	**190.7**	**195.8**	**194.8**	**194.2**	**197.7**	**204.3**	**59%**
Agricultural Equipment[d]	**31.4**	**37.0**	**37.8**	**39.4**	**39.6**	**38.7**	**39.2**	**41.4**	**42.5**	**43.6**	**46.6**	**47.3**	**49.6**	**49.0**	**45.9**	**47.2**	**48.2**	**53%**
Gasoline	7.3	8.3	8.2	8.8	8.1	6.2	5.8	7.1	7.4	7.6	9.8	9.6	11.0	9.6	5.7	6.1	6.2	-15%
Diesel	24.1	28.7	29.7	30.6	31.5	32.5	33.4	34.3	35.1	36.0	36.8	37.7	38.6	39.4	40.3	41.1	41.9	74%
Construction/ Mining Equipment[e]	**42.4**	**49.4**	**50.9**	**52.4**	**53.3**	**54.2**	**55.8**	**60.1**	**61.8**	**63.6**	**65.4**	**66.5**	**67.9**	**68.4**	**69.9**	**71.2**	**73.6**	**74%**
Gasoline	4.4	4.0	4.0	4.1	3.5	2.9	3.1	5.8	6.1	6.4	6.7	6.2	6.2	5.1	5.2	5.0	5.9	34%
Diesel	38.0	45.4	46.9	48.3	49.8	51.3	52.7	54.2	55.7	57.2	58.8	60.3	61.8	63.3	64.8	66.3	67.8	78%
Other Equipment[f]	**55.0**	**60.4**	**61.1**	**61.4**	**62.3**	**62.0**	**63.4**	**70.9**	**72.7**	**74.5**	**76.7**	**76.9**	**78.3**	**77.4**	**78.4**	**79.3**	**82.5**	**50%**
Gasoline	40.3	42.6	42.7	42.4	42.6	41.7	42.5	49.3	50.5	51.7	53.1	52.7	53.4	51.8	52.2	52.4	54.9	36%
Diesel	14.7	17.8	18.4	19.0	19.6	20.3	20.9	21.5	22.2	22.9	23.5	24.2	24.9	25.6	26.2	26.9	27.6	87%
Transportation and Non-Transportation Mobile Total	**1,677.1**	**1845.3**	**1896.1**	**1929.2**	**1968.6**	**2038.0**	**2094.1**	**2087.3**	**2125.6**	**2131.4**	**2182.5**	**2213.0**	**2194.9**	**2202.3**	**2088.8**	**2021.6**	**2042.9**	**22%**

[a] Not including emissions from international bunker fuels.

[b] Fluctuations in emission estimates reflect data collection problems.

[c] Includes only CO_2 from natural gas used to power pipelines; does not include emissions from electricity use or non-CO_2 gases.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

\+ Less than 0.05 Tg CO_2 Eq.

\- Unreported or zero

NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Table A- 112: Transportation and Mobile Source Emissions by Gas (Tg CO_2 Eq.)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Percent Change 1990-2010
CO2	1,628.4	1,767.9	1,809.5	1,833.1	1,866.2	1,930.6	1,981.9	1,973.0	2,011.9	2,018.0	2,068.6	2,100.4	2,086.5	2,102.1	1,996.5	1,936.8	1,961.9	19%
N2O	43.9	54.0	54.7	55.3	55.2	54.1	53.2	50.3	46.3	42.8	40.1	37.0	33.7	29.0	25.2	22.5	20.6	-49%
CH4	4.7	4.3	4.1	4.0	3.8	3.5	3.4	3.3	2.9	2.7	2.6	2.5	2.4	2.2	2.1	2.0	1.9	-58%
HFC	+	19.0	27.8	36.8	43.4	49.7	55.7	60.5	64.5	67.7	71.1	72.9	72.2	68.8	64.9	60.2	58.4	NA
Total	**1,677.0**	**1,845.2**	**1,896.1**	**1,929.2**	**1,968.5**	**2,037.9**	**2,094.1**	**2,087.2**	**2,125.6**	**2,131.3**	**2,182.4**	**2,212.9**	**2,194.8**	**2,202.2**	**2,088.7**	**2,021.5**	**2,042.8**	**21%**

- Unreported or zero
NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2009 (Tg CO_2 Eq.)

Table A- 113: Greenhouse Gas Emissions from Passenger Transportation (Tg CO_2 Eq.)

Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Percent Change 1990-2010
On-Road Vehicles	**1,004.1**	**1,093.5**	**1,124.4**	**1,146.2**	**1,182.4**	**1,220.5**	**1,220.5**	**1,231.8**	**1,256.3**	**1,271.2**	**1,296.0**	**1,274.5**	**1,261.1**	**1,236.1**	**1,175.9**	**1,169.1**	**1,154.6**	**15%**
Passenger Cars	657.4	646.0	657.8	660.8	682.6	697.3	695.3	701.2	714.9	693.6	691.0	709.6	682.9	847.4	807.0	798.7	787.9	20%
Light-Duty Trucks	336.6	436.6	455.2	473.7	487.8	509.9	512.1	518.6	529.8	565.2	588.1	551.3	564.0	366.4	347.0	349.5	346.4	3%
Buses	8.4	9.2	9.6	9.9	10.2	11.4	11.2	10.3	10.0	10.8	15.1	12.0	12.3	18.0	17.5	16.6	16.5	97%
Motorcycles	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.7	1.7	1.7	1.8	1.7	1.9	4.3	4.5	4.3	3.8	115%
Aircraft	**122.7**	**126.5**	**132.6**	**137.6**	**135.6**	**148.6**	**153.4**	**142.0**	**134.5**	**136.1**	**139.6**	**154.4**	**135.3**	**136.0**	**124.9**	**113.0**	**114.8**	**-6%**
General Aviation	9.6	8.2	8.6	9.1	10.5	12.3	12.1	11.5	11.6	11.3	14.3	17.5	18.5	16.9	18.8	16.1	16.1	67%
Commercial Aircraft	113.1	118.3	124.0	128.4	125.1	136.3	141.3	130.5	122.9	124.8	125.3	136.8	116.7	119.2	106.1	96.9	98.8	-13%
Recreational Boats	**14.5**	**16.4**	**15.3**	**14.4**	**15.0**	**2.2**	**12.7**	**17.4**	**17.4**	**17.4**	**17.4**	**17.4**	**17.3**	**17.3**	**14.5**	**16.9**	**16.8**	**16%**
Passenger Rail	**4.4**	**4.5**	**4.4**	**4.6**	**4.7**	**4.8**	**5.2**	**5.4**	**5.1**	**5.8**	**6.0**	**6.2**	**6.0**	**6.6**	**6.3**	**6.2**	**6.2**	**42%**
Total	**1,145.7**	**1,241.0**	**1,276.8**	**1,302.7**	**1,337.8**	**1,376.2**	**1,391.8**	**1,396.6**	**1,413.4**	**1,430.6**	**1,459.0**	**1,452.5**	**1,419.7**	**1,396.1**	**1,321.7**	**1,305.3**	**1,292.3**	**13%**

Note: Data from DOE (1993 through 2011) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

Table A- 114: Greenhouse Gas Emissions from Domestic Freight Transportation (Tg CO_2 Eq.)

By Mode	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Percent Change 1990-2009
Trucking	231.1	277.8	290.8	306.2	320.6	339.2	354.6	353.8	368.1	365.9	377.7	408.5	418.7	444.7	427.1	389.3	402.2	74%
Freight Rail	34.5	39.1	40.2	40.7	41.1	42.9	42.8	43.1	43.1	43.7	46.2	46.7	49.0	47.8	44.4	37.2	40.0	16%

Ships and Other Boats	30.6		42.2	39.0	25.4	18.6	27.5	48.3	25.4	30.1	19.9	22.7	27.9	31.1	37.9	22.6	17.0	26.5	-13%
Pipelines	36.0		38.2	38.9	41.2	35.0	35.5	35.2	34.4	36.4	32.5	31.1	32.2	32.3	34.2	35.6	36.6	38.8	8%
Commercial Aircraft	23.7		24.8	26.0	26.9	26.2	28.5	29.6	27.3	25.7	26.1	25.3	26.0	21.8	20.3	17.3	15.6	16.4	-31%
Total	**356.0**		**422.1**	**435.0**	**440.3**	**441.6**	**473.7**	**510.5**	**484.0**	**503.5**	**488.1**	**502.9**	**541.3**	**552.9**	**584.9**	**546.9**	**495.7**	**524.0**	**47%**

Note: Data from DOE (1993 through 2011) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

3.3. Methodology for Estimating CH_4 Emissions from Coal Mining

The methodology for estimating CH_4 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 CH_4 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 CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and from degasification systems. Some mines recover and use CH_4 generated from degasification systems, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

All coal mines with detectable CH_4 emissions[51] use ventilation systems to ensure that CH_4 levels remain within safe concentrations. Many coal mines do not have detectable levels of CH_4, 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 CH_4 emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of CH_4 in their ventilation air. Based on the four quarterly measurements, MSHA estimates average daily CH_4 liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996, 1998 through 2006, 2008 through 2010, 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 A- 115. Well over 90 percent of all ventilation emissions were concentrated in these subsets. For 1997 and 2007, the complete MSHA databases for all 586 mines (in 1997) and 730 mines (in 2007) with detectable CH_4 emissions were obtained. These mines were assumed to account for 100 percent of CH_4 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 A- 115). The proportion was then applied to the years 1990 through 2006 to account for the less than 5 percent of ventilation emissions coming from mines without MSHA data.

For 1990 through 1999, average daily CH_4 emissions were multiplied by the number of days in the year (i.e., coal mine assumed in operation for all four quarters) to determine the annual emissions for each mine. For 2000 through 2010, MSHA provided quarterly emissions. The average daily CH_4 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 CH_4 emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

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[51] 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 A-115: 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)*
2003	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2004	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2005	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2006	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2007	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)
2008	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2009	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2010	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**

* Factor derived from a complete set of individual mine data collected for 1997.
** Factor derived from a complete set of individual mine data collected for 2007.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Coal mines use several different types of degasification systems to remove CH_4, including vertical wells and horizontal boreholes to recover CH_4 prior to mining of the coal seam. Gob wells and cross-measure boreholes recover CH_4 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 CH_4 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 CH_4 liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell CH_4 recovered from degasification systems to a pipeline, gas sales were used to estimate CH_4 liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell CH_4 to a pipeline and have not provided information to EPA, CH_4 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 CH_4 liberated from the mine.

Step 1.3: Estimate CH_4 Recovered from Degasification Systems and Utilized (Emissions Avoided)

In 2010, fifteen active coal mines had CH_4 recovery and use projects. Fourteen mines sold the recovered CH_4 to a pipeline, one used the CH_4 on site to heat mine ventilation air, and one of the coal mines used CH_4 to generate electricity. One of the mines that sold gas to a pipeline also used CH_4 to fuel a thermal coal dryer. 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 CH_4 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 at 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 CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were not available for estimating CH_4 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 CH_4 emissions.

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

The first step in estimating CH_4 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 A- 116, which presents coal basin definitions by basin and by state.

The Energy Information Administration's (EIA) Annual Coal Report includes 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 A- 116. . 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 A- 117 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* CH_4 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* CH_4 content in the basin. For this analysis, the surface mining emission factor was determined to be twice the *in situ* CH_4 content in the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* CH_4 content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* CH_4 content in the basin. Table A- 118 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate CH_4 Emitted

The total amount of CH_4 emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual CH_4 emissions are equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions. Table A- 119 and Table A- 120 present estimates of CH_4 liberated, used, and emitted for 1990 through 2010. Table A- 121 provides emissions by state.

Table A- 116: 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 A- 117: Annual Coal Production (Thousand Short Tons)

Basin	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Underground Coal Production	**423,556**	**396,249**	**372,766**	**380,627**	**357,384**	**352,785**	**367,558**	**368,611**	**359,020**	**351,791**	**357,074**	**332,061**	**337,155**
N. Appalachia	103,865	98,103	105,374	107,025	98,643	98,369	106,915	111,151	107,827	106,024	105,228	99,629	103,109
Cent. Appalachia	198,412	166,495	150,584	152,457	137,224	130,724	128,559	123,083	117,738	110,103	114,998	98,689	96,354
Warrior	17,531	17,605	15,895	15,172	14,916	15,375	16,114	13,295	10,737	11,462	12,281	11,505	12,513
Illinois	69,167	69,009	53,720	54,364	54,016	51,780	56,320	59,180	61,726	61,924	64,609	67,186	72,178
S. West/Rockies	32,754	42,994	45,742	51,193	52,121	56,111	59,039	60,865	59,670	58,815	55,781	50,416	44,368
N. Great Plains	1,722	2,018	1,210	0	0	32	201	572	840	2,869	3,669	4,248	8,208
West Interior	105	25	241	416	464	394	410	465	482	594	508	388	425
Northwest	0	0	0	0	0	0	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**636,726**	**700,608**	**745,306**	**735,912**	**717,869**	**743,553**	**762,191**	**802,975**	**793,689**	**813,321**	**740,175**	**764,709**
N. Appalachia	60,761	39,372	34,908	35,334	30,088	27,370	28,174	28,873	28,376	26,121	30,413	26,552	26,082
Cent. Appalachia	94,343	106,250	110,479	116,983	111,340	99,419	103,968	112,222	118,388	116,226	118,962	97,778	89,788
Warrior	11,413	7,036	4,252	4,796	6,320	8,437	9,742	11,599	11,889	11,410	11,172	10,731	11,406
Illinois	72,000	40,376	33,631	40,894	39,380	36,675	34,016	33,702	33,362	33,736	34,266	34,837	32,911
S. West/Rockies	43,863	46,643	49,587	52,180	50,006	41,237	42,558	42,756	36,798	34,310	34,283	32,167	48,240
N. Great Plains	249,356	331,367	407,670	438,367	441,346	444,007	466,224	474,056	518,136	523,695	538,387	496,290	507,995
West Interior	64,310	59,116	54,170	50,613	50,459	53,411	51,706	52,263	52,021	46,867	44,361	39,960	46,136
Northwest	6,707	6,566	5,911	6,138	6,973	7,313	7,165	6,720	4,005	1,324	1,477	1,860	2,151
Total Coal Production	**1,026,309**	**1,032,975**	**1,073,374**	**1,125,933**	**1,093,296**	**1,070,654**	**1,111,111**	**1,130,802**	**1,161,995**	**1,145,478**	**1,170,395**	**1,072,236**	**1,101,864**
N. Appalachia	164,626	137,475	140,282	142,360	128,731	125,739	135,089	140,024	136,203	132,143	135,641	126,181	129,191
Cent. Appalachia	292,755	272,745	261,063	269,440	248,564	230,143	232,527	235,305	236,126	226,328	233,960	196,467	186,142
Warrior	28,944	24,641	20,147	19,967	21,236	23,812	25,856	24,894	22,626	22,872	23,453	22,236	23,919
Illinois	141,167	109,385	87,351	95,258	93,396	88,455	90,336	92,882	95,088	95,660	98,875	102,023	105,089
S. West/Rockies	76,617	89,637	95,329	103,373	102,127	97,348	101,597	103,621	96,468	93,125	90,064	82,583	92,608
N. Great Plains	251,078	333,385	408,880	438,367	441,346	444,039	466,425	474,628	518,976	526,564	542,056	500,538	516,203
West Interior	64,415	59,141	54,411	51,028	50,923	53,805	52,116	52,728	52,503	47,462	44,869	40,348	46,561
Northwest	6,707	6,566	5,911	6,138	6,973	7,313	7,165	6,720	4,005	1,324	1,477	1,860	2,151

Source for 1990-2009 data: EIA (1990 through 2009), Annual Coal Report. U.S. Department of Energy, Washington, DC, Table 1. Source for 2010 data: spreadsheet for the 2010 Annual Coal Report.
Note: Totals may not sum due to independent rounding.

Table A- 118: Coal Surface and Post-Mining CH_4 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 (Uinta 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 (WY, MT)	20.0	15.8	40.0	6.5	5.1
N. Great Plains (ND)	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)	11.0	127.9	22.0	3.6	41.6
Northwest (AK)	16.0	160.0	32.0	1.8	52.0
Northwest (WA)	16.0	47.3	32.0	5.2	15.4

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*, 1983 U.S. DOE Report (DOE/METC/83-76), *Methane Recovery from Coalbeds: A Potential Energy Source*, 1986-88 Gas Research Institute Topical Reports, A Geologic Assessment of Natural Gas from Coal Seams; *Surface Mines Emissions Assessment*, U.S. EPA Draft Report, November 2005.

Table A- 119: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Ventilation Output	112	100	90	96	94	92	87	84	79	76	83	75	79	81	100	114	117
Adjustment Factor for Mine Data*	97.8%	91.4%	91.4%	100.0%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	100.0%	99.0%	99.0%	99%
Adjusted Ventilation Output	114	109	99	96	96	94	89	86	80	77	84	77	80	81	101	115	118
Degasification System Liberated	54	36	52	43	49	40	45	49	51	50	45	48	54	45	49	49	58
Total Underground Liberated	168	146	150	139	146	134	134	135	131	127	130	124	134	126	150	163	177
Recovered & Used	(14)	(30)	(37)	(28)	(35)	(31)	(37)	(41)	(43)	(38)	(40)	(38)	(46)	(38)	(40)	(41)	(49)
Total	**154**	**116**	**113**	**111**	**110**	**103**	**98**	**95**	**88**	**89**	**90**	**86**	**88**	**88**	**109**	**123**	**128**

* Refer to Table A- 115.

Note: Totals may not sum due to independent rounding.

Table A- 120: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Underground Mining	154	150	145	120	117	116	113	111	110	103	98	95	88	89	90	86	88	88	109	123	128
Surface Mining	30	28	28	28	29	28	29	30	31	31	30	33	32	31	32	33	35	34	35	32	33
Post-Mining (Underground)	19	18	18	16	17	17	18	18	18	17	17	17	16	16	16	16	15	15	15	14	14
Post-Mining (Surface)	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	5	5
Total	**208**	**201**	**195**	**167**	**168**	**166**	**165**	**164**	**165**	**156**	**149**	**149**	**140**	**141**	**144**	**140**	**144**	**143**	**165**	**173**	**180**

Note: Totals may not sum due to independent rounding.

Table A- 121: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Alabama	32,272	33,735	29,556	26,426	26,440	25,702	23,342	21,896	18,686	19,288	18,246	15,638	14,425	17,059	20,573	21,834	21,130
Alaska	63	63	55	54	50	58	61	56	43	40	56	54	53	49	55	69	80
Arizona	192	203	177	199	192	200	223	228	217	205	216	205	139	135	136	127	132
Arkansas	7	5	4	3	4	4	2	2	2	1	1	1	4	144	237	119	130
California	1	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-	-
Colorado	10,325	7,582	5,972	9,189	9,181	9,390	10,808	11,117	12,082	13,216	12,582	13,608	13,102	13,180	12,998	14,100	16,554
Illinois	10,502	11,563	10,876	8,534	7,847	7,810	8,542	7,270	5,972	4,744	5,798	6,586	6,954	4,493	7,759	7,322	8,707
Indiana	2,795	2,025	2,192	2,742	2,878	2,650	2,231	3,373	3,496	3,821	3,531	3,702	4,029	4,347	5,452	6,155	6,293
Iowa	30	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-	-
Kansas	57	23	19	29	27	33	16	14	16	12	6	14	34	33	18	15	11
Kentucky	10,956	10,269	8,987	10,451	10,005	9,561	9,105	9,363	8,464	8,028	7,926	7,494	9,135	9,278	10,641	12,617	12,847
Louisiana	81	95	82	91	82	76	94	95	97	103	97	106	105	80	98	94	101

Maryland	519	237	259	267	251	225	331	340	401	391	411	421	435	261	325	273	294
Mississippi	-	-	-	-	0	1	57	43	165	264	256	254	271	253	203	246	286
Missouri	211	44	57	32	30	31	35	29	20	43	46	48	31	19	20	36	37
Montana	1,749	1,834	1,756	1,906	1,992	1,911	1,783	1,820	1,738	1,719	1,853	1,870	1,931	2,016	2,076	1,804	1,898
Mew Mexico	451	586	408	459	489	497	464	630	1,280	1,864	2,052	3,001	2,970	2,660	3,479	3,904	4,014
North Dakota	380	392	389	385	389	405	407	397	401	401	390	390	396	385	386	390	377
Ohio	5,065	4,189	4,068	4,349	4,350	3,914	3,519	3,619	2,831	2,649	3,183	3,385	3,413	2,672	3,959	4,746	3,889
Oklahoma	285	323	286	385	395	469	454	620	660	620	849	877	658	774	970	646	459
Pennsylvania	22,735	25,611	26,440	30,026	30,888	24,867	24,830	22,252	19,668	20,281	20,020	18,289	18,727	19,519	21,044	23,216	23,697
Tennessee	296	112	143	148	116	119	99	142	142	124	136	140	117	120	105	84	82
Texas	1,426	1,347	1,411	1,364	1,345	1,357	1,240	1,152	1,157	1,215	1,173	1,175	1,165	1,073	998	898	1,048
Utah	3,587	2,570	2,810	3,566	3,859	3,633	2,816	2,080	2,709	3,408	5,253	4,787	5,445	3,678	5,524	5,449	6,348
Virginia	46,137	20,059	19,771	16,851	13,978	13,321	12,065	11,506	11,227	11,906	11,389	8,790	9,830	10,118	9,334	8,144	9,163
Washington	186	181	170	167	173	153	159	172	217	232	210	196	96	+	-	-	-
West Virginia	49,039	30,552	36,384	33,554	35,566	33,599	30,563	33,985	31,405	28,474	29,465	30,612	29,510	29,654	37,406	41,241	41,525
Wyoming	8,496	12,185	12,838	12,994	14,549	15,607	15,725	17,147	17,352	17,497	18,435	18,784	20,752	20,974	21,601	19,903	20,419
Total	**207,844**	**165,785**	**165,109**	**164,171**	**165,075**	**155,568**	**149,371**	**149,348**	**140,449**	**140,544**	**143,581**	**140,424**	**143,729**	**142,976**	**165,397**	**175,430**	**179,520**

- Zero Cubic Feet

+ 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.

3.4. Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems

The following steps were used to estimate CH_4 and non-energy CO_2 emissions from natural gas systems.

Step 1: Select Emissions Factors/Calculate Emission Estimates for Base Year 1992 Using EPA Adjusted GRI/EPA Study

The first step in estimating CH_4 and non-energy related (i.e., fugitive, vented and flared) CO_2 emissions from natural gas systems was to select emission factors. The key source of these factors is a study by EPA/GRI (1996) which 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. Each emission factor was determined by EPA/GRI (1996) and was assumed to be representative of emissions from each source type over the period 1990 through 2010; others have been updated, as noted below.

Table A-122 through Table A-125 display the 2010 activity data, CH_4 emission factors, and CH_4 emissions for each stage.

Several emission factors have been updated since publication of the EPA/GRI 1996 study and these updated factors were included in the Inventory, beginning with the 1990 through 2009 report. Notably, emission factors for gas wells with liquids unloading (EPA 2006a, HPDI 2009), condensate storage tanks (EPA 1999, HPDI 2009, TERC 2009), and centrifugal compressors (EPA 2006b, WGC 2009) were revised.

Emissions factors for gas well completions and workovers (re-completions) with hydraulic fracturing (previously referred to as unconventional), which were not included in the EPA/GRI study, were also included, beginning with the 1990 through 2009 Inventory, using the factor presented in the Subpart W Technical Support Document, and adjusting for CH_4 content of gas in each Oil and Gas Supply Module National Energy Modeling System (OGSM/NEMS) region. The emission factor used to estimate emissions from gas well completions with hydraulic fracturing was developed using four industry data sets, together representing data from over 1,000 well completions with hydraulic fracturing. This data was determined to be appropriate for developing this emission factor, in order to estimate potential emissions from an uncontrolled hydraulically fractured gas well completion and recompletion. It is important to note that in calculating total emissions from completions with hydraulic fracturing, calculated CH_4 release was adjusted for CH_4 that is actually not emitted (i.e., that is instead flared or controlled with certain technologies and practices), see Step 4 below. Each emission factor used in the U.S. Inventory was assumed to be representative of emissions from each source type over the period 1990 through 2010. Therefore, the same emission factors are used for each year throughout this period after adjusting for changes in the CH_4 content. To adjust emission factors for CH_4 content of gas, GTI's Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used. Methane compositions from GTI 2001 are adjusted year to year using gross production by the NEMS regions from the oil and gas supply module from the EIA. Therefore, emission factors may vary from year to year due to slight changes in the CH_4 composition for each NEMS oil and gas supply module region. Table A-133 shows the CO_2 content for the different well types in the production sector of the natural gas system.

In the case of non-energy CO_2 emissions from flared sources, acid gas removal units and condensate tanks, specific industry data related to those sources was used to derive their respective emission factors. For flared sources in onshore and offshore production, an emission factor was taken from EIA's 1996 Greenhouse Gas Inventory. For acid gas removal units, the emission factor is assumed to be the average CO_2 content in the processed gas less the average CO_2 content for pipeline quality gas. For condensate tanks, a CO_2 emission factor was determined using several runs from API's E&P Tank simulator over varying API gravities.

The activity data and CH_4 emission factors are displayed in Table A-120, arranged into regions designated by the Energy Information Administration's (EIA) OGSM/NEMS plus Gulf of Mexico and Pacific Offshore platforms. The OGSM/NEMS splits the continental United States into 6 regions: Northeast (NE), Midcontinent (MC), Rocky Mountain (RM), South West (SW), West Coast (WC), and Gulf Coast (GC). GRI, however, does not evaluate activity data for each of these regions separately. The GRI national activity data (AF) estimates were allocated to the OGSM/NEMS regions using the OGSM/NEMS regional gas well counts to national well count ratios.

Step 2: Collect Activity data and Aggregate Statistics on Main Driver Variables

For most emissions sources, the GRI Study provides activity data or activity data drivers used to calculate emissions. Since publication of the GRI Study, activity data for some of the components in the system have been updated based on publicly available data. For other sources where annual activity data are not available, a set of industry activity data drivers was developed that can be used to update activity data

As detailed data on each of the over 100 sources were not available for each year for the period 1990 through 2010, activity data for some sources were estimated using aggregate statistics on key drivers, including: number of producing wells (EIA 2010a-b, New Mexico 2010a-b, Texas 2010a-b), number of gas plants (AGA 1991-1997; OGJ 1998-2010), number of shallow and deep offshore platforms (BOEMRE 2010a-d), miles of transmission pipeline (OPS 2010a), miles of distribution pipeline (OPS 2010b), miles of distribution services (OPS 2010b), and energy consumption (EIA 2010c). Table A-126 provides the activity data of some of the key drivers in the natural gas analysis.

Below information on three activity data categories with recently updated data sources is provided. As discussed in the main Inventory text, documentation of activity data and emissions factors will be improved in future Inventory reports.

Data on existing gas wells with hydraulic fracturing was taken from state websites. Fractured gas well populations are not published by all states; therefore the methodology is dependent on the best available fractured gas well data provided by states. For those EIA OGSM/NEMS regions that did not have state published fractured gas well data, the fractured gas well population was assumed to be negligible.

Gas well completions with hydraulic fracturing was estimated for each OGSM/NEMS region by taking the difference between the current year's fractured gas well count and the previous year's fractured gas well count. The total gas well completions with hydraulic fracturing in the United States. is the sum of the gas well completions with hydraulic fracturing in each OGSM/NEMS region.

The Inventory calculates the number of gas well workovers with hydraulic fracturing (i.e., re-fractured wells) using an assumption from Advanced Resources International (ARI) obtained from an expert gas drilling, fracturing, and production opinion cited in publically available studies[52] that wells are worked over on average every 10 years (i.e., 10% of the total fractured gas well count is the number of gas well workovers with hydraulic fractured in a given year).

The activity data for centrifugal compressors were also revised in the 1990 through 2009 Inventory report. Publically available industry data on centrifugal compressors[53] shows that vendors of compressors report that in 2003, 90 percent of new compressors sold were equipped with dry seals. Given that 90 percent of new centrifugal compressors since 2003 are equipped with dry seals, and that there were 0 dry seal compressors in 1992, a straight-line estimate of the percentage of new compressors that were equipped with dry seals was interpolated, based on pipeline mileage.

Step 3: Estimate CH_4 Each Year and Stage

Total potential CH_4 from each stage of the natural gas industry is estimated by multiplying the activity data by the appropriate emission factors, and summing all sources for each stage. This value is then adjusted for CH_4 that is not emitted due to voluntary CH_4 reductions, and CH_4 reductions resulting from regulations such as National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations (see Step 4 below).

Step 4: Account for CH_4 Not Emitted due to Voluntary or Regulatory Methane Controls

Voluntary reductions. Industry partners report CH_4 emission reductions by project to the Natural Gas STAR Program. The reductions from the implementation of specific technologies (e.g., plunger lifts, reduced emission completions, and vapor recovery units) are calculated by the reporting partners using actual measurement data or equipment-specific emission factors. The reductions undergo quality assurance and quality control checks to identify errors, inconsistencies, or irregular data before being incorporated into the Inventory. The Natural Gas STAR reported reductions are adjusted to remove a sunsetting time period which is relevant to Natural Gas STAR accounting but not the Inventory. For example, replacing a gas-assisted pump with an electric pump permanently reduces the vented methane emissions from that source, even after the Natural Gas STAR sunsetting period. CH_4 emission reductions from the Natural Gas STAR Program beyond the efforts reflected in the 1992 base year are summarized in Table A-127.

Federal regulations. The 1990 Clean Air Act (CAA) sets the limits on the amount of hazardous air pollutants (HAPs) that can be emitted in the United States. The NESHAP regulations set the standards to limit emissions of HAPs. The emission sources are required to use the Maximum Achievable Control Technology, giving the operators flexibility to

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[52] ARI/ICF (2008) *Greenhouse Gas Life-Cycle Emissions Study: Fuel Life-Cycle of U.S. Natural Gas Supplies and International LNG*. Prepared for Sempra LNG. <http://www.adv-res.com/pdf/ARI_LCA_NOV_10_08.pdf>

[53] EPA. *Methane Savings from Compressors*. Oklahoma City, OK. May 14, 2009. <http://epa.gov/gasstar/documents/workshops/okcity2009/icf_compressors.pdf>.

choose the type of control measure(s) to implement. In regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also reduced.

The NESHAP regulation requires that glycol dehydration unit vents and storage tanks that have HAP emissions and exceed a gas throughput and liquids throughput value, respectively, be connected to a closed loop emission control system that reduces emissions by 95 percent. Also, gas processing plants exceeding the threshold natural gas throughput limit are required to routinely implement Leak Detection and Survey (LDAR) programs. The emissions reductions achieved as a result of NESHAP regulations were calculated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation. The reductions are representative of the control measures in both the oil and natural gas industry. CH_4 emission reductions from regulations, such as NESHAP, are summarized in Table A-128.

State Regulations. Additionally, some states, such as Wyoming, require that natural gas produced during hydraulically fractured well completions be controlled and not vented. In these states, emissions from natural gas well completions and re-completions are either recovered for sale or flared. To calculate the extent of reductions from state regulations, the number of gas wells with hydraulic fracturing was obtained from the 1990 through 2008 Inventory report, as reported by the state websites. The data showed that approximately 51 percent of hydraulically fractured wells from these states are in Wyoming, a state with known regulations on venting. It was therefore assumed in this analysis that 51 percent of well completions are regulated and are required to be controlled, beyond the voluntary reductions accounted for by Natural Gas STAR. Natural Gas STAR Partners do not report reductions when they are required due to regulation. Therefore, the Inventory assumes there is no overlap between the reductions reported through Natural Gas STAR and reductions due to state regulations. Due to lack of publicly available data, 51 percent of hydraulically fractured gas well completion and workover emissions are assumed to be flared across the 1990 through 2010 time series even though it is likely that some fraction of these required reductions are recovered for sale. As noted in the Planned Improvements text of the main Inventory document, additional data on this source of emissions reductions will be evaluated.

Reductions for 1990 through 1992. The base year of the emissions estimates for Natural Gas Systems is 1992; therefore any reductions reported for 1992 or earlier are considered to be already included in the base-year emission factors and are not subtracted from the inventory estimate. If the reported reduction occurred between 1990 and 1992, then the reduction is added back into the estimate for the appropriate year(s).

Step 5: Calculated net CH_4 Emissions

The reductions described above in Step 4 are summed and deducted from the potential CH_4 emissions calculated in Step 3. These net emissions are reported in the Natural Gas Systems inventory text.

Step 6: Estimate CO_2 Emissions for Each Year and Stage

The same procedure for estimating CH_4 emissions holds true for estimating non-energy related CO_2 emissions, except the emission estimates are not corrected for reductions due to the Natural Gas STAR program or other regulations.

Produced natural gas is composed of primarily CH_4, but as shown in Table A-133, the natural gas contains, in some cases, as much as 8 percent CO_2. The same vented and fugitive natural gas that led to CH_4 emissions also contains a certain volume of CO_2. Accordingly, the CO_2 emissions for each sector can be estimated using the same activity data for these vented and fugitive sources, with emission factors derived from methane emission factors and the CO_2 and CH_4 content of gas.

The three exceptions to this methodology are CO_2 emissions from flares, acid gas removal units, and condensate tanks. In the case of flare emissions, a direct CO_2 emission factor from EIA (1996) was used. This emission factor was applied to the portion of offshore gas that is not vented and all of the gas reported as vented and flared onshore by EIA. The amount of CO_2 emissions from an acid gas unit in a processing plant is equal to the difference in CO_2 concentrations between produced natural gas and pipeline quality gas applied to the throughput of the plant. This methodology was applied to the national gas throughput using national average CO_2 concentrations in produced gas (3.45 percent) and transmission quality gas (1 percent). Data was unavailable to use annual values for CO_2 concentration. For condensate tanks, a series of E&P Tank (EPA 1999) simulations provide the total CO_2 vented per barrel of condensate throughput from fixed roof tank flash gas for condensate gravities of API 45 degree and higher. The ratios of emissions to throughput were used to estimate the CO_2 emission factor for condensate passing through fixed roof tanks. The detailed source emission estimates for CH_4 and CO_2 from the production sector are presented in Table A-129 and Table A-134, respectively.

In the processing sector, the CO_2 content of the natural gas remains the same as the CO_2 content in the production sector for the equipment upstream of the acid gas removal unit because produced natural gas is usually only minimally treated after being produced and then transported to natural gas processing plants via gathering pipelines. The CO_2 content in gas for the remaining equipment that is downstream of the acid gas removal is the same as in pipeline quality gas. The EPA/GRI study estimates the average CH_4 content of natural gas in the processing sector to be 87 percent CH_4. Consequently, the processing sector CO_2 emission factors were developed using CH_4 emission factors, proportioned to reflect the CO_2 content of either produced natural gas or pipeline quality gas using the same methodology as the production sector. The detailed source emission estimates for CH_4 and CO_2 from the processing sector are presented in Table A-130 and Table A-135, respectively.

For the transmission sector, CO_2 content in natural gas transmission pipelines was estimated for the top twenty transmission pipeline companies in the United States (separate analyses identified the top twenty companies based on gas throughput and total pipeline miles). The weighted average CO_2 content in the transmission pipeline quality gas in both cases—total gas throughput and total miles of pipeline—was estimated to be about 1 percent. To estimate the CO_2 emissions for the transmission sector the CH_4 emission factors were proportioned from the 93.4 percent CH_4 reported in EPA/GRI (1996) to reflect the 1 percent CO_2 content found in transmission quality natural gas. The detailed source emissions estimates for CH_4 and CO_2 for the transmission sector are presented in Table A-131 and Table A-136, respectively.

The natural gas in the distribution sector of the system has the same characteristics as the natural gas in the transmission sector. The CH_4 content (93.4 percent) and CO_2 content (1 percent) are identical due to the absence of any further treatment between sector boundaries. Thus, the CH_4 emissions factors were converted to CO_2 emission factors using the same methodology as discussed for the transmission sector. The detailed source emission estimates for CH_4 and CO_2 for the distribution sector are presented in Table A-132 and Table A-137, respectively.

Because Partners report only CH_4 emission reductions to the Natural Gas STAR Program, there was no need to adjust for the Natural Gas STAR program in the CO_2 emissions estimates for any of the sectors in the natural gas system. The impact of regulations, such as NESHAP, on CO_2 emission reductions are not currently addressed in the CO_2 emission estimates.

Table A-122: 2010 Data and CH_4 Emissions (Mg) for the Natural Gas Production Stage

	2010 EPA Inventory Values		
Activity	**Activity Data**	**Emission Factor**	**Emissions (Mg)[3]**
North East			
Gas Wells			
NE - Associated Gas Wells[1,2]	47,933 wells	NA	NA
NE - Non-associated Gas Wells (less wells with hydraulic fracturing)	188,696 wells	7.55 scfd/well	10,020.34
NE - Gas Wells with Hydraulic Fracturing	0 wells	7.59 scfd/well	0.00
Field Separation Equipment			
Heaters	377 heaters	15.17 scfd/heater	40.25
Separators	133,974 separators	0.96 scfd/sep	903.37
Dehydrators	1,204 dehydrators	23.21 scfd/dehy	196.51
Meters/Piping	9,465 meters	9.62 scfd/meter	639.97
Gathering Compressors			
Small Reciprocating Compressors	189 compressors	285.79 scfd/comp	379.10
Large Reciprocating Compressors	24 compressors	16,229 scfd/comp	2,738.18
Large Reciprocating Stations	3 stations	8,802.14 scfd/station	185.63
Pipeline Leaks	89,845 miles	56.73 scfd/mile	35,832.26
Drilling and Well Completion			
Gas Well Completions without Hydraulic Fracturing[3]	273 completions/yr	779 scf/comp	4.10
Gas Well Completions with Hydraulic Fracturing	0 completions/yr	7,694,435 scf/comp	0.00
Well Drilling	8,159 Wells	2,714 scf/well	426.54
Normal Operations			
Pneumatic Device Vents	91,706 controllers	368 scfd/device	237,400.49
Chemical Injection Pumps	943 active pumps	265 scfd/pump	1,755.69
Kimray Pumps	352,471 MMscf/yr	1,059 scf/MMscf	7,187.95
Dehydrator Vents	395,590 MMscf/yr	294.2 scf/MMscf	2,241.27
Condensate Tank Vents			
Condensate Tanks without Control Devices	0.5 MMbbl/yr	21.87 scf/bbl	210.61
Condensate Tanks with Control Devices	0.5 MMbbl/yr	4.37 scf/bbl	42.12

	2010 EPA Inventory Values		
Activity	**Activity Data**	**Emission Factor**	**Emissions (Mg)[3]**
Compressor Exhaust Vented			
Gas Engines	0 MMHPhr	0.26 scf/HPhr	0.00
Well Workovers			
Gas Wells without hydraulic fracturing	8,208 workovers/yr	2,607 scf/w.o.	412.19
Gas Wells with Hydraulic Fracturing	0 workovers/yr	7,694,435 scf/w.o.	0.00
Gas wells with liquids unloading	77,931 LU Gas Wells	1,359,535 scfy/LU well	2,040,606.81
Blowdowns			
Vessel BD	135,556 vessels	83 scfy/vessel	217.36
Pipeline BD	89,845 miles (gathering)	330 scfy/mile	570.72
Compressor BD	189 compressors	4,028 scfy/comp	14.64
Compressor Starts	189 compressors	9,012 scfy/comp	32.75
Upsets			
Pressure Relief Valves	361,956 PRV	36 scfy/PRV	252.99
Mishaps	22,461 miles	714 scf/mile	308.91
Midcontinent			
Gas Wells			
MC - Associated Gas Wells[1,2]	73,885 wells	NA	NA
MC - Non-associated Gas Wells (less wells with hydraulic fracturing)	76,093 wells	7.46 scfd/well	3,989.79
MC - Gas Wells with Hydraulic Fracturing	13,277 wells	8.35 scfd/well	779.56
Field Separation Equipment			
Heaters	36,284 heaters	14.92 scfd/heater	3,804.90
Separators	38,876 separators	0.94 scfd/sep	257.74
Dehydrators	13,098 dehydrators	95.64 scfd/dehy	8,806.17
Meters/Piping	121,945 meters	9.46 scfd/meter	8,106.82
Gathering Compressors			
Small Reciprocating Compressors	10,099 compressors	280.99 scfd/comp	19,948.89
Large Reciprocating Compressors	16 compressors	15,957 scfd/comp	1,794.83
Large Reciprocating Stations	2 stations	8,654.47 scfd/station	121.68
Pipeline Leaks	69,776 miles	55.78 scfd/mile	27,361.42
Drilling and Well Completion			
Gas Well Completions without Hydraulic Fracturing	130 completions/yr	769 scf/comp	1.92
Gas Well Completions with Hydraulic Fracturing	575 completions/yr	7,672,247 scf/comp	84,966.30
Well Drilling	3,864 wells	2,669 scf/well	198.63
Normal Operations			
Pneumatic Device Vents	138,614 controllers	362 scfd/device	352,809.85
Chemical Injection Pumps	12,691 active pumps	260 scfd/pump	23,219.34
Kimray Pumps	3,833,795 MMscf/yr	1,041 scf/MMscf	76,871.18
Dehydrator Vents	4,302,800 MMscf/yr	289.2 scf/MMscf	23,969.19
Condensate Tank Vents			
Condensate Tanks without Control Devices	13 MMbbl/yr	302.75 scf/bbl	75,803.69
Condensate Tanks with Control Devices	13 MMbbl/yr	60.55 scf/bbl	15,160.74
Compressor Exhaust Vented			
Gas Engines	16,711 MMHPhr	0.25 scf/HPhr	81,067.89
Well Workovers			
Gas Wells without Hydraulic Fracturing	3,888 workovers/yr	2,574 scf/w.o.	192.78
Gas Wells with Hydraulic Fracturing	1,328 workovers/yr	7,672,247 scf/w.o.	196,190.87
Gas wells with liquids unloading	31,427 LU Gas Wells	703,273 scfy/LU well	425,674.63
Blowdowns			
Vessel BD	88,259 vessels	82 scfy/vessel	139.15
Pipeline BD	69,776 miles (gathering)	324 scfy/mile	435.80
Compressor BD	10,099 compressors	3,961 scfy/comp	770.37
Compressor Starts	10,099 compressors	8,861 scfy/comp	1,723.42
Upsets			
Pressure Relief Valves	171,430 PRV	36 scfy/PRV	117.81
Mishaps	17,444 miles	702 scf/mile	235.88
Rocky Mountain			
Gas Wells			
RM - Associated Gas Wells[1,2]	15,290 wells	NA	NA
RM - Non-associated Gas Wells (less wells with hydraulic fracturing)	64,454 wells	35.24 scfd/well	15,966.53
RM - Gas Wells with Hydraulic Fracturing	23,417 wells	40.03 scfd/well	6,589.06

	2010 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions (Mg)[3]**
Field Separation Equipment					
Heaters	40,069	heaters	56.97	scfd/heater	16,047.80
Separators	43,848	separators	120.44	scfd/sep	37,126.18
Dehydrators	12,879	dehydrators	89.95	scfd/dehy	8,144.02
Meters/Piping	101,575	meters	52.22	scfd/meter	37,289.92
Gathering Compressors					
Small Reciprocating Compressors	9,754	compressors	264.30	scfd/comp	18,122.37
Large Reciprocating Compressors	32	compressors	15,009	scfd/comp	3,376.39
Large Reciprocating Stations	4	stations	8,140.30	scfd/station	228.90
Pipeline Leaks	112,782	miles	52.47	scfd/mile	41,597.99
Drilling and Well Completion					
Gas Well Completions without Hydraulic Fracturing[1]	127	completions/yr	709	scf/comp	1.74
Gas Well Completions with Hydraulic Fracturing	0	completions/yr	7,194,624	scf/comp	0.00
Well Drilling	3,800	wells	2,510	scf/well	183.70
Normal Operations					
Pneumatic Device Vents	128,643	controllers	341	scfd/device	307,979.32
Chemical Injection Pumps	15,641	active pumps	245	scfd/pump	26,917.40
Kimray Pumps	3,769,472	MMscf/yr	979	scf/MMscf	71,091.08
Dehydrator Vents	4,230,608	MMscf/yr	272.0	scf/MMscf	22,166.90
Condensate Tank Vents					
Condensate Tanks without Control Devices	12	MMbbl/yr	21.87	scf/bbl	5,054.59
Condensate Tanks with Control Devices	12	MMbbl/yr	4.37	scf/bbl	1,010.92
Compressor Exhaust Vented					
Gas Engines	16,431	MMHPhr	0.24	scf/HPhr	74,972.23
Well Workovers					
Gas Wells without Hydraulic Fracturing	3,822	workovers/yr	2,373	scf/w.o.	174.67
Gas Wells with Hydraulic Fracturing	2,342	workovers/yr	7,194,624	scf/w.o.	324,485.75
Gas wells with liquids unloading	26,620	LU Gas Wells	690,440	scfy/LU well	353,982.99
Blowdowns					
Vessel BD	96,795	vessels	77	scfy/vessel	143.54
Pipeline BD	112,782	miles (gathering)	305	scfy/mile	662.55
Compressor BD	9,754	compressors	3,725	scfy/comp	699.83
Compressor Starts	9,754	compressors	8,334	scfy/comp	1,565.63
Upsets					
Pressure Relief Valves	168,554	PRV	34	scfy/PRV	108.95
Mishaps	28,196	miles	660	scf/mile	358.62
Produced Water from Coal Bed Methane Wells					
Powder River	28,752,279,486	gal produced water	2.3E-09	Gg/gallon water drainage	64,804.14
South West					
Gas Wells					
SW - Associated Gas Wells[1,2]	57,933	wells	NA		NA
SW - Non-associated Gas Wells (less wells with hydraulic fracturing)	27,709	wells	37.24	scfd/well	7,253.83
SW - Gas Wells with Hydraulic Fracturing	13,740	wells	37.24	scfd/well	3,597.05
Field Separation Equipment					
Heaters	11,233	heaters	58.97	scfd/heater	4,656.89
Separators	23,294	separators	124.68	scfd/sep	20,417.03
Dehydrators	6,075	dehydrators	93.12	scfd/dehy	3,976.63
Meters/Piping	50,631	meters	54.31	scfd/meter	19,241.40
Gathering Compressors					
Small Reciprocating Compressors	5,637	compressors	273.59	scfd/comp	10,841.95
Large Reciprocating Compressors	16	compressors	15,537	scfd/comp	1,747.56
Large Reciprocating Stations	2	stations	8,426.57	scfd/station	118.48
Pipeline Leaks	60,789	miles	54.31	scfd/mile	23,209.64
Drilling and Well Completion					
Gas Well Completions without Hydraulic Fracturing	60	completions/yr	749	scf/comp	0.87
Gas Well Completions with Hydraulic Fracturing	3,594	completions/yr	7,387,499	scf/comp	511,365.92

	2010 EPA Inventory Values		
Activity	**Activity Data**	**Emission Factor**	**Emissions (Mg)[3]**
Well Drilling	1,792 wells	2,599 scf/well	89.70
Normal Operations			
Pneumatic Device Vents	55,044 controllers	353 scfd/device	136,412.78
Chemical Injection Pumps	2,528 active pumps	253 scfd/pump	4,504.22
Kimray Pumps	1,778,059 MMscf/yr	1,014 scf/MMscf	34,712.96
Dehydrator Vents	1,995,577 MMscf/yr	281.6 scf/MMscf	10,823.84
Condensate Tank Vents			
Condensate Tanks without Control Devices	8 MMbbl/yr	302.75 scf/bbl	43,732.90
Condensate Tanks with Control Devices	8 MMbbl/yr	60.55 scf/bbl	8,746.58
Compressor Exhaust Vented			
Gas Engines	7,751 MMHPhr	0.25 scf/HPhr	36,608.08
Well Workovers			
Gas Wells without Hydraulic Fracturing	1,803 workovers/yr	2,508 scf/w.o.	87.08
Gas Wells with Hydraulic Fracturing	1,374 workovers/yr	7,387,499 scf/w.o.	195,497.16
Gas wells with liquids unloading	11,444 LU Gas Wells	864,999 scfy/LU well	190,650.77
Blowdowns			
Vessel BD	40,602 vessels	80 scfy/vessel	62.33
Pipeline BD	60,789 miles (gathering)	316 scfy/mile	369.67
Compressor BD	5,637 compressors	3,856 scfy/comp	418.68
Compressor Starts	5,637 compressors	8,627 scfy/comp	936.66
Upsets			
Pressure Relief Valves	79,507 PRV	35 scfy/PRV	53.20
Mishaps	15,197 miles	684 scf/mile	200.09
West Coast			
Gas Wells			
WC - Associated Gas Wells[1,2]	22,942 wells	NA	NA
WC - Non-associated Gas Wells (less wells with hydraulic fracturing)	1,546 wells	42.49 scfd/well	461.81
WC - Gas Wells with Hydraulic Fracturing	0 wells	42.49 scfd/well	0.00
Field Separation Equipment			
Heaters	1,546 heaters	67.29 scfd/heater	731.36
Separators	1,129 separators	142.27 scfd/sep	1,128.71
Dehydrators	227 dehydrators	106.25 scfd/dehy	169.25
Meters/Piping	3,002 meters	61.68 scfd/meter	1,301.92
Gathering Compressors			
Small Reciprocating Compressors	1,795 compressors	312.19 scfd/comp	3,939.16
Large Reciprocating Compressors	8 compressors	17,728 scfd/comp	997.03
Large Reciprocating Stations	1 stations	9,615.15 scfd/station	67.59
Pipeline Leaks	16,098 miles	61.97 scfd/mile	7,013.27
Drilling and Well Completion			
Gas Well Completions without Hydraulic Fracturing	2 completions/yr	855 scf/comp	0.04
Gas Well Completions with Hydraulic Fracturing	0 completions/yr	8,429,754 scf/comp	0.00
Well Drilling	67 wells	2,965 scf/well	3.82
Normal Operations			
Pneumatic Device Vents	1,549 controllers	402 scfd/device	4,380.54
Chemical Injection Pumps	1,050 active pumps	289 scfd/pump	2,133.84
Kimray Pumps	66,320 MMscf/yr	1,157 scf/MMscf	1,477.39
Dehydrator Vents	74,433 MMscf/yr	321.3 scf/MMscf	460.66
Condensate Tank Vents			
Condensate Tanks without Control Devices	0 MMbbl/yr	21.87 scf/bbl	0.00
Condensate Tanks with Control Devices	0 MMbbl/yr	4.37 scf/bbl	0.00
Compressor Exhaust Vented			
Gas Engines	289 MMHPhr	0.28 scf/HPhr	1,558.05
Well Workovers			
Gas Wells without Hydraulic Fracturing	67 workovers/yr	2,861 scf/w.o.	3.69
Gas Wells with Hydraulic Fracturing	0 workovers/yr	8,429,754 scf/w.o.	0.00
Gas wells with liquids unloading	638 LU Gas Wells	1,491,925 scfy/LU well	18,346.91
Blowdowns			
Vessel BD	2,901 vessels	91 scfy/vessel	5.08
Pipeline BD	16,098 miles (gathering)	360 scfy/mile	111.70
Compressor BD	1,795 compressors	4,400 scfy/comp	152.12
Compressor Starts	1,795 compressors	9,844 scfy/comp	340.31

	2010 EPA Inventory Values		
Activity	**Activity Data**	**Emission Factor**	**Emissions (Mg)[3]**
Upsets			
Pressure Relief Valves	2,966 PRV	40 scfy/PRV	2.26
Mishaps	4,025 miles	780 scf/mile	60.47
Gulf Coast			
Gas Wells			
GC - Associated Gas Wells[1,2]	27,327 wells	NA	NA
GC - Non-associated Gas Wells (less wells with hydraulic fracturing)	75,863 wells	7.98 scfd/well	4,256.29
GC - Gas Wells with Hydraulic Fracturing	0 wells	7.98 scfd/well	0.00
Field Separation Equipment			
Heaters	16,993 heaters	64.79 scfd/heater	7,740.38
Separators	49,918 separators	136.98 scfd/sep	48,069.49
Dehydrators	11,119 dehydrators	102.31 scfd/dehy	7,996.55
Meters/Piping	88,451 meters	59.39 scfd/meter	36,930.82
Gathering Compressors			
Small Reciprocating Compressors	6,145 compressors	300.59 scfd/comp	12,984.97
Large Reciprocating Compressors	32 compressors	17,070 scfd/comp	3,840.01
Large Reciprocating Stations	4 stations	9,258.08 scfd/station	260.33
Pipeline Leaks	99,333 miles	59.67 scfd/mile	41,668.39
Drilling and Well Completion			
Gas Well Completions without Hydraulic Fracturing	110 completions/yr	823 scf/comp	1.74
Gas Well Completions with Hydraulic Fracturing	0 completions/yr	8,127,942 scf/comp	0
Well Drilling	3,280 wells	2,855 scf/well	180.37
Normal Operations			
Pneumatic Device Vents	52,725 controllers	387 scfd/device	143,558.59
Chemical Injection Pumps	2,503 active pumps	278 scfd/pump	4,899.94
Kimray Pumps	3,254,347 MMscf/yr	1,114 scf/MMscf	69,803.79
Dehydrator Vents	3,652,466 MMscf/yr	309.4 scf/MMscf	21,765.51
Condensate Tank Vents			
Condensate Tanks without Control Devices	31 MMbbl/yr	21.87 scf/bbl	12,847.09
Condensate Tanks with Control Devices	31 MMbbl/yr	4.37 scf/bbl	2,569.42
Compressor Exhaust Vented			
Gas Engines	14,186 MMHPhr	0.27 scf/HPhr	73,614.66
Well Workovers			
Gas Wells without Hydraulic Fracturing	3,300 workovers/yr	2,755 scf/w.o.	175.10
Gas Wells with Hydraulic Fracturing	0 workovers/yr	8,127,942 scf/w.o.	0.00
Gas wells with liquids unloading	31,331 LU Gas Wells	2,519,264 scfy/LU well	1,520,228.52
Blowdowns			
Vessel BD	78,030 vessels	88 scfy/vessel	131.60
Pipeline BD	99,333 miles (gathering)	347 scfy/mile	663.68
Compressor BD	6,145 compressors	4,237 scfy/comp	501.44
Compressor Starts	6,145 compressors	9,479 scfy/comp	1,121.80
Upsets			
Pressure Relief Valves	145,520 PRV	38 scfy/PRV	106.98
Mishaps	24,833 miles	751 scf/mile	359.22
Produced Water from Coal Bed Methane Wells			
Black Warrior	5,296 wells	0.0023 Gg/well	12,303.13
Offshore Platforms			
Shallow water Gas Platforms (GoM and Pacific)	1,973 Shallow water gas platforms	19,178 scfd/platform	266,066
Deepwater Gas Platforms (GoM and Pacific)	41 Deepwater gas platforms	79,452 scfd/platform	22,950

[1] Emissions from oil wells that produce associated gas are estimated in the Petroleum Systems model. Here the oil wells count is used as a driver only.

[2] NA = not applicable; i.e. this data is not applicable for the Natural Gas systems model.

[3] Totals may not sum due to independent rounding.

[4] This category was referred to as "Completion Flaring" in previous inventories, which is consistent with the category name used in the 1996 GRI/EPA study. In this Inventory, the name of the category has been changed to clarify that this category includes completions at wells without hydraulic fracturing. The emission factors for this category, and for workovers at wells without hydraulic fracturing have not changed, and are still the factors from the 1996 GRI/EPA study.

Table A-123: 2010 Data and CH_4 Emissions (Mg) for the Natural Gas Processing Stage

	2010 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions (Mg)**
Plants	585	plants	7,906	scfd/plant	32,513.36
Recip. Compressors	5,028	compressors	11,196	scfd/comp	395,749.23
Centrifugal Compressors (wet seals)	649	compressors	51,369.86	scfd/comp	234,257.04
Centrifugal Compressors (dry seals)	162	compressors	25,189.04	scfd/comp	28,635.93
Compressor Exhaust					
Gas Engines	36,124	MMHPhr	0.24	scf/HPhr	166,978.61
Gas Turbines	42,832	MMHPhr	0.01	scf/HPhr	4,702.22
AGR Vents	296	AGR units	6,083	scfd/AGR	12,679.02
Kimray Pumps	1,308,641	MMscf/yr	177.75	scf/MMscf	4,480.09
Dehydrator Vents	11,789,557	MMscf/yr	121.55	scf/MMscf	27,599.98
Pneumatic Devices	585	gas plants	164,721	scfy/plant	1,855.93
Blowdowns/Venting	585	gas plants	4,060	Mscfy/plant	45,744.43

Table A-124: 2010 Data and CH_4 Emissions (Mg) for the Natural Gas Transmission Stage

	2010 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions (Mg)**
Pipeline Leaks	304,423	miles	1.55	Scfd/ mile	3,325.53
Compressor Stations (Transmission)					
Station	1,807	Stations	8,778	Scfd/station	111,512.17
Recip Compressor	7,265	Compressors	15,205	Scfd/ comp	776,603.08
Centrifugal Compressor (wet seals)	672	Compressors	50,222	Scfd/ comp	237,143.53
Centrifugal Compressor (dry seals)	57	Compressors	32,208	Scfd/ comp	12,905.79
Compressor Stations (Storage)					
Station	408	Stations	21,507	Scfd/ comp	61,619.48
Recip Compressor	1,199	Compressors	21,116	Scfd/ comp	177,983.60
Centrifugal Compressor (wet seals)	85	Compressors	45,441	Scfd/ comp	27,266.20
Centrifugal Compressor (dry seals)	33	Compressors	31,989	Scfd/ comp	7,341.30
Wells (Storage)	19,004	Wells	114.50	Scfd/ comp	15,296.95
M&R (Trans. Co. Interconnect)	2,710	Stations	3,984	scfd/station	75,896.92
M& R (Farm Taps + Direct Sales)	80,352	Stations	31.20	scfd/station	17,623.78
Dehydrator vents (Transmission)	1,151,898	MMscf/Year	93.72	scf/MMscf	2,079.23
Dehydrator vents (Storage)	2,111,699	MMscf/Year	117.18	scf/MMscf	4,765.87
Compressor Exhaust					
Engines (Transmission)	48,175	MMHPhr	0.24	scf/HPhr	222,683.13
Turbines (Transmission)	11,495	MMHPhr	0.01	scf/HPhr	1,261.93
Engines (Storage)	5,197	MMHPhr	0.24	scf/HPhr	24,022.10
Turbines (Storage)	1,826	MMHPhr	0.01	scf/HPhr	200.41
Generators (Engines)	2,357	MMHPhr	0.24	scf/HPhr	10,897.04
Generators (Turbines)	28	MMHPhr	0.01	scf/HPhr	3.05
Pneumatic Devices Trans + Storage					
Pneumatic Devices Trans	71,130	Devices	162,197	Scfy/device	222,203.62
Pneumatic Devices Storage	16,043	Devices	162,197	Scfy/device	50,116.96
Routine Maintenance/Upsets					
Pipeline venting	304,423	Miles	31.65	Mscfy/mile	185,569.89
Station Venting Trans + Storage					
Station Venting Transmission	1,807	Compressor Stations	4,359	Mscfy/station	151,712.26
Station Venting Storage	408	Compressor Stations	4,359	Mscfy/station	34,216.24
LNG Storage					
LNG Stations	70	Stations	21,507	scfd/station	10,622.75
LNG Reciprocating Compressors	270	Compressors	21,116	scfd/comp	40,146.51
LNG Centrifugal Compressors	64	Compressors	30,573	scfd/comp	13,765.95
LNG Compressor Exhaust					
LNG Engines	579	MMHPhr	0.24	scf/HPhr	2,677.71
LNG Turbines	113	MMHPhr	0.01	scf/HPhr	12.43
LNG Station Venting	70	Stations	4,359	Mscfy/station	5,898.63
LNG Import Terminals					
LNG Stations	8	Stations	21,507	scfd/station	1,164.18

	2010 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions (Mg)**
LNG Reciprocating Compressors	37	Compressors	21,116	scfd/comp	5,551.78
LNG Centrifugal Compressors	7	Compressors	30,573	scfd/comp	1,418.51
LNG Compressor Exhaust					
LNG Engines	1,819	MMHPhr	0.24	scf/HPhr	8,407.51
LNG Turbines	439	MMHPhr	0.01	scf/HPhr	48.22
LNG Station Venting	8	Stations	4,359	Mscfy/station	646.45

Table A-125: 2010 Data and CH_4 Emissions (Mg) for the Natural Gas Distribution Stage

	2010 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions (Mg)**
Pipeline Leaks					
Mains—Cast Iron	34,534	miles	238.70	Mscf/mile-yr	158,765.30
Mains—Unprotected steel	65,745	miles	110.19	Mscf/mile-yr	139,527.81
Mains—Protected steel	482,835	miles	3.07	Mscf/mile-yr	28,520.38
Mains—Plastic	619,077	miles	9.91	Mscf/mile-yr	118,161.12
Services—Unprotected steel	4,212,570	services	1.70	Mscf/service	137,990.25
Services Protected steel	15,203,626	services	0.18	Mscf/service	51,681.81
Services—Plastic	42,638,596	services	0.01	Mscf/service	7,635.81
Services—Copper	1,059,067	services	0.25	Mscf/service	5,187.64
Meter/Regulator (City Gates)					
M&R >300	4,105	stations	179.80	scfh/station	124,512.30
M&R 100-300	14,979	stations	95.60	scfh/station	241,600.10
M&R <100	8,006	stations	4.31	scfh/station	5,821.92
Reg >300	4,487	stations	161.90	scfh/station	122,577.76
R-Vault >300	2,636	stations	1.30	scfh/station	578.06
Reg 100-300	13,575	stations	40.50	scfh/station	92,762.20
R-Vault 100-300	6,099	stations	0.18	scfh/station	185.23
Reg 40-100	40,738	stations	1.04	scfh/station	7,148.20
R-Vault 40-100	36,126	stations	0.09	scfh/station	527.23
Reg <40	17,274	stations	0.13	scfh/station	387.62
Customer Meters					
Residential	42,286,016	outdoor meters	143.27	scfy/meter	116,683.79
Commercial/Industry	4,374,387	meters	47.90	scfy/meter	4,035.61
Routine Maintenance					
Pressure Relief Valve Releases	1,202,191	mile main	0.05	Mscf/mile	1,157.71
Pipeline Blowdown	1,370,037	miles	0.10	Mscfy/mile	2,691.46
Upsets					
Mishaps (Dig-ins)	1,370,037	miles	1.59	Mscfy/mile	41,955.18

Table A-126: Key Activity Data Drivers

Variable	Units	1990	1992	1995	2000	2006	2007	2008	2009	2010
Transmission Pipelines Length	**miles**	**291,990**	**291,468**	**296,947**	**298,957**	**300,343**	**301,066**	**303,264**	**304,423**	**304,423**
Wells										
NE—Associated Gas Wells*	# wells	68,261	67,489	66,102	58,671	47,034	46,646	47,088	46,914	47,933
NE—Non-associated Gas Wells*	# wells	124,241	129,157	129,789	143,922	164,322	172,493	174,682	183,834	188,696
MC—Associated Gas Wells*	# wells	64,379	70,640	72,483	67,880	65,903	69,234	72,622	72,935	73,885
MC—Non-associated Gas Wells*	# wells	53,940	59,358	65,585	51,217	73,914	80,650	82,705	87,190	89,370
RM—Associated Gas Wells*	# wells	13,749	14,142	13,745	12,328	13,437	12,021	14,837	15,017	15,290
RM—Non-associated Gas Wells*	# wells	24,339	26,323	32,668	64,539	75,170	70,532	91,008	98,391	87,871
SW—Associated Gas Wells*	# wells	69,339	68,130	59,954	54,830	54,550	55,251	56,713	56,724	57,933
SW—Non-associated Gas Wells*	# wells	24,217	22,609	27,392	32,346	35,417	38,049	40,563	41,987	41,449
WC—Associated Gas Wells*	# wells	20,672	19,819	19,109	20,494	22,189	22,110	24,271	24,548	22,942
WC—Non-associated Gas Wells*	# wells	1,292	1,254	1,114	1,338	1,503	1,506	1,693	1,786	1,546
GC—Associated Gas Wells*	# wells	36,279	35,376	34,792	32,497	27,319	26,234	27,661	27,134	27,327
GC—Non-associated Gas Wells*	# wells	41,753	37,307	41,978	48,316	60,715	68,188	72,047	75,046	75,863
Platforms										
Gulf of Mexico and Pacific OCS Off-shore Platforms**	# platforms	3,941	3,964	3,978	4,016	3,910	3,838	3,762	3,570	3,432
GoM and Pacific OCS Deep Water Platforms**	# platforms	17	19	23	38	67	63	65	68	70
Gas Plants	**# gas plants**	**761**	**732**	**675**	**585**	**571**	**574**	**577**	**579**	**585**
Distribution Services	**# of services**	**47,883,083**	**49,142,008**	**54,644,033**	**56,761,042**	**62,255,435**	**63,524,388**	**63,559,296**	**64,293,222**	**63,113,859**
Steel—Unprotected	# of services	7,633,526	7,138,563	6,151,653	5,675,520	5,642,470	5,448,804	5,388,623	5,218,497	4,212,570
Steel—Protected	# of services	19,781,581	19,742,086	21,002,455	17,855,560	15,732,037	15,756,048	15,456,866	15,389,666	15,203,626
Plastic	# of services	18,879,865	20,692,674	26,044,545	31,795,871	39,632,313	41,092,515	41,573,069	42,601,520	42,638,596
Copper	# of services	1,588,111	1,568,685	1,445,380	1,434,091	1,248,615	1,227,021	1,140,738	1,083,539	1,059,067
Distribution Mains	**miles**	**944,157**	**888,925**	**1,001,706**	**1,048,485**	**1,209,419**	**1,198,585**	**1,188,714**	**1,208,501**	**1,202,191**
Cast Iron	miles	58,292	52,917	50,625	44,750	36,977	37,669	36,462	35,429	34,534
Steel—Unprotected	miles	108,941	99,619	94,058	82,800	71,738	69,525	69,374	67,331	65,745
Steel—Protected	miles	465,538	469,106	503,288	471,510	481,811	489,815	479,502	484,337	482,835
Plastic	miles	311,386	267,283	353,735	449,425	618,893	601,575	603,377	621,404	619,077

* NEMS (National Energy Modeling System) projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics

** Number of platforms include both oil and gas platforms.

Table A-127: CH_4 Reductions Derived from the Natural Gas STAR Program (Gg)

Process	1992*	1995	2000	2006	2007	2008	2009	2010
Production	0	75	318	1,476	1,877	2,270	2,003	2,115
Processing	0	5	17	124	119	119	57	128
Transmission and Storage	0	121	258	480	454	440	372	438
Distribution	0	19	27	48	35	28	41	51
Total	**0**	**220**	**620**	**2,128**	**2,485**	**2,857**	**2,472**	**2,732**

*Reductions are relative to 1992; therefore, there are zero reductions in 1992.

Note: These reductions will not match the Natural Gas STAR program reductions. These numbers are adjusted for reductions prior to the 1992 base year, and do not include a sunsetting period. Totals may not sum due to independent rounding.

Table A-128: CH_4 Reductions Derived from Regulations (Gg)

Process	1990	1995	2000	2006	2007	2008	2009	2010
Production	9.81	24.14	303.56	1,571.96	783.49	966.89	734.26	734.13
Processing	NA	NA	12.9	12.4	13.0	13.6	13.9	14.6
Transmission and Storage	NA	NA	NA	NA	NA	NA	NA	NA
Distribution	NA	NA	NA	NA	NA	NA	NA	NA
Total	**9.81**	**24.14**	**316.46**	**1,584.40**	**796.47**	**980.49**	**748.17**	**748.73**

NA Not applicable

Note: NESHAP regulations went into effect in 1999. Totals may not sum due to independent rounding.

Table A-129: CH_4 Emission Estimates from the Natural Gas Production Stage Excluding Reductions from the Natural Gas STAR Program, Regulations, and Non-Gas STAR Reductions (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Normal Fugitives									
Associated Gas Wells	IE	IE	IE	IE	IE	IE	IE	IE	IE
Non-Associated Gas Wells (less wells with hydraulic fracturing)	22.10	23.61	27.85	36.84	36.80	36.68	43.20	44.36	41.95
Gas Wells with Hydraulic Fracturing	0.032	0.064	0.178	1.396	7.881	9.324	9.538	10.97	10.97
Field Separation Equipment									
Heaters	12.57	13.28	16.48	23.56	28.02	28.38	34.12	34.95	33.02
Separators	43.83	44.16	54.79	76.51	90.27	94.13	109.28	112.26	107.90
Dehydrators	14.75	15.76	17.89	20.77	24.94	26.18	28.53	29.44	29.29
Meter/ Piping	43.61	44.95	54.89	73.80	87.21	90.27	104.95	107.71	103.51
Gathering Compressors									
Small Reciprocating Comp.	30.22	32.15	38.27	45.57	56.12	58.50	66.24	68.51	66.22
Large Reciprocating Comp.	7.50	8.56	9.80	11.70	12.59	12.71	13.79	13.54	14.49
Large Reciprocating Stations	0.51	0.58	0.66	0.79	0.85	0.86	0.93	0.92	0.98
Pipeline Leaks	98.03	102.22	114.49	133.58	153.00	160.06	175.25	179.71	176.68
Vented and Combusted									
Drilling and Well Completion									
Gas Well Completions without Hydraulic Fracturing	0.005	0.006	0.006	0.007	0.009	0.009	0.010	0.011	0.010
Gas Well Completions with Hydraulic Fracturing	16.48	23.53	31.66	422.38	2,502.62	855.93	1,089.76	596.33	596.33
Well Drilling	0.74	0.54	0.53	1.01	1.85	1.89	1.93	1.10	1.08
Produced Water from Coal Bed Methane Wells									
Powder River	0.04	0.47	1.48	31.39	60.94	60.93	55.36	64.80	64.80
Black Warrior	2.72	4.84	6.25	6.82	10.45	11.09	11.69	12.06	12.30
Normal Operations									
Pneumatic Device Vents	569.76	607.88	697.61	810.83	991.63	1,043.63	1,163.70	1,205.74	1,182.54
Chemical Injection Pumps	26.89	29.38	35.04	43.44	53.95	54.95	64.46	66.39	63.43
Kimray Pumps	131.82	140.65	159.45	185.01	222.10	233.43	254.28	262.49	261.14
Dehydrator Vents	41.10	43.86	49.72	57.69	69.26	72.78	79.29	81.85	81.43
Condensate Tank Vents									
Condensate Tanks without Control Device	77.69	59.56	58.09	67.47	109.76	114.96	135.58	137.65	137.65
Condensate Tanks with Control Device	15.54	11.91	11.62	13.49	21.95	22.99	27.12	27.53	27.53
Compressor Exhaust Vented									

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Gas Engines	119.06	125.48	151.43	180.03	224.23	235.27	265.92	274.78	267.82
Well Workovers									
Gas Wells without Hydraulic Fracturing	0.56	0.58	0.64	0.73	0.87	0.94	1.02	1.05	1.05
Gas Wells with Hydraulic Fracturing	2.92	7.16	16.07	98.40	492.00	574.10	685.67	716.17	716.17
Gas wells with liquids unloading	2,652	2,699	2,931	3,329	3,803	4,133	4,349	4,533	4,549
Blowdowns									
Vessel BD	0.36	0.38	0.42	0.49	0.58	0.62	0.68	0.71	0.70
Pipeline BD	1.56	1.63	1.82	2.13	2.44	2.55	2.79	2.86	2.81
Compressor BD	1.17	1.24	1.48	1.76	2.17	2.26	2.56	2.65	2.56
Compressor Starts	2.61	2.78	3.31	3.94	4.85	5.05	5.72	5.92	5.72
Upsets									
Pressure Relief Valves	0.34	0.35	0.39	0.45	0.53	0.57	0.62	0.65	0.64
Mishaps	0.85	0.88	0.99	1.15	1.32	1.38	1.51	1.55	1.52
Offshore									
Offshore water Gas Platforms (GoM & Pacific)	290.49	297.84	307.33	323.74	321.18	305.17	299.06	278.32	266.07
Deepwater Gas Platforms (GoM & Pacific)	5.21	5.94	7.40	12.81	23.20	21.10	21.78	22.39	22.95
Total	**4,232.71**	**4,351.46**	**4,809.417**	**6,018.35**	**9,418.72**	**8,271.64**	**9,105.73**	**8,898.20**	**8,850.77**

Note: Totals may not sum due to independent rounding.

IE: Included Elsewhere. These emissions are included in the Petroleum Systems estimates.

Table A-130: CH_4 Emission Estimates from the Natural Gas Processing Plants Excluding Reductions from the Natural Gas STAR Program, Regulations, and Non-Gas STAR Reductions (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Normal Fugitives									
Plants	42.30	40.68	37.52	32.51	31.74	31.90	32.07	32.18	32.51
Reciprocating Compressors	324.94	324.74	338.42	349.51	337.12	351.55	368.88	376.77	395.75
Centrifugal Compressors (wet seals)	240.29	240.15	248.60	251.32	229.92	230.99	232.27	232.85	234.26
Centrifugal Compressors (dry seals)	0.00	0.00	0.81	3.50	9.50	14.21	19.87	22.44	28.64
Vented and Combusted									
Normal Operations									
Compressor Exhaust									
Gas Engines	137.10	137.02	142.79	147.47	142.24	148.33	156.64	158.97	166.98
Gas Turbines	3.86	3.86	4.02	4.15	4.01	4.18	4.38	4.48	4.70
AGR Vents	16.49	15.87	14.63	12.68	12.38	12.44	12.51	12.55	12.68
Kimray Pumps	3.68	3.68	3.83	3.96	3.82	3.98	4.18	4.27	4.48
Dehydrator Vents	22.66	22.65	23.60	24.38	23.51	24.52	25.73	26.28	27.60
Pneumatic Devices	2.41	2.32	2.14	1.86	1.81	1.82	1.83	1.84	1.86
Routine Maintenance									
Blowdowns/Venting	59.51	57.24	52.78	45.74	44.65	44.88	45.12	45.28	45.74
Total	**853.24**	**848.20**	**869.16**	**877.08**	**840.69**	**868.81**	**902.47**	**917.89**	**955.20**

Note: Totals may not sum due to independent rounding.

Table A-131: CH_4 Emission Estimates from the Natural Gas Transmission and Storage Excluding Reductions from the Natural Gas STAR Program, Regulations, and Non-Gas STAR Reductions (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Fugitives									
Pipelines Leaks	3.19	3.18	3.24	3.27	3.28	3.29	3.31	3.33	3.33
Compressor Stations (Transmission)									
Station	106.96	106.77	108.77	109.51	110.02	110.28	111.09	111.51	111.51
Recip Compressor	744.89	743.55	757.53	762.66	766.19	768.04	773.65	776.60	776.60
Centrifugal Compressor (wet seals)	246.76	246.32	249.68	245.59	236.80	236.86	237.05	237.14	237.14
Centrifugal Compressor (dry seals)	0.00	0.00	0.81	4.53	10.92	11.27	12.34	12.91	12.91
Compressor Stations (Storage)									

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Station	54.64	58.36	60.35	62.17	54.36	58.76	60.87	59.45	61.62
Recip Compressor	157.80	168.48	174.27	179.62	157.05	169.67	175.76	171.75	177.98
Centrifugal Compressor (wet seals)	33.22	35.46	36.55	34.41	27.39	27.65	27.78	27.14	27.27
Centrifugal Compressor (dry seals)	0.00	0.00	0.13	2.54	4.10	5.72	6.53	6.53	7.34
Wells (Storage)	13.56	14.49	14.98	15.43	13.49	14.59	15.11	14.76	15.30
M&R (Trans. Co. Interconnect)	72.80	72.67	74.03	74.53	74.88	75.06	75.61	75.90	75.90
M&R (Farm Taps + Direct Sales)	16.90	16.87	17.19	17.31	17.39	17.43	17.56	17.62	17.62
Vented and Combusted									
Normal Operation									
Dehydrator Vents (Transmission)	1.99	1.99	2.03	2.04	2.05	2.06	2.07	2.08	2.08
Dehydrator Vents (Storage)	4.23	4.51	4.67	4.81	4.20	4.54	4.71	4.60	4.77
Compressor Exhaust									
Engines (Transmission)	176.92	186.65	204.91	215.30	200.09	213.12	214.70	210.74	222.68
Turbines (Transmission)	1.00	1.06	1.16	1.22	1.13	1.21	1.22	1.19	1.26
Engines (Storage)	21.30	22.75	23.53	24.24	21.19	22.91	23.73	23.18	24.02
Turbines (Storage)	0.18	0.19	0.20	0.20	0.18	0.19	0.20	0.19	0.20
Generators (Engines)	8.66	9.13	10.03	10.54	9.79	10.43	10.51	10.31	10.90
Generators (Turbines)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pneumatic Devices Trans+Stor									
Pneumatic Devices Trans	213.13	212.75	216.75	218.21	219.23	219.75	221.36	222.20	222.20
Pneumatic Devices Storage	44.44	47.46	49.09	50.56	44.21	47.79	49.51	48.36	50.12
Routine Maintenance/Upsets									
Pipeline Venting	177.99	177.67	181.01	182.24	183.08	183.52	184.86	185.57	185.57
Station venting Trans+Storage									
Station Venting Transmission	145.52	145.26	147.99	148.99	149.68	150.04	151.13	150.71	151.71
Station Venting Storage	30.34	32.41	33.51	34.52	30.18	32.63	33.80	33.01	34.22
LNG Storage									
LNG Stations	9.24	9.45	9.77	10.30	10.62	10.62	10.62	10.62	10.62
LNG Reciprocating Compressors	34.50	35.37	36.67	38.84	40.15	40.15	40.15	40.15	40.15
LNG Centrifugal Compressors	11.78	12.09	12.55	13.31	13.77	13.77	13.77	13.77	13.77
LNG Compressor Exhaust									
LNG Engines	2.59	2.61	2.63	2.66	2.68	2.68	2.68	2.68	2.68
LNG Turbines	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LNG Station Venting	5.13	5.25	5.43	5.72	5.90	5.90	5.90	5.90	5.90
LNG Import Terminals									
LNG Stations	0.21	0.21	0.21	0.21	0.42	0.42	1.06	1.16	1.16
LNG Reciprocating Compressors	1.01	1.01	1.01	1.01	2.02	2.02	5.05	5.55	5.55
LNG Centrifugal Compressors	0.26	0.26	0.26	0.26	0.52	0.52	1.29	1.42	1.42
LNG Compressor Exhaust									
LNG Engines	1.74	0.96	0.49	4.41	11.28	14.81	6.91	8.80	8.41
LNG Turbines[1]	0.01	0.00	0.00	0.03	0.07	0.09	0.04	0.05	0.05
LNG Station Venting	0.12	0.12	0.12	0.12	0.24	0.24	0.59	0.65	0.65
Total	**2,343.02**	**2,375.33**	**2,441.57**	**2,481.31**	**2,428.56**	**2,478.02**	**2,502.51**	**2,498.56**	**2,524.61**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

Table A-132: CH_4 Emission Estimates from the Natural Gas Distribution Stage Excluding Reductions from the Natural Gas STAR Program, Regulations, and Non-Gas STAR Reductions (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Pipeline Leaks									
Mains—Cast Iron	267.99	243.28	232.74	205.73	170.00	173.18	167.63	162.88	158.77
Mains—Unprotected steel	231.20	211.42	199.62	175.72	152.25	147.55	147.23	142.89	139.53
Mains—Protected steel	27.50	27.71	29.73	27.85	28.46	28.93	28.32	28.61	28.52
Mains—Plastic	59.43	51.02	67.52	85.78	118.13	114.82	115.16	118.61	118.16
Services—Unprotected steel	250.05	233.84	201.51	185.91	184.83	178.49	176.51	170.94	137.99
Services Protected steel	67.24	67.11	71.39	60.70	53.48	53.56	52.54	52.31	51.68

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Services—Plastic	3.38	3.71	4.66	5.69	7.10	7.36	7.44	7.63	7.64
Services—Copper	7.78	7.68	7.08	7.02	6.12	6.01	5.59	5.31	5.19
Meter/Regulator (City Gates)									
M&R >300	110.41	117.93	121.96	125.62	109.84	118.73	123.00	120.14	124.51
M&R 100-300	214.25	228.82	236.64	243.76	213.13	230.38	238.67	233.11	241.60
M&R <100	5.16	5.51	5.70	5.87	5.14	5.55	5.75	5.62	5.82
Reg >300	108.70	116.09	120.06	123.67	108.13	116.88	121.09	118.27	122.58
R-Vault >300	0.51	0.55	0.57	0.58	0.51	0.55	0.57	0.56	0.58
Reg 100-300	82.26	87.86	90.86	93.59	81.83	88.45	91.64	89.50	92.76
R-Vault 100-300	0.16	0.18	0.18	0.19	0.16	0.18	0.18	0.18	0.19
Reg 40-100	6.34	6.77	7.00	7.21	6.31	6.82	7.06	6.90	7.15
R-Vault 40-100	0.47	0.50	0.52	0.53	0.47	0.50	0.52	0.51	0.53
Reg <40	0.34	0.37	0.38	0.39	0.34	0.37	0.38	0.37	0.39
Customer Meters									
Residential	103.47	110.51	114.29	117.72	102.93	111.26	115.27	112.58	116.68
Commercial/Industry	3.97	4.25	4.78	4.66	3.85	3.98	4.04	3.82	4.04
Routine Maintenance									
Pressure Relief Valve Releases	0.91	0.86	0.96	1.01	1.16	1.15	1.14	1.16	1.16
Pipeline Blowdown	2.39	2.55	2.64	2.72	2.37	2.57	2.66	2.60	2.69
Upsets									
Mishaps (Dig-ins)	37.20	39.74	41.09	42.33	37.01	40.01	41.45	40.48	41.96
Total	**1,591.13**	**1,568.23**	**1,561.87**	**1,524.27**	**1,393.54**	**1,437.28**	**1,453.87**	**1,424.98**	**1,410.09**

Note: Totals may not sum due to independent rounding.

Table A-133: U.S. Production Sector CO_2 Content in Natural Gas by NEMS Region and Formation Type

	U.S. Region						
Formation Types	**North East**	**Midcontinent**	**Gulf Coast**	**South West**	**Rocky Mountain**	**West Coast**	**Lower-48 States**
Conventional	0.92%	0.79%	2.17%	3.81%	7.95%	0.16%	3.41%
Non-conventional*	7.42%	0.31%	0.23%	NA	0.64%	NA	4.83%
All types	3.04%	0.79%	2.17%	3.81%	7.58%	0.16%	3.45%

Source: GRI-01/0136 GTI's Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. August, 2001

*In GTI, this refers to shale, coal bed methane, and tight geologic formations.

Table A-134: CO_2 Emission Estimates from the Natural Gas Production Stage (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Normal Fugitives									
Gas Wells									
Non-Associated Gas Wells	2.92	3.00	3.61	5.72	5.24	4.82	6.22	6.84	6.10
Gas Wells with Hydraulic Fracturing	0.00	0.00	0.00	0.03	0.13	0.15	0.15	0.14	0.14
Field Separation Equipment									
Heaters	1.86	1.91	2.32	3.95	4.61	4.48	5.53	5.93	5.43
Separators	6.04	5.97	7.17	11.29	13.20	13.16	15.76	16.80	15.63
Dehydrators	1.50	1.54	1.73	2.58	2.94	2.93	3.38	3.60	3.42
Meter/ Piping	5.85	5.85	6.95	10.90	12.69	12.57	15.12	16.12	14.96
Gathering Compressors									
Small Reciprocating Comp.	2.95	2.98	3.57	5.46	6.41	6.38	7.63	8.14	7.57
Large Reciprocating Comp.	0.69	0.91	1.02	1.33	1.40	1.40	1.62	1.62	1.68
Large Reciprocating Stations	0.05	0.06	0.07	0.09	0.09	0.09	0.11	0.11	0.11
Pipeline Leaks	10.75	10.85	11.99	16.04	18.21	18.25	20.78	21.92	20.86
Vented and Combusted									
Drilling and Well Completion									
Gas Well Completions without Hydraulic Fracturing[2]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas Well Completions with Hydraulic Fracturing	2.18	1.59	5.27	122.2	748.86	166.74	108.05	85.45	85.45
Well Drilling	0.07	0.05	0.05	0.12	0.21	0.20	0.21	0.12	0.12
Produced Water from Coal Bed Methane Wells									
Powder River[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Black Warrior[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Normal Operations									
Pneumatic Device Vents	58.49	60.24	69.38	101.86	119.29	118.75	139.61	148.96	139.96
Chemical Injection Pumps	2.95	3.11	3.75	6.33	7.45	7.20	8.91	9.58	8.75
Kimray Pumps	13.41	13.71	15.43	22.91	26.12	26.05	30.00	31.95	30.40
Dehydrator Vents	4.18	4.28	4.81	7.14	8.15	8.12	9.35	9.96	9.48
Condensate Tank Vents									
Condensate Tanks without Control Device	10.25	9.43	8.79	9.34	11.26	11.17	11.90	11.62	11.62
Condensate Tanks with Control Device	2.05	1.89	1.76	1.87	2.25	2.23	2.38	2.32	2.32
Compressor Exhaust Vented									
Gas Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Well Workovers									
Gas Wells without Hydraulic Fracturing	0.06	0.06	0.06	0.08	0.10	0.10	0.11	0.12	0.11
Gas Wells with Hydraulic Fracturing	0.47	0.85	2.35	22.89	118.9	135.6	146.4	145.5	145.2
Gas wells with liquids unloading	251.41	252.88	273.66	339.56	367.69	377.12	413.38	439.68	430.24
Blowdowns									
Vessel BD	0.04	0.04	0.04	0.06	0.07	0.07	0.08	0.08	0.08
Pipeline BD	0.17	0.17	0.19	0.26	0.29	0.29	0.33	0.35	0.33
Compressor BD	0.11	0.12	0.14	0.21	0.25	0.25	0.29	0.31	0.29
Compressor Starts	0.25	0.26	0.31	0.47	0.55	0.55	0.66	0.70	0.65
Upsets									
Pressure Relief Valves	0.03	0.03	0.04	0.05	0.06	0.06	0.07	0.07	0.07

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Mishaps	0.09	0.09	0.10	0.14	0.16	0.16	0.18	0.19	0.18
Flaring Emissions - Onshore	9,092.72	10,172.49	17,167.79	5,525.04	7,812.35	8,664.25	10,024.82	9,545.39	9,545.39
Offshore									
Offshore water Gas Platforms (GoM & Pacific)	1.47	1.51	1.56	1.64	1.63	1.55	1.52	1.41	1.35
Deepwater Gas Platforms (GoM & Pacific)	0.03	0.03	0.04	0.07	0.12	0.11	0.11	0.11	0.12
Flaring Emissions - Offshore	230.37	163.13	197.22	204.31	146.48	160.05	360.00	360.00	360.00
Total	**9,703.42**	**10,719.01**	**17,791.17**	**6,423.92**	**9,437.13**	**9,744.80**	**11,334.61**	**10,874.84**	**10.848.06**

[1] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.

[2] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

Table A-135: CO_2 Emission Estimates from the Natural Gas Processing Plants (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Normal Fugitives									
Plants – Before CO_2 removal	2.56	2.46	2.27	1.97	1.92	1.93	1.94	1.95	1.97
Plants – After CO_2 removal	0.57	0.55	0.50	0.44	0.43	0.43	0.43	0.43	0.44
Reciprocating Compressors – Before CO_2 removal	19.67	19.66	20.49	21.16	20.41	21.28	22.33	22.81	23.96
Reciprocating Compressors – After CO_2 removal	4.37	4.36	4.55	4.70	4.53	4.72	4.96	5.06	5.32
Centrifugal Compressors (wet seals) – Before CO_2 removal	14.55	14.54	15.05	15.21	13.92	13.98	14.06	14.09	14.18
Centrifugal Compressors (wet seals) – After CO_2 removal	3.23	3.23	3.34	3.38	3.09	3.10	3.12	3.13	3.15
Centrifugal Compressors (dry seals) – Before CO_2 removal	0	0	0.05	0.21	0.58	0.86	1.20	1.36	1.73
Centrifugal Compressors (dry seals) – After CO_2 removal	0	0	0.01	0.05	0.13	0.19	0.27	0.30	0.38
Vented and Combusted									
Normal Operations									
Compressor Exhaust									
Gas Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Gas Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
AGR Vents	27,708.20	26,652.30	24,577.92	23,288.24	21,160.97	21,144.38	21,328.16	21,130.48	21,286.71
Kimray Pumps	0.39	0.39	0.41	0.42	0.41	0.43	0.45	0.46	0.48
Dehydrator Vents	2.42	2.42	2.52	2.61	2.51	2.62	2.75	2.81	2.95
Pneumatic Devices	0.29	0.27	0.25	0.22	0.21	0.22	0.22	0.22	0.22
Routine Maintenance									
Blowdowns/Venting	6.36	6.12	5.64	4.89	4.78	4.80	4.83	4.84	4.89
Total	**27,762.60**	**26,706.31**	**24,632.01**	**23,343.49**	**21,213.87**	**21,198.94**	**21,384.71**	**21,187.94**	**21,346.38**

[1] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.

Note: Totals may not sum due to independent rounding.

Table A-136: CO_2 Emission Estimates from the Natural Gas Transmission and Storage (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Fugitives									
Pipelines Leaks	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10
Compressor Stations (Transmission)									
Station	3.09	3.08	3.14	3.16	3.17	3.18	3.20	3.22	3.22
Recip Compressor	21.49	21.45	21.85	22.00	22.10	22.15	22.32	22.40	22.40
Centrifugal Compressor (wet seals)	7.12	7.11	7.20	7.08	6.83	6.83	6.84	6.84	6.84
Centrifugal Compressor (dry seals)	0	0	0.02	0.13	0.31	0.33	0.36	0.37	0.37
Compressor Stations (Storage)									

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Station	1.58	1.68	1.74	1.79	1.57	1.69	1.76	1.72	1.78
Recip Compressor	4.55	4.86	5.03	5.18	4.53	4.89	5.07	4.95	5.13
Centrifugal Compressor (wet seals)	0.96	1.02	1.05	0.99	0.79	0.80	0.80	0.78	0.79
Centrifugal Compressor (dry seals)	0	0	0.00	0.07	0.12	0.17	0.19	0.19	0.21
Wells (Storage)	0.39	0.42	0.43	0.45	0.39	0.42	0.44	0.43	0.44
M&R (Trans. Co. Interconnect)	2.10	2.10	2.14	2.15	2.16	2.17	2.18	2.19	2.20
M&R (Farm Taps + Direct Sales)	0.49	0.49	0.50	0.50	0.50	0.50	0.51	0.51	0.51
Vented and Combusted									
Normal Operation									
Dehydrator Vents (Transmission)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Dehydrator Vents (Storage)	0.12	0.13	0.13	0.14	0.12	0.13	0.14	0.13	0.14
Compressor Exhaust									
Engines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Engines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Engines)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Turbines)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Pneumatic Devices Trans+Stor									
Pneumatic Devices Trans	6.15	6.14	6.25	6.29	6.32	6.34	6.39	6.41	6.41
Pneumatic Devices Storage	1.28	1.37	1.42	1.46	1.28	1.38	1.43	1.39	1.45
Routine Maintenance/Upsets									
Pipeline Venting	5.13	5.13	5.22	5.26	5.28	5.30	5.33	5.35	5.35
Station venting Trans+Storage									
Station Venting Transmission	4.20	4.19	4.27	4.30	4.32	4.33	4.36	4.38	4.38
Station Venting Storage	0.88	0.93	0.97	1.00	0.87	0.94	0.98	0.95	0.99
LNG Storage									
LNG Stations	0.31	0.32	0.33	0.35	0.36	0.36	0.36	0.36	0.36
LNG Reciprocating Compressors	1.16	1.18	1.23	1.30	1.34	1.34	1.34	1.34	1.34
LNG Centrifugal Compressors	0.39	0.41	0.42	0.45	0.46	0.46	0.46	0.46	0.46
LNG Compressor Exhaust									
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting	0.17	0.18	0.18	0.19	0.20	0.20	0.20	0.20	0.20
LNG Import Terminals									
LNG Stations	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.04	0.04
LNG Reciprocating Compressors	0.03	0.03	0.03	0.03	0.07	0.07	0.17	0.19	0.19
LNG Centrifugal Compressors	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.05	0.05
LNG Compressor Exhaust									
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting[2]	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02
Total	**61.75**	**62.37**	**63.73**	**64.44**	**63.29**	**64.17**	**65.05**	**65.02**	**65.40**

[1] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.

[2] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

Table A-137: CO_2 Emission Estimates from the Natural Gas Distribution Stage (Gg)

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
Pipeline Leaks									
Mains—Cast Iron	7.73	7.02	6.71	5.93	4.90	5.00	4.84	4.70	4.58
Mains—Unprotected steel	6.67	6.10	5.76	5.07	4.39	4.26	4.25	4.12	4.02
Mains—Protected steel	0.79	0.80	0.86	0.80	0.82	0.83	0.82	0.83	0.82
Mains—Plastic	1.71	1.47	1.95	2.47	3.41	3.31	3.32	3.42	3.41
Total Pipeline Miles									
Services—Unprotected steel	7.21	6.75	5.81	5.36	5.33	5.15	5.09	4.93	3.98
Services Protected steel	1.94	1.94	2.06	1.75	1.54	1.54	1.52	1.51	1.49
Services—Plastic	0.10	0.11	0.13	0.16	0.20	0.21	0.21	0.22	0.22
Services—Copper	0.22	0.22	0.20	0.20	0.18	0.17	0.16	0.15	0.15
Meter/Regulator (City Gates)									

Activity	1990	1992	1995	2000	2006	2007	2008	2009	2010
M&R >300	3.18	3.40	3.52	3.62	3.17	3.42	3.55	3.47	3.59
M&R 100-300	6.18	6.60	6.83	7.03	6.15	6.65	6.88	6.72	6.97
M&R <100	0.15	0.16	0.16	0.17	0.15	0.16	0.17	0.16	0.17
Reg >300	3.14	3.35	3.46	3.57	3.12	3.37	3.49	3.41	3.54
R-Vault >300	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02
Reg 100-300	2.37	2.53	2.62	2.70	2.36	2.55	2.64	2.58	2.68
R-Vault 100-300	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01
Reg 40-100	0.18	0.20	0.20	0.21	0.18	0.20	0.20	0.20	0.21
R-Vault 40-100	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.02
Reg <40	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Customer Meters									
Residential	2.98	3.19	3.30	3.40	2.97	3.21	3.33	3.25	3.37
Commercial/Industry	0.11	0.12	0.14	0.13	0.11	0.11	0.12	0.11	0.12
Routine Maintenance									
Pressure Relief Valve Releases	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Pipeline Blowdown	0.07	0.07	0.08	0.08	0.07	0.07	0.08	0.07	0.08
Upsets									
Mishaps (Dig-ins)	1.07	1.15	1.19	1.22	1.07	1.15	1.20	1.17	1.21
Total	**45.90**	**45.24**	**45.05**	**43.97**	**40.20**	**41.46**	**41.94**	**41.11**	**40.68**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

3.5. Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems

The methodology for estimating CH_4 and non-combustion CO_2 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* (EPA/GRI 1996). Sixty-four activities that emit CH_4 and thirty activities that emit non-combustion CO_2 from petroleum systems were examined from these reports. Most of the activities analyzed involve crude oil production field operations, which accounted for about 98 percent of total oil industry CH_4 emissions. Crude transportation and refining accounted for the remaining CH_4 emissions of less than 0.5 and about 1.5 percent, respectively. Non-combustion CO_2 emissions were analyzed for production operations and asphalt blowing in refining operations. Non-combustion CO_2 emissions from transportation operations are not included because they are negligible. The following steps were taken to estimate CH_4 and CO_2 emissions from petroleum systems.

Step 1: Determine Emission Factors for all Activities

The CH_4 emission factors for the majority of the activities for 1995 are taken from the 1999 EPA draft report, which contained the most recent and comprehensive determination of CH_4 emission factors for the 64 CH_4-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 1996c study. The gas engine emission factor is taken from the EPA/GRI 1996b study. The oil tank venting emission factor is taken from the API E&P Tank Calc weighted average for API gravity less than 45 API degrees with the distribution of gravities taken from a sample of production data from the HPDI database. Offshore emissions from shallow water and deep water oil platforms are taken from analysis of the Gulf-wide Offshore Activity Data System (GOADS) report (EPA 2005, BOEMRE 2004). The emission factors determined for 1995 were assumed to be representative of emissions from each source type over the period 1990 through 2010. Therefore, the same emission factors are used for each year throughout this period.

The CO_2 emission factors were derived from the corresponding source CH_4 emission factors. The amount of CO_2 in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying CO_2 contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. The standard approach used to estimate CO_2 emission factors was to use the existing CH_4 emissions factors and multiply them by a conversion factor, which is the ratio of CO_2 content to methane content for the particular stream. Ratios of CO_2 to CH_4 volume in emissions are presented in Table A-142. The two exceptions are the emissions factor for storage tanks, which is estimated using API E&P Tank Calc simulation runs of tank emissions for crude oil of different gravities less than 45 API degrees; and the emissions factor for uncontrolled asphalt blowing, which is estimated using the data and methods provided by API (2009).

Step 2: Determine Activity Data for Each Year

Activity levels change from year to year. Some data changes 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 the rate and number of facilities.

For most sources, activity data found in the EPA/GRI 1996 for the 1995 base year are extrapolated to other years using publicly-available data sources. For the remaining sources, the activity data are obtained directly from publicly available data.

For both sets of data, a determination was made on a case-by-case basis as to which measure of petroleum industry activity best reflects the change in annual activity. Publicly-reported data from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Energy Information Administration (EIA), American Petroleum Institute (API), the Oil & Gas Journal (O&GJ), the Interstate Oil and Gas Compact Commission (IOGCC), and the U.S Army Corps of Engineers (USACE) were used to extrapolate the activity data from the base year to each year between 1990 and 2010. Data used include total domestic crude oil production, number of domestic crude oil wells, total imports and exports of crude oil, total petroleum refinery crude runs, and number of oil-producing offshore platforms. The activity data for the total crude transported in the transportation sector is not available. In this case, all the crude oil that was transported was assumed to go to refineries. Therefore, the activity data for the refining sector was used also for the transportation sector. In the few cases where no data was located, oil industry data based on expert judgment was used. In the case of non-combustion CO_2 emission sources, the activity factors are the same as for CH_4 emission sources.

Step 3: Estimate Methane and Carbon Dioxide Emissions for Each Activity for Each Year

Annual CH_4 emissions from each of the 64 petroleum system activities and CO_2 emissions from the 30 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 summed to estimate the total annual CH_4 and CO_2 emissions, respectively.

Table A-138, Table A-139, Table A-140, and Table A-143 provide 2010 activity data, emission factors, and emission estimates and Table A-141 and Table A-144 provide a summary of emission estimates for the years 1990, 1995, 2000, and 2005 through 2010. Table A-142provides the CO_2 content in natural gas for equipment in different crude streams to estimate CO_2 emission factors using CH_4 emission factors.

Table A-138: 2010 CH_4 Emissions from Petroleum Production Field Operations

	2010 EPA Inventory Values			
Activity/Equipment	**Emission Factor**	**Activity Data**	**Emissions (Bcf/yr)**	**Emissions (Gg/yr)**
Vented Emissions			**68.988**	**1,307**
Oil Tanks	7.39 scf of CH_4/bbl crude	1,505 MMbbl/yr (non stripper wells)	11.130	214.0
Pneumatic Devices, High Bleed	330 scfd CH_4/device	140,096 No. of high-bleed devices	16.895	324.9
Pneumatic Devices, Low Bleed	52 scfd CH_4/device	260,179 No. of low-bleed devices	4.938	94.97
Chemical Injection Pumps	248 scfd CH_4/pump	28,166 No. of pumps	2.550	49.04
Vessel Blowdowns	78 scfy CH_4/vessel	182,867 No. of vessels	0.014	0.274
Compressor Blowdowns	3,775 scf/yr of CH_4/compressor	2,479 No. of compressors	0.009	0.180
Compressor Starts	8,443 scf/yr. of CH_4/compressor	2,479 No. of compressors	0.021	0.403
Stripper wells	2,345 scf/yr of CH_4/stripper well	300,471 No. of stripper wells vented	0.705	13.55
Well Completion Venting	733 scf/completion	18,456 Oil well completions	0.014	0.260
Well Workovers	96 scf CH_4/workover	39,450 Oil well workovers	0.004	0.073
Pipeline Pigging	2.40 scfd of CH_4/pig station	0 No. of crude pig stations	-	-
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	54,795 scfd CH_4/platform	1,447 No. of shallow water oil platforms	28.930	556.4
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	260,274 scfd CH_4/platform	29 No. of deep water oil platforms	2.778	53.42
Fugitive Emissions			**2.638**	**50.72**
Oil Wellheads (heavy crude)	0.13 scfd/well	15,900 No. of hvy. crude wells	0.001	0.014
Oil Wellheads (light crude)	16.6 scfd/well	209,629 No. of lt. crude wells	1.272	24.47
Separators (heavy crude)	0.15 scfd CH_4/separator	10,762 No. of hvy. crude seps.	0.001	0.012
Separators (light crude)	14 scfd CH_4/separator	97,942 No. of lt. crude seps.	0.495	9.52
Heater/Treaters (light crude)	19 scfd CH_4/heater	74,163 No. of heater treaters	0.520	10.00
Headers (heavy crude)[1]	0.08 scfd CH_4/header	13,721 No. of hvy. crude hdrs.	0.000	0.007
Headers (light crude)	11 scfd CH_4/header	42,536 No. of lt. crude hdrs.	0.169	3.241
Floating Roof Tanks	338,306 scf CH_4/floating roof tank/yr.	24 No. of floating roof tanks	0.008	0.159
Compressors	100 scfd CH_4/compressor	2,479 No. of compressors	0.090	1.740
Large Compressors	16,360 scfd CH_4/compressor	0 No. of large comprs.	-	-
Sales Areas	41 scf CH_4/loading	1,664,742 Loadings/year	0.068	1.298
Pipelines	NE scfd of CH_4/mile of pipeline	11,249 Miles of gathering line	NE	NE
Well Drilling	NE scfd of CH_4/oil well drilled	20,794 No. of oil wells drilled	NE	NE
Battery Pumps	0.24 scfd of CH_4/pump	157,800 No. of battery pumps	0.014	0.265
Combustion Emissions			**4.846**	**93.2**

	2010 EPA Inventory Values					
Activity/Equipment	**Emission Factor**		**Activity Data**		**Emissions (Bcf/yr)**	**Emissions (Gg/yr)**
Gas Engines	0.24	scf CH_4/HP-hr	15,620	MMHP-hr	3.749	72.10
Heaters	0.52	scf CH_4/bbl	1998.0	MMbbl/yr	1.041	20.02
Well Drilling	2,453	scf CH_4/well drilled	20,794	Oil wells drilled	0.051	0.981
Flares	20	scf CH_4/Mcf flared	244,865	Mcf flared/yr	0.005	0.094
Process Upset Emissions					**0.179**	**3.443**
Pressure Relief Valves	35	scf/yr/PR valve	166,894	No. of PR valves	0.006	0.111
Well Blowouts Onshore	2.5	MMscf/blowout	69.3	No. of blowouts/yr	0.173	3.332
Total					**75.65**	**1,455**

- Zero Emissions

[1] Emissions are not actually 0, but too small to show at this level of precision.

NE: Not estimated for lack of data

Table A-139: 2010 CH_4 Emissions from Petroleum Transportation

Activity/Equipment	**Emission Factor**	**Units**	**Activity Factor**	**Units**	**Emissions (Bcf/yr)**	**Emissions (Gg/yr)**
Vented Emissions					**0.212**	**4.075**
Tanks	0.021	scf CH_4/yr/bbl of crude delivered to refineries	5,374	MMbbl crude feed/yr	0.111	2.129
Truck Loading	0.520	scf CH_4/yr/bbl of crude transported by truck	72.2	MMbbl crude trans. by truck	0.038	0.722
Marine Loading	2.544	scf CH_4/1000 gal. crude marine loadings	18,576,037	1,000 gal./yr loaded	0.047	0.909
Rail Loading	0.520	scf CH_4/yr/bbl of crude transported by rail	4.3	MMbbl Crude by rail/yr	0.002	0.043
Pump Station Maintenance[1]	36.80	scf CH_4/station/yr	496	No. of pump stations	0.000	0.000
Pipeline Pigging	39	scfd of CH_4/pig station	992	No. of pig stations	0.014	0.271
Fugitive Emissions					**0.050**	**0.958**
Pump Stations	25	scf CH_4/mile/yr.	49,585	No. of miles of crude p/l	0.001	0.019
Pipelines	NE	scf CH_4/bbl crude transported by pipeline	6,431	MMbbl crude piped	NE	NE
Floating Roof Tanks	58,965	scf CH_4/floating roof tank/yr.	824	No. of floating roof tanks	0.049	0.942
Combustion Emissions					**NE**	**NE**
Pump Engine Drivers	0.24	scf CH_4/hp-hr	NE	No. of hp-hrs	NE	NE
Heaters	0.521	scf CH_4/bbl burned	NE	No. of bbl Burned	NE	NE
Total					**0.262**	**5.033**

[1] Emissions are not actually 0, but too small to show at this level of precision.

NE: Not estimated for lack of data

Table A-140: 2010 CH_4 Emissions from Petroleum Refining

	2010 EPA Inventory Values					
Activity/Equipment	**Emission Factor**		**Activity Factor**		**Emissions (Bcf/yr)**	**Emissions (Gg/yr)**
Vented Emissions					**0.785**	**15.12**
Tanks	20.6	scf CH_4/Mbbl	1,889	Mbbl/calendar day heavy crude feed	0.014	0.273
System Blowdowns	137	scf CH_4/Mbbl	14,721	Mbbl/calendar day refinery feed	0.735	14.14
Asphalt Blowing	2,555	scf CH_4/Mbbl	38	Mbbl/calendar day production	0.036	0.684
Fugitive Emissions					**0.088**	**1.696**
Fuel Gas System	439	Mscf CH_4/refinery/yr	148	Refineries	0.065	1.249

Activity/Equipment	2010 EPA Inventory Values					
	Emission Factor		Activity Factor		Emissions (Bcf/yr)	Emissions (Gg/yr)
Floating Roof Tanks[1]	587	scf CH_4/floating roof tank/yr.	767	No. of floating roof tanks	0.000	0.009
Wastewater Treating	1.88	scf CH_4/Mbbl	14,721	Mbbl/calendar day refinery feed	0.010	0.194
Cooling Towers	2.36	scf CH_4/Mbbl	14,721	Mbbl/calendar day refinery feed	0.013	0.244
Combustion Emissions					**0.093**	**1.79**
Atmospheric Distillation	3.61	scf CH_4/Mbbl	15,177	Mbbl/calendar day refinery feed	0.020	0.385
Vacuum Distillation	3.61	scf CH_4/Mbbl	6,895	Mbbl/calendar day feed	0.009	0.173
Thermal Operations	6.01	scf CH_4/Mbbl	2,167	Mbbl/calendar day feed	0.005	0.092
Catalytic Cracking	5.17	scf CH_4/Mbbl	4,940	Mbbl/calendar day feed	0.009	0.179
Catalytic Reforming	7.22	scf CH_4/Mbbl	3,062	Mbbl/calendar day feed	0.008	0.155
Catalytic Hydrocracking	7.22	scf CH_4/Mbbl	1,442	Mbbl/calendar day feed	0.004	0.073
Hydrorefining	2.17	scf CH_4/Mbbl	2,175	Mbbl/calendar day feed	0.002	0.033
Hydrotreating	6.50	scf CH_4/Mbbl	9,975	Mbbl/calendar day feed	0.024	0.454
Alkylation/Polymerization	12.6	scf CH_4/Mbbl	1,054	Mbbl/calendar day feed	0.005	0.093
Aromatics/Isomeration	1.80	scf CH_4/Mbbl	987	Mbbl/calendar day feed	0.001	0.013
Lube Oil Processing	0.00	scf CH_4/Mbbl	174	Mbbl/calendar day feed	0.000	0.000
Engines	0.006	scf CH_4/hp-hr	1,114	MMhp-hr/yr	0.006	0.122
Flares	0.189	scf CH_4/Mbbl	14,721	Mbbl/calendar day refinery feed	0.001	0.019
Total					**0.966**	**18.61**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Table A-141: Summary of CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2006	2007	2008	2009	2010
Production Field Operations	**1,653**	**1,557**	**1,467**	**1,365**	**1,396**	**1,404**	**1,437**	**1,455**
Pneumatic device venting	489	463	428	396	398	416	419	420
Tank venting	250	226	214	188	192	182	206	214
Combustion & process upsets	88	82	76	71	72	75	94	97
Misc. venting & fugitives	799	762	726	692	714	706	693	700
Wellhead fugitives	26	25	22	17	20	24	24	24
Crude Oil Transportation	**7**	**6**	**5**	**5**	**5**	**5**	**5**	**5**
Refining	**18**	**18**	**19**	**19**	**19**	**19**	**18**	**19**
Total	**1,677**	**1,581**	**1,492**	**1,389**	**1,420**	**1,427**	**1,460**	**1,478**

Note: Totals may not sum due to independent rounding.

Table A-142: Ratios of CO_2 to CH_4 Volume in Emissions from Petroleum Production Field Operations

	Whole Crude, Post-Separator	Associated Gas	Tank Flash Gas	Offshore
Ratio %CO_2 / %CH_4	0.052	0.020	0.017	0.004

Table A-143: 2010 CO_2 Emissions from Petroleum Production Field Operations and Petroleum Refining

Activity/Equipment	2010 EPA Inventory Values					
	Emission Factor		Activity Factor		Emissions (Bcf/yr)	Emissions (Gg/yr)
Vented Emissions					**6.028**	**319.5**
Oil Tanks	3.53	scf of CO_2/bbl crude	1,505	MMbbl/yr (non stripper wells)	5.310	281.4
Pneumatic Devices, High Bleed	6.704	scfd CO_2/device	140,096	No. of high-bleed	0.343	18.17

	2010 EPA Inventory Values					
Activity/Equipment	**Emission Factor**		**Activity Factor**		**Emissions (Bcf/yr)**	**Emissions (Gg/yr)**
				devices		
Pneumatic Devices, Low Bleed	1.055	scfd CO_2/device	260,179	No. of low-bleed devices	0.100	5.314
Chemical Injection Pumps	5.033	scfd CO_2/pump	28,166	No. of pumps	0.052	2.742
Vessel Blowdowns[1]	1.583	scfy CO_2/vessel	182,867	No. of vessels	0.000	0.015
Compressor Blowdowns[1]	77	scf/yr of CO_2/compressor	2,479	No. of compressors	0.000	0.010
Compressor Starts[1]	171	scf/yr. of CO_2/compressor	2,479	No. of compressors	0.000	0.023
Stripper wells	48	scf/yr of CO_2/stripper well	300,471	No. of stripper wells vented	0.014	0.758
Well Completion Venting[1]	14.87	scf/completion	18,756	Oil well completions	0.000	0.014
Well Workovers[1]	1.95	scf CO_2/workover	39,450	Oil well workovers	0.000	0.004
Pipeline Pigging	NE	scfd of CO_2/pig station	NE	No. of crude pig stations	NE	NE
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	358	scfd CO_2/platform	1,447	No. of shallow water oil platforms	0.189	10.02
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	1,701	scfd CO_2/platform	29	No. of deep water oil platforms	0.018	0.962
Fugitive Emissions					**0.054**	**2.864**
Oil Wellheads (heavy crude)[1]	0.003	scfd/well	15,900	No. of hvy. crude wells	0.000	0.001
Oil Wellheads (light crude)	0.337	scfd/well	209,629	No. of lt. crude wells	0.026	1.359
Separators (heavy crude)[1]	0.003	scfd CO_2/separator	10,762	No. of hvy. crude seps.	0.000	0.001
Separators (light crude)	0.281	scfd CO_2/separator	97,942	No. of lt. crude seps.	0.010	0.529
Heater/Treaters (light crude)	0.319	scfd CO_2/heater	74,163	No. of heater treaters	0.009	0.454
Headers (heavy crude)[1]	0.002	scfd CO_2/header	13,721	No. of hvy. crude hdrs.	0.000	0.000
Headers (light crude)	0.220	scfd CO_2/header	42,536	No. of lt. crude hdrs.	0.003	0.180
Floating Roof Tanks[1]	17,490	scf CO_2/floating roof tank/yr.	24	No. of floating roof tanks	0.000	0.023
Compressors	2.029	scfd CO_2/compressor	2,479	No. of compressors	0.002	0.097
Large Compressors	332	scfd CO_2/compressor	0	No. of large comprs.	0.000	0.000
Sales Areas	2.096	scf CO_2/loading	1,664,742	Loadings/year	0.003	0.184
Pipelines	NE	scfd of CO_2/mile of pipeline	11,249	Miles of gathering line	NE	NE
Well Drilling	NE	scfd of CO_2/oil well drilled	20,794	No. of oil wells drilled	NE	NE
Battery Pumps	0.012	scfd of CO_2/pump	157,800	No. of battery pumps	0.001	0.038
Process Upset Emissions					**0.004**	**0.201**
Pressure Relief Valves[1]	1.794	scf/yr/PR valve	166,894	No. of PR valves	0.000	0.016
Well Blowouts Onshore	0.051	MMscf/blowout	69	No. of blowouts/yr	0.004	0.185
Refining Emissions					**0.289**	**15.2**
Asphalt Blowing[2]	20,736	scf CO_2/Mbbl	38	Mbbl/calendar day production	0.289	15.2
Total					**6.375**	**337.1**

[1] Emissions are not actually 0, but too small to show at this level of precision.

[2] Asphalt Blowing emissions are the only significant vented emissions from the refining sector; other sources are too small to show at this level of precision.

NE: Not estimated for lack of data

Energy use CO_2 emissions not estimated to avoid double counting with fossil fuel combustion

Table A-144: Summary of CO_2 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2006	2007	2008	2009	2010
Production Field Operations	**376**	**341**	**323**	**285**	**292**	**280**	**311**	**322**
Pneumatic device venting	27	26	24	22	22	23	23	23
Tank venting	328	296	281	246	252	239	270	281
Misc. venting & fugitives	18	18	17	16	16	16	16	16
Wellhead fugitives	1	1	1	1	1	1	1	1
Refining								
Asphalt Blowing	18	19	21	20	18	17	14	15
Total	**394**	**360**	**344**	**306**	**310**	**297**	**325**	**337**

3.6. Methodology for Estimating CO_2, N_2O and CH_4 Emissions from the Incineration of Waste

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), and incineration of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Incineration of waste also results in emissions of N_2O and CH_4. The methodology for calculating emissions from each of these waste incineration sources is described in this Annex.

CO_2 from Plastics Incineration

In the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a), the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2010, the quantity generated, recovered, and discarded for each resin is shown in Table A-145. The data set for 1990 through 2010 is incomplete, and several assumptions were employed to bridge the data gaps. The EPA reports do not provide estimates for individual materials landfilled and incinerated, although they do provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and incinerated, total discards were apportioned based on the proportions of landfilling and incineration for the entire U.S. waste stream for each year in the time series according to *Biocycle's State of Garbage in America* (van Haaren et al. 2010). For those years when distribution by resin category was not reported (1990 through 1994), total values were apportioned according to 1995 (the closest year) distribution ratios. Generation and recovery figures for 2002 and 2004 were linearly interpolated between surrounding years' data.

Table A-145: 2010 Plastics in the Municipal Solid Waste Stream by Resin (Gg)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	3,611	4,944	826	6,740	6,831	1,869	3,293	**28,114**
Recovery	508	517	0	381	54	18	662	**2,141**
Discard	3,103	4,427	826	6,359	6,777	1,851	2,631	**25,973**
Landfill	2,829	4,037	753	5,799	6,179	1,688	2,399	**23,683**
Combustion	274	390	73	561	597	163	232	**2,290**
Recovery*	14%	10%	0%	6%	1%	1%	20%	**8%**
Discard*	86%	90%	100%	94%	99%	99%	80%	**92%**
Landfill*	78%	82%	91%	86%	90%	90%	73%	**84%**
Combustion*	8%	8%	9%	8%	9%	9%	7%	**8%**

*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, C content, and fraction oxidized (see Table A-146). The C 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 A-146: 2010 Plastics Incinerated (Gg), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (Gg)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	274	390	73	561	597	163	232	2,290
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%	-
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	-
Carbon in Resin Combusted	168	328	27	471	502	148	150	1,793
Emissions (Tg CO_2 Eq.)	**0.6**	**1.2**	**0.1**	**1.7**	**1.8**	**0.5**	**0.5**	**6.6**

[a] Weighted average of other plastics produced.

Note: Totals may not sum due to independent rounding.

CO_2 from Incineration of Synthetic Rubber and Carbon Black in Tires

Emissions from tire incineration require two pieces of information: the amount of tires incinerated and the C content of the tires. "U.S. Scrap Tire Management Summary 2005-2009" (RMA 2011) reports that 2084.8 thousand of the 4,391.1 thousand tons of scrap tires generated in 2009 (approximately 47 percent of generation) were used for fuel purposes. Using RMA's estimates of average tire composition and weight, the mass of synthetic rubber and C black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent C by weight, based on the weighted average C contents of the major elastomers used in new tire consumption.[54] Table A- 147 shows consumption and C content of elastomers used for tires and other products in 2002, the most recent year for which data are available.
- C black is 100 percent C (Aslett Rubber Inc. n.d.).

Multiplying the mass of scrap tires incinerated by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yielded CO_2 emissions, as shown in Table A- 148. The disposal rate of rubber in tires (0.4 Tg C/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-145 (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 may also reflect the lag time between consumption and disposal of tires. Tire production and fuel use for 1990 through 2009 were taken from RMA 2006, RMA 2009, RMA 2011; where 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.

In 2009, RMA changed the reporting of scrap tire data from millions of tires to thousands of short tons of scrap tire. As a result, the average weight and percent of the market of light duty and commercial scrap tires was used to convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; RMA 2002 through 2006, 2012a).

Table A- 147: Elastomers Consumed in 2002 (Gg)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	**768**	**91%**	**700**
For Tires	660	91%	602
For Other Products*	108	91%	98
Polybutadiene	**583**	**89%**	**518**
For Tires	408	89%	363
For Other Products	175	89%	155
Ethylene Propylene	**301**	**86%**	**258**
For Tires	6	86%	5
For Other Products	295	86%	253
Polychloroprene	**54**	**59%**	**32**
For Tires	0	59%	0
For Other Products	54	59%	32
Nitrile butadiene rubber solid	**84**	**77%**	**65**
For Tires	1	77%	1
For Other Products	83	77%	64
Polyisoprene	**58**	**88%**	**51**
For Tires	48	88%	42
For Other Products	10	88%	9
Others	**367**	**88%**	**323**
For Tires	184	88%	161
For Other Products	184	88%	161
Total	**2,215**	-	**1,950**
For Tires	**1,307**	-	**1,174**

*Used to calculate C content of non-tire rubber products in municipal solid waste.

- Not applicable

Note: Totals may not sum due to independent rounding.

Table A- 148: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Incineration in 2010

Material	Weight of Material (Tg)	Fraction Oxidized	Carbon Content	Emissions (Tg CO_2 Eq.)
Synthetic Rubber	0.4	98%	90%	1.6
Carbon Black	0.5	98%	100%	1.9
Total	**1.0**	-	-	**3.5**

- Not applicable

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[54] The carbon content of tires (1,174 Gg C) divided by the mass of rubber in tires (1,307 Gg) equals 90 percent.

CO_2 from Incineration 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 incinerated by an average rubber C content. The amount of rubber discarded in the MSW stream was estimated from generation and recycling data[55] provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) and unpublished backup data (Schneider 2007). 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. EPA (2011a) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009 and 2010. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009 and 2010 were set equal to the quantity reported for 2008. Since there was negligible recovery for these product types, all the waste generated is considered to be discarded. Similar to the plastics method, discards were apportioned into landfilling and incineration 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 of 70 percent was assigned to each product type, as shown in Table A-149.[56] A C content of 85 percent was assigned to synthetic rubber for all product types (based on the weighted average C content of rubber consumed for non-tire uses), and a 98 percent fraction oxidized was assumed.

Table A-149: Rubber and Leather in Municipal Solid Waste in 2010

Product Type	Incinerated (Gg)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (Tg CO_2 Eq.)
Durables (not Tires)	275	70%	85%	98%	0.9
Non-Durables	83	-	-	-	0.3
Clothing and Footwear	63	70%	85%	98%	0.2
Other Non-Durables	20	70%	85%	98%	0.1
Containers and Packaging	2	70%	85%	98%	+
Total	**361**	**-**	**-**	**-**	**1.1**

+ Less than 0.05 Tg CO_2 Eq.
- Not applicable.

CO_2 from Incineration of Synthetic Fibers

CO_2 emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average C content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) for textiles. Production data for the synthetic fibers was based on data from the American Chemical Society (FEB 2009). The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table A-150). As with the other materials in the MSW stream, discards were apportioned based on the annually variable proportions of landfilling and incineration for the entire U.S. waste stream, as found in van Haaren et al. (2010). 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 C content of 70 percent was assigned to synthetic fiber using the production-weighted average of the C contents of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 1999 (see Table A-151). The equation relating CO_2 emissions to the amount of textiles combusted is shown below.

$$\text{CO}_2 \text{ Emissions from the Incineration of Synthetic Fibers} = \text{Annual Textile Incineration (Gg)} \times \\ \text{(Percent of Total Fiber that is Synthetic)} \times \text{(Average C Content of Synthetic Fiber)} \times \\ (44\text{g CO}_2/12\text{ g C})$$

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[55] Discards = Generation minus recycling.

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

Table A-150: Synthetic Textiles in MSW (Gg)

Year	Generation	Recovery	Discards	Incineration
1990	2,884	328	2,557	332
1995	3,674	447	3,227	442
1996	3,832	472	3,361	467
1997	4,090	526	3,564	458
1998	4,269	556	3,713	407
1999	4,498	611	3,887	406
2000	4,706	655	4,051	417
2001	4,870	715	4,155	432
2002	5,123	750	4,373	459
2003	5,297	774	4,522	472
2004	5,451	884	4,567	473
2005	5,714	913	4,800	480
2006	5,893	933	4,959	479
2007	6,041	953	5,088	470
2008	6,309	948	5,361	473
2009	6,463	948	5,515	486
2010	6,513	978	5,535	488

Table A-151: Synthetic Fiber Production in 1999

Fiber	Production (Tg)	Carbon Content
Polyester	1.8	63%
Nylon	1.2	64%
Olefin	1.4	86%
Acrylic	0.1	68%
Total	**4.5**	**70%**

N_2O and CH_4 from Incineration of Waste

Estimates of N_2O emissions from the incineration of waste in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995) and presented in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) and unpublished backup data (Schneider 2007). According to this methodology, emissions of N_2O from waste incineration are the product of the mass of waste incinerated, an emission factor of N_2O emitted per unit mass of waste incinerated, and an N_2O emissions control removal efficiency. The mass of waste incinerated was derived from the information published in *BioCycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 50 g N_2O/metric ton MSW based on the 2006 IPCC Guidelines and an estimated emissions control removal efficiency of zero percent were used (IPCC 2006). It was assumed that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009).

Estimates of CH_4 emissions from the incineration of waste in the United States are based on the methodology outlined in IPCC's *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). According to this methodology, emissions of CH_4 from waste incineration are the product of the mass of waste incinerated and an emission factor of CH_4 emitted per unit mass of waste incinerated. Similar to the N_2O emissions methodology, the mass of waste incinerated was derived from the information published in *Biocycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 0.20 kg CH_4/Gg MSW was used based on the 2006 IPCC Guidelines and assuming that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009). No information was available on the mass of waste incinerated from *Biocycle* in 2009 or 2010, so these values were assumed to remain constant at the 2008 level.

Despite the differences in methodology and data sources, the two series of references (EPA's and BioCycle's) provide estimates of total solid waste incinerated that are relatively consistent (see Table A-151).

Table A-152: U.S. Municipal Solid Waste Incinerated, as Reported by EPA and BioCycle (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,632,057
1995	32,241,888	29,639,040
1996	32,740,848	29,707,171
1997	33,294,240	27,798,368
1998	31,216,752	25,489,893
1999	30,881,088	24,296,249
2000	30,599,856	25,974,978
2001	30,481,920	25,942,036[a]
2002	30,255,120	25,802,917
2003	30,028,320	25,930,542[b]
2004	28,585,872	26,037,823
2005	28,685,664	25,973,520[c]
2006	28,985,040	25,853,401
2007	29,003,184	24,788,539[d]
2008	28,622,160	23,674,017
2009	26,317,872	NA
2010	26,544,672	NA

NA (Not Available)

[a] Interpolated between 2000 and 2002 values.

[b] Interpolated between 2002 and 2004 values.

[c] Interpolated between 2004 and 2006 values.

[d] Interpolated between 2006 and 2008 values

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

Bunker fuel emissions estimates for the Department of Defense (DoD) are developed using data generated by the Defense Energy Support Center (DESC) for aviation and naval fuels. The DESC of the Defense Logistics Agency (DLA) prepared a special report based on data in the Fuels Automated System (FAS), a database that recently replaced the Defense Fuels Automated Management System (DFAMS). Data for intermediate fuel oil, however, currently remains in the original DFAMS database. DFAMS/FAS contains data for 1995 through 2010, 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 DoD between 1992 and 1995.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS 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 international fuel transactions/deliveries (i.e., sales abroad).

Step 2: Allocate JP-8 between Aviation and Land-based Vehicles

As a result of DoD[57] and NATO[58] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with JP8 (a type of jet fuel) in compression ignition and turbine engines in land-based equipment. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of JP8 consumption should be attributed to ground vehicle use. Based on available Service data and expert judgment, it was determined that a small fraction of the total JP8 use should be reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. The amount of JP8 reallocated was determined to be between 1.78 and 2.7 times the amount of diesel fuel used, depending on the Service. As a result of this reallocation, the JP8 use reported for aviation will be reduced and the total fuel use for land-based equipment will increase. DoD's total fuel use will not change.

Table A-153 displays DoD's consumption of fuels that remain at the completion of Step 1, summarized by fuel type. Table A-153 reflects the adjustments for jet fuel used in land-based equipment, as described above.

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: 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

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[57] DoD Directive 4140.43, Fuel Standardization, 1998; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 1999.

[58] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipments Using Compression Ignition or Turbine Engines, 1987.

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 DLA Energy were assumed to be zero.

Step 5: 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 A-154 and Table A-155 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 GHG emissions. CO_2 emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy Chapter were based on the totals provided in Table A-154 and Table A-155, below. CO_2 emissions from aviation bunkers and distillate marine bunkers presented in Table A-158, and are based on emissions from fuels tallied in Table A-154 and Table A-155.

Table A-153: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aviation	**4,598.4**	**3,099.9**	**2,941.9**	**2,685.6**	**2,741.4**	**2,635.2**	**2,664.4**	**2,900.6**	**2,609.8**	**2,615.0**	**2,703.1**	**2,338.1**	**2,092.0**	**2,081.0**	**2,067.8**	**1,831.1**	**1,654.6**
Total Jet Fuels	**4,598.4**	**3,099.9**	**2,941.9**	**2,685.6**	**2,741.4**	**2,635.2**	**2,664.4**	**2,900.6**	**2,609.6**	**2,614.9**	**2,703.1**	**2,338.0**	**2,091.9**	**2,080.9**	**2,067.7**	**1,830.9**	**1,654.4**
JP8	285.7	2,182.8	2,253.1	2,072.0	2,122.5	2,066.5	2,122.7	2,326.2	2,091.4	2,094.3	2,126.2	1,838.8	1,709.3	1,618.5	1,616.2	1,374.9	1,118.6
JP5	1,025.4	691.2	615.8	552.8	515.6	505.5	472.1	503.2	442.2	409.1	433.7	421.6	325.5	376.1	362.2	361.4	372.1
Other Jet Fuels	3,287.3	225.9	72.9	60.9	103.3	63.3	69.6	71.2	76.1	111.4	143.2	77.6	57.0	86.3	89.2	94.6	163.6
Aviation Gasoline	+	+	+	+	+	+	+	+	0.1	0.1	+	0.1	0.1	0.2	0.1	0.2	0.2
Marine	**686.8**	**438.9**	**493.3**	**639.8**	**674.2**	**598.9**	**454.4**	**418.4**	**455.8**	**609.1**	**704.5**	**604.9**	**531.6**	**572.8**	**563.4**	**500.5**	**489.1**
Middle Distillate (MGO)	+	+	38.5	47.5	51.1	49.2	48.3	33.0	41.2	88.1	71.2	54.0	45.8	45.7	55.2	56.8	47.9
Naval Distillate (F76)	686.8	438.9	449.0	583.4	608.4	542.9	398.0	369.1	395.1	460.9	583.5	525.9	453.6	516.0	483.4	412.5	425.9
Intermediate Fuel Oil (IFO)[b]	+	+	5.9	9.0	14.7	6.7	8.1	16.3	19.5	60.2	49.9	25.0	32.2	11.1	24.9	31.2	15.3
Other[c]	**717.1**	**310.9**	**276.9**	**263.3**	**256.8**	**256.0**	**248.2**	**109.8**	**211.1**	**221.2**	**170.9**	**205.6**	**107.3**	**169.0**	**173.6**	**174.6**	**187.5**
Diesel	93.0	119.9	126.1	132.6	139.5	146.8	126.6	26.6	57.7	60.8	46.4	56.8	30.6	47.3	49.1	49.0	53.4
Gasoline	624.1	191.1	150.8	119.0	93.9	74.1	74.8	24.7	27.5	26.5	19.4	24.3	11.7	19.2	19.7	19.7	19.4
Jet Fuel[d]	+	+	+	11.7	23.4	35.0	46.7	58.4	125.9	133.9	105.1	124.4	65.0	102.6	104.8	105.9	114.8
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,712.1**	**3,588.8**	**3,672.4**	**3,490.1**	**3,367.0**	**3,428.8**	**3,276.7**	**3,445.3**	**3,578.5**	**3,148.6**	**2,730.9**	**2,822.8**	**2,804.9**	**2,506.2**	**2,331.2**

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 0.05 million gallons.

Table A-154: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
JP8	**56.7**	**300.4**	**308.8**	**292.0**	**306.4**	**301.4**	**307.6**	**341.2**	**309.5**	**305.1**	**309.8**	**285.6**	**262.5**	**249.1**	**229.4**	**212.5**	**182.4**
Navy	56.7	38.3	39.8	46.9	53.8	55.5	53.4	73.8	86.6	76.3	79.2	70.9	64.7	62.7	59.2	56.4	60.4
Air Force	0.0	262.2	269.0	245.1	252.6	245.9	254.2	267.4	222.9	228.7	230.6	214.7	197.8	186.5	170.3	156.1	122.0
JP5	**370.5**	**251.5**	**221.3**	**196.4**	**186.6**	**175.8**	**160.9**	**168.9**	**158.2**	**146.5**	**159.0**	**162.1**	**128.0**	**147.1**	**141.8**	**138.7**	**144.8**
Navy	365.3	246.3	216.1	191.2	181.4	170.6	155.6	163.7	153.0	141.3	153.8	156.9	122.8	141.8	136.5	133.4	139.6
Air Force	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
JP4	**420.8**	**21.5**	**1.1**	**0.1**	+	+	+	+	+	+	+	+	+	+	+	+	0.1
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	420.8	21.5	1.1	0.1	+	+	+	+	+	+	+	+	+	+	+	+	0.1
JAA	**13.7**	**9.2**	**10.3**	**9.4**	**10.8**	**10.8**	**12.5**	**12.6**	**13.7**	**21.7**	**30.0**	**15.5**	**11.7**	**15.6**	**16.8**	**18.1**	**31.5**
Navy	8.5	5.7	6.6	5.9	6.6	6.3	7.9	8.0	9.8	15.5	21.5	11.6	9.1	11.7	12.5	12.3	13.8
Air Force	5.3	3.5	3.7	3.5	4.2	4.5	4.5	4.6	3.8	6.2	8.6	3.9	2.6	3.9	4.3	5.8	17.7
JA1	+	+	+	+	+	+	+	0.1	0.6	0.2	0.5	0.5	0.4	1.1	1.0	0.5	+
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	0.6	+	+	0.5	+	1.0	0.8	0.6	+
JAB	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy Subtotal	**430.5**	**290.2**	**262.5**	**244.0**	**241.8**	**232.4**	**216.9**	**245.5**	**249.4**	**233.1**	**254.4**	**239.4**	**196.6**	**216.3**	**208.3**	**202.1**	**213.4**
Air Force Subtotal	**431.3**	**292.4**	**279.0**	**253.9**	**262.1**	**255.6**	**264.0**	**277.3**	**232.6**	**240.3**	**244.9**	**224.4**	**206.0**	**196.6**	**180.7**	**167.8**	**145.2**
Total	**861.8**	**582.6**	**541.5**	**497.9**	**503.9**	**488.0**	**480.9**	**522.8**	**482.0**	**473.4**	**499.3**	**463.8**	**402.6**	**412.9**	**389.0**	**369.8**	**358.6**

+ Does not exceed 0.05 million gallons.

Note: Totals may not sum due to independent rounding.

Table A-155: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Navy—MGO	+	+	30.3	35.6	31.9	39.7	23.8	22.5	27.1	63.7	56.2	38.0	33.0	31.6	40.9	39.9	32.5
Navy—F76	522.4	333.8	331.9	441.7	474.2	466.0	298.6	282.6	305.6	347.8	434.4	413.1	355.9	404.1	376.9	320.0	332.9
Navy—IFO	+	+	4.6	7.1	11.6	5.3	6.4	12.9	15.4	47.5	39.4	19.7	25.4	8.8	19.0	24.1	11.8
Total	**522.4**	**333.8**	**366.8**	**484.3**	**517.7**	**511.0**	**328.8**	**318.0**	**348.2**	**459.0**	**530.0**	**470.7**	**414.3**	**444.4**	**436.7**	**384.0**	**377.2**

+ Does not exceed 0.005 million gallons.

Note: Totals may not sum due to independent rounding.

Table A-156: Aviation and Marine Carbon Contents (Tg Carbon/QBtu) and Fraction Oxidized

Mode (Fuel)	Carbon Content Coefficient	Fraction Oxidized
Aviation (Jet Fuel)	Variable	1.00
Marine (Distillate)	20.17	1.00
Marine (Residual)	20.48	1.00

Source: EPA (2010) and IPCC (2006)

Table A-157: Annual Variable Carbon Content Coefficient for Jet Fuel (Tg Carbon/QBtu)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jet Fuel	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70

Source: EPA (2010)

Table A-158: Total U.S. DoD CO_2 Emissions from Bunker Fuels (Tg CO_2 Eq.)

Mode	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aviation	8.1	5.6	5.3	4.8	4.9	4.7	4.7	5.1	4.7	4.6	4.9	4.5	3.9	4.0	3.8	3.6	3.5
Marine	5.4	3.4	3.8	5.0	5.3	5.2	3.4	3.3	3.6	4.7	5.4	4.8	4.2	4.6	4.5	3.9	3.9
Total	**13.4**	**9.0**	**9.0**	**9.8**	**10.2**	**10.0**	**8.0**	**8.3**	**8.3**	**9.3**	**10.3**	**9.3**	**8.2**	**8.6**	**8.3**	**7.5**	**7.4**

Note: Totals may not sum due to independent rounding.

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

Emissions of HFCs and PFCs from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. 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. consumption 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 five ODS substitute end-use sectors: air-conditioning and refrigeration, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 60 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and the characteristics of each end-use such as market size or charge sizes and loss rates. 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 or otherwise common in the industry. 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 and Earth Technologies Forums. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy; the Air-Conditioning, Heating 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 emission 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 determining the transition path of each regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives have been used, and what fraction of the ODS market in each end-use has been 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 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 ODS, as well as data on how the substitutes are replacing the ODS, to simulate the implementation of new technologies that enter the market in 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 seen historically and 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. For any given year, these lifetime emissions (for existing equipment) and disposal emissions (from discarded equipment) 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:

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

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 leakage and servicing (including 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 A- 159, 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.

Table A- 159: Refrigeration and Air-Conditioning Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Centrifugal Chillers													
CFC-11	HCFC-123	1993	1993	45%	Unknown								0.5%
	HCFC-22	1991	1993	16%	HFC-134a	2000	2010	100%	None				
	HFC-134a	1992	1993	39%	None								
CFC-12	HFC-134a	1992	1994	53%	None								0.5%
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	None				
	HCFC-123	1993	1994	31%	Unknown								
R-500	HFC-134a	1992	1994	53%	None								0.5%
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	None				
	HCFC-123	1993	1994	31%	Unknown								
CFC-114	HFC-236fa	1993	1996	100%	HFC-134a	1998	2009	100%	None				0.2%
Cold Storage													
CFC-12	HCFC-22	1990	1993	65%	R-404A	1996	2010	75%	None				2.5%
					R-507	1996	2010	25%	None				
	R-404A	1994	1996	26%	None								
	R-507	1994	1996	9%	None								
HCFC-22	HCFC-22	1992	1993	100%	R-404A	1996	2009	8%	None				2.5%
					R-507	1996	2009	3%	None				
					R-404A	2009	2010	68%	None				
					R-507	2009	2010	23%	None				
R-502	HCFC-22	1990	1993	40%	R-404A	1996	2010	38%	None				2.5%
					R-507	1996	2010	12%	None				
					Non-ODP/GWP	1996	2010	50%	None				
	R-404A	1993	1996	45%	None								
	R-507	1994	1996	15%	None								
Commercial Unitary Air Conditioners (Large)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	2001	2005	5%	None				0.8%
					R-407C	2006	2009	1%	None				
					R-410A	2006	2009	9%	None				
					R-407C	2009	2010	5%	None				
					R-410A	2009	2010	81%	None				
Commercial Unitary Air Conditioners (Small)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	1996	2000	3%	None				0.8%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				
Dehumidifiers													
HCFC-22	HFC-134a	1997	1997	89%	None								0.2%
	R-410A	2007	2010	11%	None								

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Ice Makers													
CFC-12	HFC-134a	1993	1995	100%	None								2.5%
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	Unknown								2.5%
	HFC-134a	1992	1994	15%	None								
	HCFC-22	1991	1994	15%	HFC-134a	1995	2010	100%	None				
CFC-12	HCFC-22	1991	1994	10%	HFC-134a	1995	2010	15%	None				2.5%
					R-404A	1995	2010	50%	None				
					R-410A	1999	2010	20%	None				
					R-507	1995	2010	15%	None				
	HCFC-123	1992	1994	35%	Unknown								
	HFC-134a	1992	1994	50%	None								
	R-401A	1995	1996	5%	HFC-134a	1997	2000	100%	None				
HCFC-22	HFC-134a	1995	2009	2%	None								2.5%
	R-404A	1995	2009	5%	None								
	R-410A	1999	2009	2%	None								
	R-507	1995	2009	2%	None								
	HFC-134a	2009	2010	14%	None								
	R-404A	2009	2010	45%	None								
	R-410A	2009	2010	18%	None								
	R-507	2009	2010	14%	None								
Mobile Air Conditioners (Passenger Cars)													
CFC-12	HFC-134a	1992	1994	100%	None								1.9%
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	None								-0.4%
Mobile Air Conditioners (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				2.6%
	HFC-134a	1994	1997	99.5%	None								
Mobile Air Conditioners (Transit Buses)													
HCFC-22	HFC-134a	1995	2009	100%	None								2.6%
Mobile Air Conditioners (Trains)													
HCFC-22	HFC-134a	2002	2009	50%	None								2.6%
	R-407C	2002	2009	50%	None								
Packaged Terminal Air Conditioners and Heat Pumps													
HCFC-22	R-410A	2006	2009	10%	None								0.8%
	R-410A	2009	2010	90%	None								
Positive Displacement Chillers													
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	None				0.5%
					R-410A	2010	2020	40%	None				
	R-407C	2000	2009	1%	None								
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
									R-410A	2010	2020	40%	
					R-407C	2009	2010	9%	None				
CFC-12	HCFC-22	1993	1993	100%	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	0.2%
									R-410A	2010	2020	40%	
					R-407C	2000	2009	1%	None				
					HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	
									R-410A	2010	2020	40%	
					R-407C	2009	2010	9%	None				
Refrigerated Appliances													
CFC-12	HFC-134a	1994	1995	100%	None								0.5%
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				0.8%
					R-410A	2010	2010	71%	None				
	R-410A	2000	2005	5%	R-410A	2006	2006	100%	None				
	R-410A	2000	2006	5%	None								
	R-410A	2006	2006	20%	None								
Retail Food (Large)													
CFC-12[59]	R-404A	1995	2000	17.5%	R-404A	2000	2000	100%	R-404A	2000	2009	1.7%	0.8%
									R-507	2000	2009	0.3%	
									R-404A	2000	2009	16.2%	
									R-507	2000	2009	1.4%	
									R-407A	2000	2009	0.4%	
	R-507	1995	2000	7.5%	R-507	2000	2000	100%	R-404A	2000	2009	1.7%	
									R-507	2000	2009	0.3%	
									R-404A	2000	2009	16.2%	
									R-507	2000	2009	1.4%	
									R-407A	2000	2009	0.4%	
	HCFC-22	2000	2000	75%	R-404A	2001	2010	1.7%	None				
					R-507	2001	2010	0.3%	None				
					R-404A	2001	2010	16%	None				
					R-507	2001	2010	1%	None				
					R-407A	2001	2010	0%	None				
					R-404	2009	2010	64%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	

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[59] The CFC-12 retail food market transitioned to R-502 in 1988 (reaching 100% market penetration in 1990) and subsequently transitioned to HCFC-22 in 1991 (reaching 100% market penetration in 1993). These transitions are not shown in this table in order to provide the HFC transitions in greater detail.

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	
R-502[60]	HCFC-22	1995	2000	75%	R-507	2009	2010	8%	R-404A	2010	2010	4.3%	0.8%
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-407A	2009	2010	4%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-404A	2010	2010	4%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-404A	2001	2010	16.2%					
					R-507	2001	2010	1.4%					
					R-407A	2001	2010	0.4%					
					R-404A	2001	2010	1.7%					
					R-507	2001	2010	0.3%					
					R-404A	2009	2010	64%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-507	2009	2010	8.0%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-407A	2009	2010	4.0%	R-404A	2010	2010	4.3%	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
					R-404A	2010	2010	4.0%	R-404A	2010	2010	4.3%	

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[60] The R-502 retail food market transitioned to HCFC-22 in 1990 (reaching 100% market penetration in 1993). This transition is not shown in this table in order to provide the HFC transitions in greater detail.

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
									R-507A	2010	2010	0.8%	
									R-404A	2010	2010	31.5%	
									R-507A	2010	2010	2.8%	
									R-407A	2010	2010	0.7%	
	R-404A	1995	2000	17.5%	R-404A	2000	2009	1.7%	None				
					R-507	2000	2009	0.3%	None				
					R-404A	2000	2009	16.2%	None				
					R-507	2000	2009	1.4%	None				
					R-407A	2000	2009	0.4%	None				
	R-507	1995	2000	7.5%	R-404A	2000	2009	1.7%	None				
					R-507	2000	2009	0.3%	None				
					R-404A	2000	2009	16.2%	None				
					R-507	2000	2009	1.4%	None				
					R-407A	2000	2009	0.4%	None				
Retail Food (Large Condensing Units)													
HCFC-22	R-402	1995	2005	5%	R-404	2006	2006	100%	None				0.9%
	R-404A	1995	2005	25%	None								
	R-507	1995	2005	10%	None								
	R-404A	2008	2010	45%	None								
	R-507	2008	2010	15%	None								
Retail Food (Small Condensing Units)													
HCFC-22	R-401	1995	2005	6%	HFC-134a	2006	2006	100%	None				0.9%
	R-402	1995	2005	4%	HFC-134a	2006	2006	100%	None				
	HFC-134a	1993	2005	30%									
	R-404A	1995	2005	30%									
	R-404A	2008	2010	30%									
Retail Food (Small)													
CFC-12	HCFC-22	1990	1993	90%	HFC-134a	1993	1995	90%	CO_2	2010	2010	5%	0.8%
					R-404A	2000	2009	7.5%	None				
					R-507	2000	2009	2.5%	None				
	R-404A	1993	1996	7.5%	None								
	R-507	1993	1996	2.5%	None								
Transport Refrigeration													
CFC-12	HFC-134a	1993	1995	98%	None								2.5%
	HCFC-22	1993	1995	2%	HFC-134a	1995	1999	100%	None				
R-502	HFC-134a	1993	1995	55%	None								2.5%
	R-404A	1993	1995	45%	None								
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%					None				0.8%
	R-410A	2000	2006	5%					None				
	HFC-134a	2000	2009	2%					None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
	R-407C	2006	2009	2.5%					None				
	R-410A	2006	2009	4.5%					None				
	HFC-134a	2009	2010	18%					None				
	R-407C	2009	2010	22.5%					None				
	R-410A	2009	2010	40.5%					None				
Window Units													
HCFC-22	R-410A	2008	2009	10%	None								5.0%
	R-410A	2009	2010	90%	None								

Table A- 160 presents the average equipment lifetimes and annual HFC emission rates (for servicing and leaks) for each end-use assumed by the Vintaging Model.

Table A- 160. Refrigeration and Air-conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Emission Rates (%)
Centrifugal Chillers	20 – 27	2.0 – 10.9
Cold Storage	20 – 25	15.0
Commercial Unitary A/C	15	7.9 – 8.6
Dehumidifiers	11	0.5
Ice Makers	20	3.0
Industrial Process Refrigeration	25	3.6 – 12.3
Mobile Air Conditioners	5 –12	2.3 – 18.0
Positive Displacement Chillers	20	0.5 – 1.5
PTAC/PTHP	12	3.9
Retail Food	18 – 20	1.0 – 25
Refrigerated Appliances	14	0.6
Residential Unitary A/C	15	11.8
Transport Refrigeration	12	20.6 – 27.9
Water & Ground Source Heat Pumps	20	3.9
Window Units	12	0.6

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: metered dose inhalers (MDI) and consumer aerosols. In the United States, the use of CFCs in consumer aerosols was banned in 1978, and many products transitioned to hydrocarbons or "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays. However, MDIs can continue to use CFCs as propellants because their use has been deemed essential. Essential use exemptions granted to the United States under the Montreal Protocol for CFC use in MDIs are limited to the treatment of asthma and chronic obstructive pulmonary disease.

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.

Transition 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 A- 161.

Table A- 161. Aerosol Product Transition Assumptions

Initial Market Segment	**Primary Substitute**				**Secondary Substitute**				**Growth Rate**
	Name of Substitute	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	
				MDIs					
CFC Mix*	HFC-134a	1997	1997	6%	None				0.8%
	Non-ODP/GWP	1998	2007	7%	None				
	CFC Mix*	2000	2000	87%	HFC-134a	2002	2002	34%	
					HFC-134a	2003	2009	47%	
					HFC-227ea	2006	2009	5%	
					HFC-134a	2010	2011	6%	
					HFC-227ea	2010	2011	1%	
					HFC-134a	2011	2012	3%	
					HFC-227ea	2011	2012	0.3%	
					HFC-134a	2014	2014	3%	
					HFC-227ea	2014	2014	0.3%	
				Consumer Aerosols (Non-MDIs)					
NA**	HFC-152a	1990	1991	50%	None				2.0%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	
					HFC-152a	2001	2005	36%	

*CFC Mix consists of CFC-11, CFC-12 and CFC-114 and represents the weighted average of several CFCs consumed for essential use in MDIs from 1993 to 2008.

**Consumer Aerosols transitioned away from ODS prior to 1985, the year in which the Vintaging Model begins. 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, 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.

Transition 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 A- 162.

Table A-162. Solvent Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Adhesives									
CH_3CCl_3	Non-ODP/GWP	1994	1995	100%	None				2.0%
Electronics									
CFC-113	Semi-Aqueous	1994	1995	52%	None				2.0%
	HCFC-225ca/cb	1994	1995	0.2%	Unknown				
	HFC-4310mee	1995	1996	0.7%	None				
	HFE-7100	1994	1995	0.7%	None				
	nPB	1992	1996	5%	None				
	Methyl Siloxanes	1992	1996	0.8%	None				
	No-Clean	1992	1996	40%	None				
CH_3CCl_3	Non-ODP/GWP	1996	1997	99.8%	None				2.0%
	PFC/PFPE	1996	1997	0.2%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
Metals									
CH_3CCl_3	Non-ODP/GWP	1992	1996	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	1996	100%	None				2.0%
CCl_4	Non-ODP/GWP	1992	1996	100%	None				2.0%
Precision									
CH_3CCl_3	Non-ODP/GWP	1995	1996	99.3%	None				2.0%
	HFC-4310mee	1995	1996	0.6%	None				
	PFC/PFPE	1995	1996	0.1%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
CFC-113	Non-ODP/GWP	1995	1996	96%	None				2.0%
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

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, non-halon emissions are assumed to be 3.5 percent of all chemical in use in each year, while in flooding systems 2.5 percent of the installed base of chemical is assumed to leak annually. Halon systems are assumed to leak at higher rates. 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, streaming applications have a 12-year lifetime and flooding applications have a 20-year lifetime.

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

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.

Transition Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table A- 163.

Table A- 163. Fire Extinguishing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Flooding Agents									
Halon-1301	Halon-1301*	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	18%	FK-5-1-12	2003	2010	10%	
					HFC-125	2001	2008	10%	
	Non-ODP/GWP	1994	1994	46%	FK-5-1-12	2003	2010	7%	
	Non-ODP/GWP	1995	2034	10%	None				
	Non-ODP/GWP	1998	2027	10%	None				
	C_4F_{10}	1994	1999	1%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	11%	None				
Streaming Agents									
Halon-1211	Halon-1211*	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1997	4%	Non-ODP/GWP	2015	2015	25%	
					HFC-236fa	2015	2015	75%	
	Non-ODP/GWP	1993	1994	58%	None				
	Non-ODP/GWP	1995	2024	20%	None				
	Non-ODP/GWP	1999	2018	10%	None				

*Despite the 1994 consumption ban, a small percentage of new halon systems are assumed to continue to be built and filled with stockpiled or recovered supplies.

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 content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion after disposal; these portions vary by end-use.

Step 1: Calculate manufacturing emissions (open-cell and closed-cell foams)

Manufacturing emissions occur in the year of foam manufacture, and are calculated as presented in the following equation.

$$Em_j = lm \times Qc_j$$

Where:

Em_j = Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.

lm = Loss Rate. Percent of original blowing agent emitted during foam manufacture. For open-cell foams, lm is 100%.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

j = Year of emission.

Step 2: Calculate lifetime emissions (closed-cell foams)

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated as presented in the following equation.

$$Eu_j = lu \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where:

Eu_j = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

lu = Leak Rate. Percent of original blowing agent emitted each year during lifetime use.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

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

j = Year of emission.

k = Lifetime. The average lifetime of foam product.

Step 3: Calculate disposal emissions (closed-cell foams)

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in the following equation.

$$Ed_j = ld \times Qc_{j-k}$$

Where:

Ed_j = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

ld = Loss Rate. Percent of original blowing agent emitted at disposal.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

j = Year of emission.

k = Lifetime. The average lifetime of foam product.

Step 4: Calculate post-disposal emissions (closed-cell foams)

Post-Disposal emissions occur in the years after the foam is disposed; for example, emissions might occur while the disposed foam is in a landfill. Currently, the only foam type assumed to have post-disposal emissions is polyurethane foam used as domestic refrigerator and freezer insulation, which is expected to continue to emit for 26 years post-disposal, calculated as presented in the following equation.

$$Ep_j = lp \times \sum Qc_{j-m} \quad for\ m=k \rightarrow k + 32$$

Where:

Ep_j = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

lp = Leak Rate. Percent of original blowing agent emitted post disposal.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

k = Lifetime. The average lifetime of foam product.

m = Counter. Runs from lifetime (k) to (k+26).

j = Year of emission.

Step 5: Calculate total emissions (open-cell and closed-cell foams)

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in the following equation.

$$E_j = Em_j + Eu_j + Ed_j + Ep_j$$

Where:

E_j = Total Emissions. Total emissions of a specific chemical in year *j*, by weight.

Em = Emissions from manufacturing. Total emissions of a specific chemical in year *j* due to manufacturing losses, by weight.

Eu_j = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

Ed_j = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

Ep_j = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

Assumptions

The Vintaging Model contains 13 foam types, whose transition assumptions away from ODS and growth rates are presented in Table A- 164. The emission profiles of these 13 foam types are shown in Table A- 165.

Table A- 164. Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	
Commercial Refrigeration Foam													
CFC-11	HCFC-141b	1989	1996	40%	HFC-245fa	2002	2003	80%	None				6.0%
					Non-ODP/GWP	2002	2003	20%	None				
	HCFC-142b	1989	1996	8%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	None				
	HCFC-22	1989	1996	52%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	None				
Flexible PU Foam: Integral Skin Foam													
CFC-11	HCFC-141b	1989	1990	100%	HFC-134a	1993	1996	25%	None				2.0%
					HFC-134a	1994	1996	25%	None				
					CO_2	1993	1996	25%	None				
					CO_2	1994	1996	25%	None				
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								2.0%
Phenolic Foam													
CFC-11	HCFC-141b	1989	1990	100%	Non-ODP/GWP	1992	1992	100%	None				2.0%
Polyolefin Foam													
CFC-114	HFC-152a	1989	1993	10%	Non-ODP/GWP	2005	2010	100%	None				2.0%
	HCFC-142b	1989	1993	90%	Non-ODP/GWP	1994	1996	100%	None				
PU and PIR Rigid: Boardstock													
CFC-11	HCFC-141b	1993	1996	100%	Non-ODP/GWP	2000	2003	95%	None				6.0%
					HC/HFC-245fa Blend	2000	2003	5%	None				
PU Rigid: Domestic Refrigerator and Freezer Insulation													
CFC-11	HCFC-141b	1993	1995	100%	HFC-134a	1996	2001	7%	Non-ODP/GWP	2002	2003	100%	0.8%
					HFC-245fa	2001	2003	50%	Non-ODP/GWP	2015	2029	100%	
					HFC-245fa	2006	2009	10%	Non-ODP/GWP	2015	2029	100%	
					Non-ODP/GWP	2002	2005	10%	None				
					Non-ODP/GWP	2006	2009	3%	None				
					Non-ODP/GWP	2009	2014	20%	None				
PU Rigid: One Component Foam													
CFC-12	HCFC-142b/22 Blend	1989	1996	70%	Non-ODP/GWP	2009	2010	80%	None				4.0%
					HFC-134a	2009	2010	10%	None				
					HFC-152a	2009	2010	10%	None				
	HCFC-22	1989	1996	30%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-134a	2009	2010	10%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	
					HFC-152a	2009	2010	10%	None				
PU Rigid: Other: Slabstock Foam													
CFC-11	HCFC-141b	1989	1996	100%	CO_2	1999	2003	45%	None				2.0%
					Non-ODP/GWP	2001	2003	45%	None				
					HCFC-22	2003	2003	10%	Non-ODP/GWP	2009	2010	100%	
PU Rigid: Sandwich Panels: Continuous and Discontinuous													
CFC-11	HCFC-141b	1989	1996	82%	HCFC-22/Water Blend	2001	2003	20%	HFC-245fa/CO_2 Blend	2009	2010	50%	6.0%
									Non-ODP/GWP	2009	2010	50%	
					HFC-245fa/CO_2 Blend	2002	2004	20%	None				
					Non-ODP/GWP	2001	2004	40%	None				
					HFC-134a	2002	2004	20%	None				
	HCFC-22	1989	1996	18%	HFC-245fa/CO_2 Blend	2009	2010	40%	None				
					Non-ODP/GWP	2009	2010	20%	None				
					CO_2	2009	2010	20%	None				
					HFC-134a	2009	2010	20%	None				
PU Rigid: Spray Foam													
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	30%	None				6.0%
					HFC-245fa/CO_2 Blend	2002	2003	60%	None				
					Non-ODP/GWP	2001	2003	10%	None				
XPS: Boardstock Foam													
CFC-12	HCFC-142b/22 Blend	1989	1994	10%	HFC-134a	2009	2010	70%	None				2.5%
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
	HCFC-142b	1989	1994	90%	HFC-134a	2009	2010	70%	None				
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
XPS: Sheet Foam													
CFC-12	CO_2	1989	1994	1%	None								2.0%
	Non-ODP/GWP	1989	1994	99%	CO_2	1995	1999	9%	None				
					HFC-152a	1995	1999	10%	None				

Table A- 165. 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 Foam: Slabstock Foam, Moulded Foam	100	0	1	0	100
Commercial Refrigeration	6	0.25	15	90.25	100
Rigid PU: Spray Foam	15	1.5	56	1	100
Rigid PU: Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic Foam	23	0.875	32	49	100
Polyolefin Foam	95	2.5	2	0	100
Rigid PU: One Component Foam	100	0	1	0	100
XPS: Sheet Foam*	40	2	25	0	90
XPS: Boardstock Foam	25	0.75	50	37.5	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation*	4	0.25	14	40.0	47.5
PU and PIR Rigid: Boardstock	6	1	50	44	100
PU Sandwich Panels: Continuous and Discontinuous	5.5	0.5	50	69.5	100

PIR (Polyisicyanurate)
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 emission; it is unclear at this time whether that was intentional. In the Rigid PU Appliance Foam end-use, the source of emission rates and lifetimes did not yield 100 percent emission; the remainder is anticipated to be emitted at a rate of 2.0%/year post-disposal for the next 26 years.

Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12 percent ethylene oxide (EtO) and 88 percent CFC-12, known as “12/88.” In that blend, ethylene oxide sterilizes the equipment and CFC-12 is a dilutent solvent to form a non-flammable blend. 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.

Assumptions

The Vintaging Model contains 1 sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A- 166.

Table A-166. Sterilization Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment**	**Maximum Market Penetration**	
Commercial Refrigeration Foam													
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	1%	None								
	HCFC/EtO Blends	1993	1994	4%	Non-ODP/GWP	2010	2010	100%	None				

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 or sector basis. Values for use and emissions are calculated both in metric tons and in teragrams of CO_2 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.

Bank of ODS and ODS Substitutes

The bank of an ODS or an ODS substitute is "the cumulative difference between the chemical that has been consumed in an application or sub-application and that which has already been released" (IPCC 2006). For any given year, the bank is equal to the previous year's bank, less the chemical in equipment disposed of during the year, plus chemical in new equipment entering the market during that year, less the amount emitted but not replaced, plus the amount added to replace chemical emitted prior to the given year, as shown in the following equation:

$$Bc_j = Bc_{j-1} - Qd_j + Qp_j + E_e - Q_r$$

Where:

Bc_j = Bank of Chemical. Total bank of a specific chemical in year *j*, by weight.

Qd_j = Quantity of Chemical in Equipment Disposed. Total quantity of a specific chemical in equipment disposed of in year *j*, by weight.

Qp_j = Quantity of Chemical Penetrating the Market. Total quantity of a specific chemical that is entering the market in year *j*, by weight.

E_e = Emissions of Chemical Not Replaced. Total quantity of a specific chemical that is emitted during year j but is not replaced in that year. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors except foam blowing.

Q_r = Chemical Replacing Previous Year's Emissions. Total quantity of a specific chemical that is used to replace emissions that occurred prior to year j. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors.

j = Year of emission.

Table A- 167 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990-2010.

Table A- 167. Banks of ODS and ODS Substitutes, 1990-2010 (MT)

	CFC	HCFC	HFC
1990	669,869	283,288	868
1995	764,257	497,567	52,559
2000	629,594	922,760	183,071
2001	604,142	991,621	210,409
2002	580,462	1,044,581	240,774
2003	557,254	1,080,071	277,173
2004	535,367	1,117,629	313,636
2005	517,882	1,159,409	347,363
2006	503,839	1,196,960	381,821
2007	491,705	1,226,674	416,534
2008	483,578	1,246,132	448,792
2009	480,177	1,241,545	491,133
2010	466,203	1,206,136	559,470

References

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.9. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and the non-horse equids (mules, burros, and donkeys). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle. The IPCC Tier 1 methodology was used to estimate emissions for the other types of livestock, including horses, goats, sheep, swine, American bison, mules, burros, and donkeys.

Estimate Methane Emissions from Cattle

This section describes the process used to estimate methane emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM).[61] The CEFM was developed based on recommendations provided in IPCC/UNEP/OECD/IEA (1997), IPCC (2000) and IPCC (2006), and uses information on population, energy requirements, digestible energy, and CH_4 conversion rates to estimate methane emissions.[62] The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emission profiles; (2) characterize cattle diets to generate information needed to estimate emission factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

The state-level cattle population estimates in the inventory submission are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2011). A summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-168. Cattle populations used in the Enteric Fermentation sector were estimated using the cattle transition matrix in the CEFM, which uses January 1 USDA population estimates and weight data to simulate the population of U.S. cattle from birth to slaughter, and results in an estimate of the number of animals in a particular cattle grouping while taking into account the monthly rate of weight gain, the average weight of the animals, and the death and calving rates. The use of supplemental USDA data and the cattle transition matrix in the CEFM results in cattle population estimates for this sector differing slightly from the January 1 or July 1 USDA point estimates and the cattle population data obtained from the Food and Agriculture Organization of the United Nations (FAO).

Table A-168: Cattle Population Estimates from the CEFM Transition Matrix for 1990-2010 (1,000 head)

Livestock Type	1990	1995	2000	2005	2007	2008	2009	2010
Calves 0-6 months	22,561	23,499	22,569	21,678	21,483	21,155	21,001	20,856
Dairy								
Dairy Cows	10,015	9,482	9,183	9,004	9,145	9,257	9,333	9,086
Dairy Replacements 7-11 months	1,214	1,216	1,196	1,257	1,299	1,304	1,327	1,345
Dairy Replacements 12-23 months	2,915	2,892	2,812	2,905	3,043	3,097	3,101	3,177
Beef								
Bulls	2,160	2,385	2,293	2,214	2,214	2,207	2,184	2,190
Beef Cows	32,455	35,190	33,575	32,674	32,644	32,435	31,712	31,371
Beef Replacements 7-11 months	1,269	1,493	1,313	1,363	1,349	1,312	1,288	1,241
Beef Replacements 12-23 months	2,967	3,637	3,097	3,171	3,276	3,169	3,097	3,047
Steer Stockers	10,321	11,716	8,724	8,185	8,302	8,233	8,515	8,226
Heifer Stockers	5,946	6,699	5,371	5,015	4,966	4,868	5,061	5,040
Feedlot Cattle	9,549	11,064	13,006	12,652	13,404	13,070	12,954	13,254

The population transition matrix in the CEFM simulates the U.S. cattle population over time and provides an estimate of the population age and weight structure by cattle type on a monthly basis.[63] Since cattle often do not remain in a single population type for an entire year (e.g., calves become stockers, stockers become feedlot animals), and emission profiles vary both between and within each cattle type, these monthly age groups are tracked in the enteric fermentation model to obtain more accurate emission estimates than would be available from annual point estimates of population (such as available from USDA statistics) and weight for each cattle type.

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[61] The IPCC recommends the use of a methane conversion factor of zero for calves, because they consume mainly milk; therefore, this results in no methane emissions from calves through 6 months.

[62] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

[63] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2011).

The transition matrix tracks both dairy and beef populations, and divides the populations into males and females, and subdivides the population further into specific cattle groupings for calves, replacements, stocker, feedlot, and mature animals. The matrix is based primarily on two types of data: population statistics and weight statistics (including target weights, slaughter weights, and weight gain). Using the weight data, the transition matrix simulates the growth of animals over time by month. The matrix also relies on supplementary data, such as feedlot placement statistics, slaughter statistics, death rates, and calving rates.

The basic method for tracking population of animals per category is based on the 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 (such as stockers to feedlot placements).

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 CH_4 emissions associated with each life stage. Given that a stage can last less than one year (e.g., beef calves are weaned at 7 months), each is modeled on a per-month basis. The type of cattle also impacts CH_4 emissions (e.g., beef versus dairy). Consequently, there is an independent transition matrix for each of three separate lifecycle phases, 1) calves, 2) replacements and stockers, and 3) feedlot animals. In addition, the number of mature cows and bulls are tabulated for both dairy and beef stock. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-169.

Table A-169: Cattle Population Categories Used for Estimating CH_4 Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers & Steers)
	Cows
	Bulls*

* Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories are as follows:

Calves. 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 (2011). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month), beef births are distributed according to Table A-170, based on estimates from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). To determine whether calves were born to dairy or beef cows, the dairy cow calving rate (USDA/APHIS/VS 2002, USDA/APHIS/VS 1996) was multiplied by the total dairy cow population to determine the number of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows. Total annual calf births are obtained from USDA, and distributed into monthly cohorts by cattle type (beef or dairy). Calf growth is modeled by month, based on estimated monthly weight gain for each cohort (approximately 61 pounds per month). The total calf population is modified through time to account for veal calf slaughter at 4 months and a calf death loss of 0.35 percent annually (distributed across age cohorts up to six months of age). An example of a transition matrix for calves is shown in Table A-171. Note that calves age one through six months available in January have been tracked through the model based on births and death loss from the previous year.

Table A-170: Estimated Beef Cow Births by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7%	15%	28%	22%	9%	3%	2%	2%	3%	4%	3%	3%

Table A-171: Example of Monthly Average Populations from Calf Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	1,177	1,169	1,365	1,616	1,546	1,540	2,483	4,680	8,174	6,612	3,052	1,500
5	1,170	1,367	1,616	1,547	1,540	2,484	4,681	8,177	6,615	3,054	1,501	1,104
4	1,449	1,691	1,626	1,609	2,544	4,750	8,254	6,692	3,126	1,572	1,176	1,167
3	1,692	1,627	1,609	2,545	4,752	8,257	6,695	3,127	1,573	1,177	1,168	1,443
2	1,629	1,610	2,546	4,754	8,260	6,697	3,128	1,573	1,178	1,168	1,444	1,682
1	1,612	2,548	4,756	8,263	6,699	3,129	1,574	1,178	1,169	1,445	1,684	1,619
0	2,550	4,760	8,267	6,702	3,130	1,574	1,179	1,169	1,446	1,685	1,621	1,602

Replacements and Stockers. At seven months of age, calves "graduate" and are separated into the applicable cattle types. First the number of replacements required for beef and dairy cattle are calculated based on estimated death losses and population changes between beginning and end of year population estimates. All steer, and remaining heifers (after subtracting required replacements), are considered "stockers," that is backgrounding animals that are eligible for placement into feedlots as they reach the appropriate weight class. During the stocker phase animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2011).

The data and calculations that occur for the stocker category include matrices that estimate the population of backgrounding heifers and steer, as well as a matrix for total combined stockers. The matrices start with the beginning of year populations in January and model the progression of each cohort. The age structure of the January population is based on estimated births by month from the previous two years, although in order to balance the population properly, an adjustment is added that slightly reduces population percentages in the older populations. The populations are modified through addition of graduating calves (month 7, bottom row of Table A-172) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may reach zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-172.

Table A-172: Example of Monthly Average Populations from Stocker Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23	202	214	126	47	20	12	10	11	9	7	5	51
22	353	174	59	23	15	12	13	13	9	7	103	311
21	286	81	29	17	15	15	15	12	9	153	421	559
20	133	40	22	17	18	18	14	12	197	526	765	457
19	66	30	22	21	21	17	14	273	620	965	629	212
18	49	30	27	25	20	17	321	779	1,141	795	291	305
17	49	37	31	24	20	379	882	1,442	942	368	546	49
16	60	43	30	24	453	1,004	1,636	1,193	435	779	49	49
15	71	41	30	531	1,160	1,867	1,355	551	985	49	49	61
14	68	41	669	1,324	2,162	1,547	625	1,337	49	49	61	71
13	67	918	1,607	2,471	1,796	716	1,669	49	49	61	71	68
12	1,076	1,774	2,813	2,017	857	2,242	282	49	61	71	68	67
11	2,027	3,105	2,297	962	2,765	365	179	82	91	76	72	1,094
10	3,532	2,542	1,082	3,229	507	253	209	261	213	128	1,151	2,683
9	2,860	1,204	3,588	607	451	425	504	464	429	1,353	2,916	6,195
8	1,328	4,083	770	617	664	915	782	831	1,682	3,596	6,832	5,605
7	4,450	878	871	1,060	1,295	1,232	1,230	2,114	4,188	7,484	6,012	2,665

In order to ensure a balanced population of both stockers and placements, additional data tables are utilized in the stocker matrix calculations. The tables summarize the placement data by weight class and month, and is based on the total number of animals within the population that are available to be placed in feedlots and the actual feedlot placement statistics provided by USDA (2011). In cases where there are discrepancies between the USDA estimated placements by weight class and the calculated animals available by weight, the model pulls available stockers from one higher weight category if available. If there are still not enough animals to fulfill requirements the model pulls animals from one lower weight category. In the current time series, this method was able to ensure that total placement data matched USDA estimates, and no shortfalls have occurred.

In addition, 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 at 515 lbs. Other reported target weights were available for 12, 15, 24, and 36 month-old animals, depending on the animal type. Beef cow mature weight was taken from measurements provided by a major British Bos taurus breed (Enns 2008) and increased during the time series through 2007. Bull mature weight was calculated as 1.5 times the beef cow mature weight (Doren et al. 1989). Beef replacement weight was calculated as 70 percent of mature weight at 15 months and 85 percent of mature weight at 24 months. As dairy weights are not a trait that is typically tracked, mature weight for dairy cows was estimated at 1,500 for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010). Dairy replacement at 15 months was assumed to be 875 lbs and replacement at 24 months is 1,300 lbs. Live slaughter weights were estimated from dressed slaughter weight (USDA 2011) divided by 0.63. This ratio represents the dressed weight (i.e., weight of the carcass after removal of the internal organs), to the live weight (i.e., weight taken immediately before slaughter). The annual typical animal mass for each livestock type are presented in Table A-173.

Weight gain for stocker animals was based on monthly gain estimates from Johnson (1999) for 1989, and from average daily estimates from Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), and Skogerboe et al. (2000) for 2000 through 2010. Interim years were calculated linearly, as shown in Table A-174, and weight gain was held constant starting in 2000. Table A-174 provides weight gains that vary by year in the CEFM.

Table A-173: Typical Animal Mass (lbs)

Year/Cattle Type	Dairy Cows	Dairy Replacements	Beef Cows	Bulls	Beef Replacements	Steer Stockers	Heifer Stockers	Steer Feedlot	Heifer Feedlot
1990	1,500	900	1,221	1,832	820	692	652	923	846
1991	1,500	898	1,225	1,838	822	695	656	975	867
1992	1,500	897	1,263	1,895	841	714	673	984	878
1993	1,500	899	1,280	1,920	852	721	683	930	864
1994	1,500	898	1,280	1,920	854	721	689	944	876
1995	1,500	898	1,282	1,923	858	735	701	947	880
1996	1,500	898	1,285	1,928	859	739	707	940	878
1997	1,500	900	1,286	1,929	861	737	708	939	877
1998	1,500	897	1,296	1,944	866	736	710	957	892
1999	1,500	899	1,292	1,938	862	731	709	960	895
2000	1,500	897	1,272	1,908	849	720	702	961	899
2001	1,500	898	1,272	1,908	850	726	707	963	901
2002	1,500	897	1,276	1,914	852	726	708	982	915
2003	1,500	900	1,308	1,962	872	719	702	973	905
2004	1,500	897	1,323	1,985	878	719	702	967	905
2005	1,500	895	1,327	1,991	880	718	706	975	917
2006	1,500	898	1,341	2,012	890	725	713	984	925
2007	1,500	897	1,348	2,022	895	721	707	992	928
2008	1,500	898	1,348	2,022	895	721	705	1,000	939
2009	1,500	897	1,348	2,022	895	731	715	1,007	948
2010	1,500	898	1,348	2,022	896	725	712	998	938

Table A-174: Weight Gains that Vary by Year (lbs)

Year/Cattle Type	Steer Stockers to 12 months(lbs/day)	Steer Stockers to 24 months (lbs/day)	Heifer Stockers to 12 months(lbs/day)	Heifer Stockers to 24 months(lbs/day)
1990	1.53	1.23	1.23	1.08
1991	1.56	1.29	1.29	1.15
1992	1.59	1.35	1.35	1.23
1993	1.62	1.41	1.41	1.30
1994	1.65	1.47	1.47	1.38
1995	1.68	1.53	1.53	1.45
1996	1.71	1.59	1.59	1.53
1997	1.74	1.65	1.65	1.60
1998	1.77	1.71	1.71	1.68
1999	1.80	1.77	1.77	1.75
2000 onwards	1.83	1.83	1.83	1.83

Sources: Enns (2008), Johnson (1999), Lippke et al. (2000), NRC (1999), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000).

Feedlot Animals. Feedlot placement statistics from USDA provide data on the placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model uses 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 25 days on a step-up diet to become acclimated to the new feed type, during this time weight gain is estimated to be 2.8 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 3 to 3.3 pounds per day (Johnson 1999). 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 target weight (as determined by weights at slaughter). Additionally, animals remaining in feedlots at the end of the year are tracked for inclusion in the following year's emission and population counts. For 1990 to 1995, only the total placement data were available, therefore placements for each weight category (categories displayed in Table A-175) for those years are based on the average of monthly placements from the 1996 to 1998 reported figures. Placement data is available by weight class for all years from 1996 onward. Table A-175 provides a summary of the reported feedlot placement statistics for 2010.

Table A-175: Feedlot Placements in the United States for 2010 (Number of animals placed in 1,000 Head)

Weight Placed	**When:**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
< 600 lbs		395	320	395	365	450	440	415	495	510	725	625	475
600 – 700 lbs		445	370	375	305	410	300	305	395	455	640	590	495
700 – 800 lbs		562	519	601	469	535	408	448	566	603	515	374	439
> 800 lbs		420	465	485	495	635	480	590	815	895	625	370	380
Total		**1,822**	**1,674**	**1,856**	**1,634**	**2,030**	**1,628**	**1,758**	**2,271**	**2,463**	**2,505**	**1,959**	**1,789**

Source: USDA (2011).

Note: Totals may not sum due to independent rounding.

Mature Animals. 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 CH_4 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 3.3, 5.1, 8.7, 12.0, 13.6, 13.3, 11.7, 9.3, 6.9, 4.4, 3.0, and 2.8 lbs milk/animal/day for beef cows. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2010 are shown in Table A-176. Beef and dairy cow and bull populations are assumed to remain relatively static throughout the year, as large fluctuations in population size are assumed to not occur. These estimates are taken from the USDA beginning and end of year population datasets.

Table A-176: Dairy Lactation Rates by State (lbs/ year/cow)*

State/Year	1990	1995	2000	2005	2007	2008	2009	2010
Alabama	12,214	14,176	13,920	14,000	15,154	15,333	14,909	14,455
Alaska	13,300	17,000	14,500	12,273	14,667	12,000	10,000	11,833
Arizona	17,500	19,735	21,820	22,679	23,260	23,382	23,028	23,441
Arkansas	11,841	12,150	12,436	13,545	12,941	12,400	12,692	12,833
California	18,456	19,573	21,130	21,404	22,440	22,344	22,000	23,025
Colorado	17,182	18,687	21,618	22,577	22,932	22,930	23,081	23,664
Connecticut	15,606	16,438	17,778	19,200	19,211	19,158	18,579	19,263
Delaware	13,667	14,500	14,747	16,622	16,618	16,923	17,000	16,981
Florida	14,033	14,698	15,688	16,591	16,832	17,167	18,070	18,658
Georgia	12,973	15,550	16,284	17,259	18,169	17,829	18,182	17,885
Hawaii	13,604	13,654	14,358	12,889	12,241	10,882	14,200	13,316
Idaho	16,475	18,147	20,816	22,332	22,513	22,432	22,091	22,658
Illinois	14,707	15,887	17,450	18,827	18,612	18,569	18,873	19,170
Indiana	14,590	15,375	16,568	20,295	20,307	19,683	20,137	20,320
Iowa	15,118	16,124	18,298	20,641	20,085	19,995	20,367	20,751
Kansas	12,576	14,390	16,923	20,505	19,882	20,641	21,085	21,000
Kentucky	10,947	12,469	12,841	12,896	13,889	13,444	14,190	14,833
Louisiana	11,605	11,908	12,034	12,400	12,034	12,269	11,870	11,750
Maine	14,619	16,025	17,128	18,030	17,788	18,273	18,061	18,344
Maryland	13,461	14,725	16,083	16,099	18,121	18,375	18,255	18,537
Massachusetts	14,871	16,000	17,091	17,059	17,000	16,933	17,571	17,429
Michigan	15,394	17,071	19,017	21,635	22,761	22,180	22,445	23,260
Minnesota	14,127	15,894	17,777	18,091	18,817	18,927	19,230	19,366
Mississippi	12,081	12,909	15,028	15,280	15,429	14,550	13,889	13,118
Missouri	13,632	14,158	14,662	16,026	14,982	14,682	14,654	14,596
Montana	13,542	15,000	17,789	19,579	18,500	18,412	19,933	20,643
Nebraska	13,866	14,797	16,513	17,950	18,220	18,672	19,672	19,797
Nevada	16,400	18,128	19,000	21,680	20,481	20,704	21,821	22,143
New Hampshire	15,100	16,300	17,333	18,875	19,333	19,933	19,533	19,867
New Jersey	13,538	13,913	15,250	16,000	16,800	16,900	17,889	17,500
New Mexico	18,815	18,969	20,944	21,192	21,958	23,269	24,320	24,551
New York	14,658	16,501	17,378	18,639	19,303	19,859	20,071	20,807
North Carolina	15,220	16,314	16,746	18,741	19,188	18,979	19,644	19,591
North Dakota	12,624	13,094	14,292	14,182	15,310	16,077	16,739	18,286
Ohio	13,767	15,917	17,027	17,567	18,109	18,321	18,744	19,446
Oklahoma	12,327	13,611	14,440	16,480	16,580	16,578	16,983	17,125
Oregon	16,273	17,289	18,222	18,876	19,417	19,772	19,719	20,331
Pennsylvania	14,726	16,492	18,081	18,722	19,422	19,262	19,360	19,841
Rhode Island	14,250	14,773	15,667	17,000	16,455	18,091	17,818	17,727
South Carolina	12,771	14,481	16,087	16,000	17,889	17,889	19,000	17,875
South Dakota	12,257	13,398	15,516	17,741	19,306	19,956	20,128	20,478
Tennessee	11,825	13,740	14,789	15,743	15,857	16,068	16,232	16,346
Texas	14,350	15,244	16,503	19,646	18,982	20,134	20,898	21,375
Utah	15,838	16,739	17,573	18,875	20,376	20,894	21,036	21,400
Vermont	14,528	16,210	17,199	18,469	18,079	18,400	18,289	18,544
Virginia	14,213	15,116	15,833	16,990	17,530	17,612	18,083	18,095
Washington	18,532	20,091	22,644	23,270	23,239	23,344	23,171	23,510
West Virginia	11,250	12,667	15,588	14,923	15,000	15,083	14,727	15,700
Wisconsin	13,973	15,397	17,306	18,500	19,310	19,546	20,079	20,630
Wyoming	12,337	13,197	13,571	14,878	18,831	19,386	19,036	20,067

Source: USDA (2011).
* Beef lactation data shown in text above.

Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digested by the animal) and CH_4 conversion rate (Y_m, the fraction of gross energy converted to CH_4) 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, the United States Department of Agriculture, expert opinion, and other literature sources. The designated regions for this analysis for dairy cattle for all years and foraging beef cattle from 1990 through 2006 are shown in Table A-177. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the National

Animal Health Monitoring System 2007-2008 survey on cow-calf system management practices (USDA 2010) and are shown in and Table A-178. The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine feed chemical composition for use in estimating DE and Y_m for each animal type.

Table A-177: Regions used for Dairy Cattle (all years) and Foraging Cattle from 1990-2006

West	California	Northern Great Plains	Midwestern	Northeast	Southcentral	Southeast
Alaska	California	Colorado	Illinois	Connecticut	Arkansas	Alabama
Arizona		Kansas	Indiana	Delaware	Louisiana	Florida
Hawaii		Montana	Iowa	Maine	Oklahoma	Georgia
Idaho		Nebraska	Michigan	Maryland	Texas	Kentucky
Nevada		North Dakota	Minnesota	Massachusetts		Mississippi
New Mexico		South Dakota	Missouri	New Hampshire		North Carolina
Oregon		Wyoming	Ohio	New Jersey		South Carolina
Utah			Wisconsin	New York		Tennessee
Washington				Pennsylvania		Virginia
				Rhode Island		
				Vermont		
				West Virginia		

Source: USDA (1996).

Table A-178: Regions used for Foraging Cattle from 2007-2010

West	Central	Northeast	Southeast
Alaska	Illinois	Connecticut	Alabama
Arizona	Indiana	Delaware	**Arkansas**
California	Iowa	Maine	Florida
Colorado	**Kansas**	Maryland	Georgia
Hawaii	Michigan	Massachusetts	Kentucky
Idaho	Minnesota	New Hampshire	**Louisiana**
Montana	Missouri	New Jersey	Mississippi
Nevada	**Nebraska**	New York	North Carolina
New Mexico	**North Dakota**	Pennsylvania	**Oklahoma**
Oregon	Ohio	Rhode Island	South Carolina
Utah	**South Dakota**	Vermont	Tennessee
Washington	Wisconsin	West Virginia	**Texas**
Wyoming			Virginia

Source: Based on data from USDA (2010).

Note: States in **bold** represent a change in region.

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for all other cattle (IPCC 2006). 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 were developed for dairy and feedlot cattle. Digestible energy and Y_m values were estimated across the time series for each cattle population category based on physiological modeling, published values, and/or expert opinion.

For dairy cows, ruminant digestion models were used to estimate Y_m. The three major categories of input required by the models 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 Y_m values were estimated for 1990 using the Donovan and Baldwin model (1999) that represents physiological processes in the ruminant animals and diet characteristics from USDA (1996). The Donovan and Baldwin model accounts for differing diets (i.e., grain-based or forage-based), so that Y_m values for the variable feeding characteristics within the U.S. cattle population can be estimated. Subsequently, a literature review of dairy diets was conducted and nearly 250 diets were analyzed from 1990 through 2009 across 23 states. Kebreab et al. (2008) conducted an evaluation of models and found that the COWPOLL model was the best model for estimating Y_m for dairy. Therefore, the COWPOLL model was used to estimate Y_m values for each of the diets. Due to the high variability associated with cattle diets from the literature, a function based on the national trend observed from the analysis of the dairy diets was used to calculate 1991 and beyond regional values based on the regional 1990 Y_m values from Donovan and Baldwin. The resulting scaling factor is shown below:

$$Y_m = Y_m(1990)EXP\left(\frac{1.22}{(Year-1980)}\right) / EXP\left(\frac{1.22}{(1990-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the annual trends observed in the data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region, but did vary over time, and was grouped by the following years 1990-1993, 1994-1998, 1999-2002, 2003, 2004-2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers, so assumptions were based on the relationship of the collected data literature on dairy heifers to the data on dairy cow diets. From this relationship, DE was estimated as the mature cow DE minus three percent, and Y_m was estimated as that of the mature dairy cow plus 0.1 percent.

To calculate the DE values for grazing beef cattle, diet composition assumptions were used to estimate weighted DE values for a combination of forage and supplemental diets. The forage portion makes up 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the US. Currently there is no comprehensive survey of this data, so for this analysis two regional DE values were developed to account for the generally lower forage quality in the western United States. For all non-western grazing cattle, the forage DE was an average of the estimated seasonal values for grass pasture diets for a calculated DE of 66.4 percent. For foraging cattle in the west, the forage DE was calculated as the seasonal average for grass pasture, meadow and range diets, for a calculated DE of 61.4 percent. The assumed specific components of each of the broad forage types, along with their corresponding DE value and the calculated regional DE values can be found in Table A-179. In addition, it was assumed that each region fed a supplemental diet, and two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Archibeque 2011, USDA 2010) as shown in Table A-180 and Table A-181 along with the percent of each total diet that is assumed to be made up of the supplemental portion. By weighting the calculated DE values from the forage and supplemental diets, the DE values for the composite diet were calculated.[64] These values are used for steer and heifer stockers and beef replacements. Finally, for mature beef cows and bulls, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of mature cattle based on Johnson (2002). Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002). The Y_m values and the resulting final weighted DE values by region for 2007 onwards are shown in Table A-182.

For feedlot animals, DE and Y_m are adjusted over time as diet compositions in actual feedlots are adjusted based on new and improved nutritional information and availability of feed types. Feedlot diets are assumed to not differ significantly by state, and therefore only a single set of national diet values is utilized for each year. The DE and Y_m values for 1990 were estimated by Dr. Don Johnson (1999). In the CEFM, the DE values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and Y_m values from 2000 through the current year were estimated using the MOLLY model as described in Kebreab et al. (2008), based on a series of average diet feed compositions from Galyean and Gleghorn (2001) for 2000 through 2006 and Vasconcelos and Galyean (2007) for 2007 onwards. In addition, feedlot animals are assumed to spend the first 25 days in the feedlot on a "step-up" diet to become accustomed to the higher quality feedlot diets. The step-up DE and Y_m are calculated as the average of all state forage and feedlot diet DE and Y_m values.

Table A-183 shows the regional DE and Y_m for U.S. cattle in each region for 2010.

Table A-179: Feed Components assumed for Forage Diets

Forage Type	**DE, (% of GE)**	**Grass pasture - Spring**	**Grass pasture - Summer**	**Grass pasture - Fall**	**Range June**	**Range July**	**Range August**	**Range September**	**Range Winter**	**Meadow - Spring**	**Meadow - Fall**
Bahiagrass Paspalum notatum, fresh	61.38			x							
Bermudagrass Cynodon dactylon, fresh	66.29		x								
Bremudagrass, Coastal Cynodon dactylon, fresh	65.53		x								
Bluegrass, Canada Poa compressa, fresh, early vegetative	73.99	x									
Bluegrass, Kentucky Poa pratensis, fresh, early vegetative	75.62	x									
Bluegrass, Kentucky Poa pratensis, fresh, mature	59.00		x	x							
Bluestem Andropagon spp, fresh, early vegetative	73.17				x						
Bluestem Andropagon spp, fresh, mature	56.82					x	x	x	x		x
Brome Bromus spp, fresh, early vegetative	78.57	x									

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[64] For example, the West has a forage DE of 61.4 which makes up 90 percent of the diet and a supplemented diet DE of 67.4 percent was used for 10 percent of the diet, for a total weighted DE of 61.9 percent, as shown in Table A-182.

Forage Type	DE, (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Brome, Smooth Bromus inermis, fresh, early vegetative	75.71	x									
Brome, Smooth Bromus inermis, fresh, mature	57.58		x	x					x		
Buffalograss, Buchloe dactyloides, fresh	64.02				x	x					
Clover, Alsike Trifolium hybridum, fresh, early vegetative	70.62	x									
Clover, Ladino Trifolium repens, fresh, early vegetative	73.22	x									
Clover, Red Trifolium pratense, fresh, early bloom	71.27	x									
Clover, Red Trifolium pratense, fresh, full bloom	67.44		x		x						
Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw)	55.28			x							
Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured	64.69				x	x	x			x	
Fescue Festuca spp, hay, sun-cured, early vegetative	67.39	x									
Fescue Festuca spp, hay, sun-cured, early bloom	53.57			x							
Grama Bouteloua spp, fresh, early vegetative	67.02	x									
Grama Bouteloua spp, fresh, mature	63.38		x	x						x	
Millet, Foxtail Setaria italica, fresh	68.20	x			x						
Napiergrass Pennisetum purpureum, fresh, late bloom	57.24		x	x							
Needleandthread Stipa comata, fresh, stem cured	60.36					x	x	x			
Orchardgrass Dactylis glomerata, fresh, early vegetative	75.54	x									
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x								
Pearlmillet Pennisetum glaucum, fresh	68.04	x									
Prairie plants, Midwest, hay, sun-cured	55.53			x							x
Rape Brassica napus, fresh, early bloom	80.88	x									
Rye Secale cereale, fresh	71.83	x									
Ryegrass, Perennial Lolium perenne, fresh	73.68	x									
Saltgrass Distichlis spp, fresh, post ripe	58.06		x	x							
Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative	73.27	x									
Squirreltail Stanion spp, fresh, stem-cured	62.00		x			x					
Summercypress, Gray Kochia vestita, fresh, stem-cured	65.11			x	x	x					
Timothy Phleum pratense, fresh, late vegetative	73.12	x									
Timothy Phleum pratense, fresh, midbloom	66.87		x								
Trefoil, Birdsfoot Lotus corniculatus, fresh	69.07	x									
Vetch Vicia spp, hay, sun-cured	59.44			x							
Wheat Triticum aestivum, straw	45.77			x							
Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative	79.78	x									
Wheatgrass, Crested Agropyron desertorum, fresh, full bloom	65.89		x			x					
Wheatgrass, Crested Agropyron desertorum, fresh, post ripe	52.99			x					x		x
Winterfat, Common Eurotia lanata, fresh, stem-cured	40.89								x		
Weighted Average DE		**72.99**	**62.45**	**57.26**	**67.11**	**62.70**	**60.62**	**58.59**	**52.07**	**64.03**	**55.11**
Forage Diet for West	**61.4**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**
Forage Diet for All Other Regions	**66.4**	**33.3%**	**33.3%**	**33.3%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Source: Archibeque (2011).

Table A-180: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990-2006

Feed	Source of DE (NRC 1984)	Unweighted DE (% of GE)	California[a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	30%	29%	12%	30%	
Barley		85.08	10%	15%					
Bermuda	Table 8, feed #030	66.29							35%
Bermuda Hay	Table 8, feed #031	50.79				40%			
Corn	Table 8, feed #089	88.85	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 8, feed #095	72.88			25%		20%	20%	
Cotton Seed Meal						7%			
Grass Hay	Table 8, feed #126, 170, 274	58.37		40%				30%	
Orchard	Table 8, feed #147	60.13							40%
Soybean Meal Supplement		77.15		5%	5%				5%
Sorghum	Table 8, feed #211	84.23							20%
Soybean Hulls		66.86						7%	
Timothy Hay	Table 8, feed #244	60.51					50%		
Whole Cotton Seed		75.75	5%				5%		
Wheat Middlings	Table 8, feed #257	68.09			15%	13%			
Wheat	Table 8, feed #259	87.95	10%						
Weighted Total DE (%)			**70.1**	**67.4**	**73.0**	**62.0**	**67.6**	**66.9**	**68.0**
Percent of Diet that is Supplement			**5%**	**10%**	**15%**	**10%**	**15%**	**10%**	**5%**

Source of representative regional diets: Donovan (1999).

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

Table A-181: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007-2010

Feed	Source of DE (NRC1984)	Unweighted DE (% of GE)	West	Central	Northeast	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	12%	
Bermuda	Table 8, feed #030	66.29				20%
Bermuda Hay	Table 8, feed #031	50.79				20%
Corn	Table 8, feed #089	88.85	10%	15%	13%	10%
Corn Silage	Table 8, feed #095	72.88		35%	20%	
Grass Hay	Table 8, feed #126, 170, 274	58.37	10%			
Orchard	Table 8, feed #147	60.13				30%
Protein supplement (West)	Table 8, feed #082, 134, 225[b]	81.01	10%			
Protein Supplement (Central and Northeast)	Table 8, feed #082, 134, 225[b]	80.76		10%	10%	
Protein Supplement (Southeast)	Table 8, feed #082, 134, 101[b]	77.89				10%
Sorghum	Table 8, feed #211	84.23		5%		10%
Timothy Hay	Table 8, feed #244	60.51			45%	
Wheat Middlings	Table 8, feed #257	68.09		5%		
Wheat	Table 8, feed #259	87.95	5%			
Weighted Total DE			**67.4**	**73.1**	**68.9**	**66.6**
Percent of Diet that is Supplement			**10%**	**15%**	**5%**	**15%**

Source of representative regional diets: Donovan (1999), Archibeque (2011), USDA (2010).

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

[b] Not in equal proportions.

Table A-182: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007-2010

Animal Type	Data	West[c]	Central	Northeast	Southeast
Beef Repl. Heif.	DE[a]	61.9	65.6	64.5	64.6
	Y_m[b]	6.5%	6.5%	6.5%	6.5%
Steer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Beef Cows	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Bulls	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%

[a] DE is the digestible energy in units of percent of GE (MJ/Day).
[b] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.
[c] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. To see the regional designation per state, please see Table A-178.

Table A-183: Regional DE (% of GE) and Y_m Rates for Non-Foraging Cattle by Animal Type for 2010

Animal Type	Data	California[c]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
DairyRepl. Heif.	DE[a]	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym[b]	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Dairy Cows	DE	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	Ym	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
Steer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%

[a] DE is the digestible energy in units of percent of GE (MJ/Day).
[b] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.
[c] Note that emissions are currently calculated on a state-by-state basis, but diets are applied Table A-177 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-177.

Step 3: Estimate CH_4 Emissions from Cattle

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the Tier 2 IPCC (2006) equations, b) determine an emission factor using the GE values, Y_m and a conversion factor, and c) sum the daily emissions for each animal type. Finally, the state emissions were aggregated to obtain the national emissions estimate. The necessary data values for each state and animal type include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity (C_a, MJ/day)[65]
- Standard Reference Weight (kg)[66]
- 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 CH_4)
- Population

Step 3a: Determine 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 (2006).

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[65] Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, and 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 (IPCC 2006).

[66] Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM}\right) + \left(\frac{NE_g}{REG}\right)}{\frac{DE\%}{100}} \right]$$

Where,

GE = Gross energy (MJ/day)
NE_m = Net energy required by the animal for maintenance (MJ/day)
NE_a = Net energy for animal activity (MJ/day)
NE_l = Net energy for lactation (MJ/day)
NE_{work} = Net energy for work (MJ/day)
NE_p = Net energy required for pregnancy (MJ/day)
REM = Ratio of net energy available in a diet for maintenance to digestible energy consumed
NE_g = Net energy needed for growth (MJ/day)
REG = Ratio of net energy available for growth in a diet to digestible energy consumed
DE = Digestible energy expressed as a percent of gross energy (percent)

Step 3b: Determine Emission Factor

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

$$DayEmit = \frac{GE \times \mathrm{Y_m}}{55.65}$$

Where,

DayEmit = Emission factor (kg CH_4/head/day)
GE = Gross energy intake (MJ/head/day)
Y_m = CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4 (%)
55.65 = A factor for the energy content of methane (MJ/kg CH_4)

The daily emission factors were estimated for each animal type and state, calculated annual national emission factors are shown by animal type in Table A-184.

Table A-184: Calculated Annual National Emission Factors for Cattle by Animal Type (kg CH_4/head/year)

Cattle Type	1990	1995	2000	2005	2007	2008	2009	2010
Dairy								
Cows	124	125	132	133	139	139	140	142
Replacements 7-11 months	48	46	46	45	46	46	46	46
Replacements 12-23 months	73	69	70	67	70	70	70	69
Beef								
Bulls	91	94	94	97	98	98	98	98
Cows	89	92	91	94	95	95	95	95
Replacements 7-11 months	54	57	56	59	60	60	60	60
Replacements 12-23 months	63	66	66	68	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60
Feedlot Cattle	39	38	39	39	41	42	43	42

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

Step 3c: Estimate Total Emissions

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

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

Where,

$\text{Emissions}_{\text{state}}$ = Emissions for state (kg CH_4)
$\text{DayEmit}_{\text{state}}$ = Emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month = Number of days in the month
$\text{SubPop}_{\text{state}}$ = Number of animals in the subcategory and state during the month

This process was repeated for each month, and the totals for each state subcategory were summed to achieve an emission estimate for a state for the entire year and state estimates were summed to obtain the national total. The estimates for each of the 10 subcategories of cattle are listed in Table A-185. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-185: CH_4 Emissions from Cattle (Gg)

Cattle Type	1990	1995	2000	2005	2007	2008	2009	2010
Dairy	**1,513**	**1,440**	**1,460**	**1,449**	**1,544**	**1,564**	**1,581**	**1,569**
Cows	1,242	1,183	1,209	1,197	1,271	1,289	1,304	1,287
Replacements 7-11 months	58	56	55	56	60	60	61	62
Replacements 12-23 months	212	201	196	196	213	216	216	221
Beef	**4,581**	**5,226**	**4,884**	**4,829**	**4,953**	**4,909**	**4,857**	**4,812**
Bulls	196	225	215	214	217	216	214	214
Cows	2,884	3,222	3,058	3,056	3,086	3,066	2,998	2,965
Replacements 7-11 months	69	85	74	80	81	79	77	75
Replacements 12-23 months	188	241	204	217	228	221	216	212
Steer Stockers	563	662	509	473	485	480	496	480
Heifer Stockers	306	375	323	299	300	293	304	304
Feedlot Cattle	375	416	502	488	556	554	552	562
Total	**6,093**	**6,665**	**6,344**	**6,277**	**6,497**	**6,473**	**6,438**	**6,382**

Notes: Totals may not sum due to independent rounding. Because calves younger than 7 months consume mainly milk the IPCC recommends the use of methane conversion factor of zero, resulting in no methane emissions from this subcategory of cattle.

Emission Estimates from Other Livestock

All livestock population data, except for horses and American bison for years prior to 2002, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2011) or earlier census data (USDA 1992, 1997). The Manure Management Annex discusses the methods for obtaining and shows the resulting population data for horses, sheep, swine, and goats that were used for estimating all livestock-related emissions (See Table A- 190). For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. All data were downloaded from the USDA-NASS agricultural database (USDA 2011) or taken from older census reports (USDA 1992, 1997). The Food and Agriculture Organization (FAO) publishes annual horse population data. These data were accessed from the FAOSTAT database (FAO 2011).

The American bison population data was collected and estimated from a variety of sources. Population was collected as part of USDA's Census of Agriculture (USDA 2011), which provided American bison population data for 2002 and 2007. American bison populations for 1997 through1999 were provided by a survey from the National Bison Association (1999). For 1990 through 1996 populations were derived by estimating the totals from the "Historic and Current Bison Populations" graph in the National Bison Association (1999) report and holding the smaller populations constant (e.g., zoos, overseas animals, public herds in the United States and Canada, and U.S. Native American herds) and applying proportions from 1997 to the totals for the historic years to separate the U.S. and Canadian private herds. For 2000 and 2001, as well as 2003 through 2006, populations were interpolated between the known estimates. For 2008 through 2010, the American bison population was calculated based on USDA bison slaughter data (USDA 2011) and scaled from the 2007 Census of Agriculture population estimate.

Population data for mules, burros, and donkeys was available for 1987, 1992, 1997, 2002, and 2007 from USDA's Census of Agriculture (USDA 1992, 1997, 2011). For all non-reported years between 1987 and 2007, population estimates were linearly interpolated between each reported year. For 2007 through 2010, populations were held constant.

Methane emissions from sheep, goats, swine, horses, mules, burros, and donkeys were estimated by multiplying published national population estimates by the default IPCC emission factor (IPCC 2006). For American bison the emission factor for buffalo (IPCC 2006) was used and adjusted based on the ratio of live weights of 300 kg for buffalo (IPCC 2006) and 1,130 pounds (513 kg) for American Bison (National Bison Association 2011) to the 0.75 power. This methodology for determining emission factors is recommended by IPCC (2006) for animals with similar digestive systems. Table A-187 shows the emission factors used for these other livestock.

Enteric fermentation emissions from all livestock types are shown in Table A-188 and Table A-189.

Table A- 186: Population Estimates for American Bison and Mules, Burros, and Donkeys (1,000 head)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
American Bison	47	104	194	213	232	225	218	212	205	198	207	202	189
Mules, Burros, and Donkeys	63	101	112	109	105	141	177	212	248	284	284	284	284

Sources: USDA (1992, 1997, 2011), National Bison Association (1999).

Table A-187: Emission Factors for Other Livestock (kg CH_4/head/year)

Livestock Type	Emission Factor
Sheep	8
Goats	5
Horses	18
Swine	1.5
Mules and Asses	10.0
American Bison	82.2

Source: IPCC (2006), except American Bison, as described in text.

Table A-188: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Beef Cattle	96.2	109.7	102.6	101.8	101.9	102.0	100.3	101.4	103.0	104.0	103.1	102.0	101.1
Dairy Cattle	31.8	30.2	30.7	30.5	30.6	28.4	29.9	30.4	31.1	32.4	32.9	33.2	33.0
Horses	1.9	1.9	2.0	2.1	2.3	2.6	3.0	3.5	3.6	3.6	3.6	3.6	3.6
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9
Swine	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.1	2.1	2.1	2.0
Goats	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Mules, Burros, and Donkeys	+	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1
Total	**133.8**	**145.7**	**138.8**	**138.1**	**138.5**	**136.8**	**136.8**	**139.0**	**141.4**	**143.8**	**143.4**	**142.6**	**141.3**

Notes: Totals may not sum due to independent rounding.
+ indicates emissions are less than 0.05.

Table A-189: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Beef Cattle	4,581	5,226	4,884	4,850	4,854	4,859	4,776	4,829	4,904	4,953	4,909	4,857	4,812
Dairy Cattle	1,513	1,440	1,460	1,453	1,457	1,354	1,422	1,449	1,479	1,544	1,564	1,581	1,569
Horses	91	92	94	99	108	126	144	166	171	171	171	171	171
Sheep	91	72	56	55	53	51	49	49	50	49	48	46	45
Swine	81	88	88	88	90	90	91	92	93	98	101	99	97
Goats	13	12	12	12	13	13	14	15	15	16	16	16	16
American Bison	4	9	16	18	19	19	18	17	17	16	17	17	16
Mules, Burros, and Donkeys	1	1	1	1	1	1	2	2	3	3	3	3	3
Total	**6,373**	**6,939**	**6,612**	**6,576**	**6,594**	**6,513**	**6,516**	**6,618**	**6,731**	**6,850**	**6,829**	**6,788**	**6,728**

Note: Totals may not sum due to independent rounding.

3.10. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management

The following steps were used to estimate methane (CH_4) and nitrous oxide (N_2O) 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 emission estimates for Agricultural Soil Management (see the Agricultural Soils Management Annex).

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2010 for all livestock types, except horses and goats were obtained from the USDA National Agricultural Statistics Service (NASS). The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Quick Stats Database (USDA 2011a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2011b, and 2011c). Horse population data were obtained from the Food and Agriculture Organization (FAO) FAOSTAT database (FAO 2011). Goat population data for 1992, 1997, 2002, and 2007 were obtained from the Census of Agriculture (USDA 2009a). Additional data sources used and adjustments to these data sets are described below.

Cattle: For all cattle groups (cows, heifers, steers, bulls, and calves), the USDA data provide cattle inventories from January (for each state) and July (as a U.S. total only) of each year. Cattle inventories change over the course of the year, sometimes significantly, as new calves are born and as cattle are moved into feedlots and subsequently slaughtered; therefore, to develop the best estimate for the annual animal population, the populations and the individual characteristics, such as weight and weight gain, pregnancy, and lactation of each animal type were tracked in the Cattle Enteric Fermentation Model (CEFM). For animals that have relatively static populations throughout the year, such as mature cows and bulls, the January 1 values were used. For animals that have fluctuating populations throughout the year, such as calves and growing heifers and steer, the populations are modeled based on a transition matrix that uses annual population data from USDA along with USDA data on animal births, placement into feedlots, and slaughter statistics.

Swine: The USDA provides quarterly data for each swine subcategory: breeding, market under 50 pounds (under 23 kg), market 50 to 119 pounds (23 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 emission calculations. For states where only December inventory is reported, the December data were used directly.

Sheep: Population data for lamb and sheep on feed are not available after 1993 (USDA 1994). The number of lamb and sheep on feed for 1994 through 2010 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 1992, 1997, 2002, and 2007 (USDA 2009a). The data for 1992 were used for 1990 through 1992 and the data for 2007 were used for 2007 through 2010. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated based on the 1992, 1997, and 2002 Census data.

Poultry: The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), broilers, other chickens, and turkeys (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2011b, and 2011c). The annual population data for boilers and turkeys were adjusted for the turnover (i.e., slaughter) rate (Lange 2000). All poultry population data were adjusted to account for states that report non-disclosed populations to USDA NASS. The combined populations of the states reporting non-disclosed populations are reported as "other" states. State populations for the non-disclosed states were estimated by equally distributing the population attributed to "other" states to each of the non-disclosed states.

Horses: The FAO publishes annual total U.S. horse population, which were accessed from the FAOSTAT database (FAO 2011). State horse population data were estimated using state population distributions from the 1992, 1997, 2002, and 2007 Census of Agriculture and the FAO national population data. A summary of the livestock population characterization data used to calculate CH_4 and N_2O emissions is presented in Table A- 190.

Step 2: Waste Characteristics Data

Methane and N_2O emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids (VS) excretion rate;
- Maximum methane producing capacity (B_o) for U.S. animal waste;
- Nitrogen excretion rate (Nex); and
- Typical animal mass (TAM).

Table A- 191 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 Agricultural Waste Management Field Handbook (AWMFH; USDA 1996a, 2008) is one of the primary sources of waste characteristics. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and Nex for most animal groups across the time series of the inventory, as shown in Table A- 192 (ERG 2010b and 2010c). In some cases, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) were used to supplement the USDA data. The VS and Nex data for breeding swine are from 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). Due to the change in USDA reporting of hens and pullets, new nitrogen and VS excretion rates were calculated for the combined population of hens and pullets; a weighted average rate was calculated based on hen and pullet population data from 1990 to 2004.

The method for calculating VS excretion and Nex from beef and dairy cows, heifers, and steers is based on the relationship between animal performance characteristics such as diet, lactation, and weight gain and energy utilization. The method used is outlined by the IPCC Tier II methodology, and is modeled in the enteric fermentation portion of the inventory in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle.

Volatile solids content of manure is the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material; fecal material combined with urinary excretions constitutes manure. The enteric fermentation model requires the estimation of gross energy intake and its fractional digestibility to estimate enteric CH_4 emissions (see the Enteric Fermentation Annex for details on the enteric energy model). These two inputs are used to calculate the indigestible energy per animal unit as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal unit (2 or 4 percent). This value is then converted to VS production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 18.45 MJ/kg, after subtracting out the ash content of manure. The current equation recommended by the 2006 IPCC Guidelines is:

$$\text{VS production (kg)} = \left[\left(\text{GE - DE}\right) + \left(\text{UE} \times \text{GE}\right)\right] \times \frac{1 - ASH}{18.45}$$

Where,

GE = Gross energy intake (MJ)

DE = Digestible energy (MJ)

(UE × GE) = Urinary energy expressed as fraction of GE, assumed to be 0.04 except for feedlots which are reduced 0.02 as a result of the high grain content of their diet.

ASH = Ash content of manure calculated as a fraction of the dry matter feed intake (assumed to be 0.08).

18.45 = Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Nitrogen uptake in cattle is carried out through dietary protein intake. However, when feed intake of protein exceeds the nutrient requirements of the animal, the excess nitrogen is excreted, primarily through the urine. To calculate the nitrogen excreted by each animal type, the cattle enteric fermentation model (CEFM) utilizes the energy balance calculations recommended by the IPCC (2006) for gross energy and the energy required for growth along with inputs of weight gain, milk production, and the percent of crude protein in the diets. The total nitrogen excreted is measured in the CEFM as nitrogen consumed minus nitrogen retained by the animal for growth and in milk. The basic equation for calculating Nex is shown below, followed by the equations for each of the constituent parts.

$$\mathrm{N}_{\mathrm{excreted}} = \mathrm{N}_{\mathrm{consumed}} - \left(\mathrm{N}_{\mathrm{growth}} + \mathrm{N}_{\mathrm{milk}}\right)$$

Where,

$\mathrm{N}_{\mathrm{excreted}}$ = Daily N excreted per animal, kg per animal per day.
$\mathrm{N}_{\mathrm{consumed}}$ = Daily N intake per animal, kg per animal per day
$\mathrm{N}_{\mathrm{growth}}$ = Nitrogen retained by the animal for growth, kg per animal per day
$\mathrm{N}_{\mathrm{milk}}$ = Nitrogen retained in milk, kg per animal per day

The equation for N consumed is based on the 2006 IPCC Guidelines, and is estimated as:

$$N_{consumed} = \left[\frac{GE}{18.45} * \left(\frac{\frac{CP\%}{100}}{6.25}\right)\right]$$

Where:

$\mathrm{N}_{\mathrm{consumed}}$ = Daily N intake per animal, kg per animal per day
GE = Gross energy intake, as calculated in the CEFM, MJ per animal per day
18.45 = Conversion factor for dietary GE per kg of dry matter, MJ per kg.
CP% = Percent crude protein in diet, input into the CEFM
6.25 = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N

The portion of consumed N that is retained as product equals the nitrogen required for weight gain plus that in milk. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NEg), weight gain (WG), and other conversion factors and constants. The equation matches current 2006 IPCC Guidelines recommendations, and is as follows:

$$N_{growth} = \frac{\dfrac{\left\{WG * \left[268 - \dfrac{(7.03 * NEg)}{WG}\right]\right\}}{1000}}{6.25}$$

Where,

$\mathrm{N}_{\mathrm{growth}}$ = Nitrogen retained by the animal for growth, kg per animal per day
WG = Daily weight gain of the animal, kg per day
268 = Constant from 2006 IPCC Guidelines
7.03 = Constant from 2006 IPCC Guidelines
NEg = Net energy required for growth, MJ per animal per day
1,000 = Conversion from grams to kilograms
6.25 = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N

The N content of milk produced also currently matches the 2006 IPCC Guidelines. Milk N retained as product is calculated using the following equation:

$$N_{milk} = \frac{milk * \left(\dfrac{pr\%}{100}\right)}{6.38}$$

Where,

N_{milk} = Nitrogen retained in milk, kg per animal per day
milk = Milk production, kg per day
pr% = Percent protein in milk, estimated from the fat content as 1.9 + 0.4 * %Fat
100 = Conversion from percent to value (e.g., 4% to 0.04)
6.38 = Conversion from kg Protein to kg N

The VS and N equations above were used to calculate VS and Nex rates for each state, cattle type, and year. Table A- 193 presents the state-specific VS and Nex production rates used for cattle in 2010.

Step 3: Waste Management System Usage Data

Table A- 194 summarizes 2010 manure distribution data among waste management systems (WMS) at beef feedlots, dairies, dairy heifer facilities, and swine, layer, broiler, and turkey operations. Manure from the remaining animal types (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. Definitions of each WMS type are presented in Table A- 195.

Beef Cattle and Dairy Heifers: The beef feedlot and dairy heifer 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 (EPA 2002b). Based on EPA site visits and state contacts supporting this work and additional contacts with the national USDA office to estimate the percent of beef steers and heifers in feedlots (Milton 2000), 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 2000b) and was used to estimate the percentage of manure managed in runoff ponds in addition to drylots; this percentage ranges from 0.4 to 1.3 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, or 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 were 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, 1997, 2002, and 2007 Census of Agriculture (USDA 2009a). It was assumed that the data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2007 were the same as that for 2008 through 2010. Data for 1993 through 1996,1998 through 2001, and 2003 through 2006 were extrapolated using the 1992, 1997, 2002, and 2007 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 2002b). Manure management system data for small (fewer than 200 head) dairies were obtained from USDA (2000a). 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 (includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (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 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 et al. 1999). Census of Agriculture population data for 1992, 1997, and 2002 (USDA 2009a) 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 2010, which were obtained from the USDA NASS (USDA 2011a).

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. Due to limitations in how USDA reports the manure management data, the total percent of systems for a region and farm size is greater than 100 percent. However, manure is typically partitioned to use only one manure management system, rather than transferred between several different systems. Emissions estimates are only calculated for the final manure management system used for each portion of manure. 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 2000a).

Swine: The distribution of manure managed in each WMS was estimated using data from a USDA report and EPA's Office of Water site visits (USDA 1998, ERG 2000a). For operations with less than 200 head, manure management system data were obtained from USDA (USDA 1998). It was assumed that those operations use pasture, range, or paddock systems. For swine operations with greater than 200 head, the percent of waste managed in each system was estimated using the EPA and USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992, 1997, 2002, and 2007 Census of Agriculture (USDA 2009a) were used to determine the percentage of all swine utilizing the various manure management systems. 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 2007 were the same as that for 2008 through 2010. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated using the 1992, 1997, 2002, and 2007 data. The reported manure management systems were deep pit, liquid/slurry (includes above- and below-ground slurry), anaerobic lagoon, and solid storage (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 was greater than 100 percent. Typically, this means that a portion of the manure at a swine operation is handled in one system (e.g., liquid system), and a separate portion 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, which could result in increased emissions, so reported systems data were normalized to 100 percent for incorporation into the WMS distribution, using the same method as described above for dairy operations.

Sheep: Waste management system data for sheep were obtained from USDA NASS sheep report for years 1990 through 1993 (USDA 1994). Data for 2001 are obtained from USDA APHIS sheep report (USDA 2003). The data for years 1994-2000 are calculated assuming a linear progression from 1993 to 2001. Due to lack of additional data, data for years 2002 and beyond are assumed to be the same as 2001. It was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

Goats and Horses: Waste management system data for 1990 to 2010 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 was managed in dry systems.

Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens: Waste management system data for 1992 were obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). These data were also used to represent 1990 and 1991. 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 a United Egg Producers voluntary survey (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 2000b). 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 2010 was equal to that estimated for 1999. Data collected for EPA's Office of Water, including information collected during site visits (EPA 2002b), were used to estimate the distribution of waste by management system and animal type.

Poultry—Broilers and Turkeys: The percentage of turkeys and broilers on pasture was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that one percent of poultry waste is deposited in pastures, ranges, 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 N_2O emission factors (EFs) used in the emission calculations were determined using the methodologies presented below.

Methane Conversion Factors (MCFs)

Climate-based IPCC default MCFs (IPCC 2006) were used for all dry systems; these factors are presented in Table A- 196. A U.S.-specific methodology was used to develop MCFs for all lagoon and liquid systems.

For animal waste managed in dry systems, the appropriate IPCC default MCF was applied based on annual average temperature data. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2011) and each state and year in the inventory was assigned a climate classification of cool, temperate or warm. Although there are some specific locations in the U.S. that may be included in the warm climate category, no aggregated state-level annual average temperatures are included in this category. In addition, some counties in a particular state may be included in the cool climate category, although the aggregated state-level annual average temperature may be included in the temperate category. Although considering the temperatures at a state level instead of a county level may be causing some specific locations to be classified into an inappropriate climate category, using the state level annual average temperature provides an estimate that is appropriate for calculating the national average.

For anaerobic lagoons and other liquid systems a climate-based approach based on the van't Hoff-Arrhenius equation was developed to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time. This approach is consistent with the recently revised guidelines from IPCC (IPCC 2006). The van't Hoff-Arrhenius equation, with a base temperature of 30°C, is 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 = 303.15K
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 VS that are biologically available for conversion to CH_4 based on the temperature of the system. For those animal populations using liquid manure management systems or manure runoff ponds (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). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, 2002, and 2007 Census data (USDA 2009a). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data; county population data for 1998 through 2001 were extrapolated based on 1997 and 2002 data; county population data for 2003 through 2006 were extrapolated based on 2002 and 2007 data; and county population data for 2008 to 2010 were assumed to be the same as 2007.

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

- The weighted-average temperature for a state is calculated using the county population estimates and average monthly temperature in each county. 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 uncovered anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems.

- Monthly production of VS added to the system is estimated based on the number of animals present.

- For lagoon systems, the calculation of methane includes a management and design practices (MDP) factor. This factor, equal to 0.8, was developed based on model comparisons to empirical CH_4 measurement data from anaerobic lagoon systems in the United States (ERG 2001). The MDP factor represents a variety of factors that may affect methane production in lagoon systems.

- The amount of VS available for conversion to CH_4 is assumed to be equal to the amount of VS produced during the month (from Step 3). For anaerobic lagoons, the amount of VS available also includes VS that may remain in the system from previous months.

- The amount of VS consumed during the month is equal to the amount available for conversion multiplied by the "f" factor.
- For anaerobic lagoons, the amount of VS 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.
- The estimated amount of CH_4 generated during the month is equal to the monthly VS consumed multiplied by the maximum CH_4 potential of the waste (B_o).

The annual MCF is then calculated as:

$$\mathrm{MCF}_{\mathrm{annual}} = \frac{\mathrm{CH_4\ generated}_{\mathrm{annual}}}{\mathrm{VS\ produced}_{\mathrm{annual}} \times \mathrm{B_o}}$$

Where,

$\mathrm{MCF}_{\mathrm{annual}}$ = Methane conversion factor
$\mathrm{VS\ produced}_{\mathrm{annual}}$ = Volatile solids excreted annually
B_o = Maximum CH_4 producing potential of the waste

In order to account for the carry-over of VS from one year to the next, it is assumed that a portion of the VS from the previous year are available in the lagoon system in the next year. For example, the VS from October, November, and December of 2005 are available in the lagoon system starting January of 2006 in the MCF calculation for lagoons in 2006. Following this procedure, the resulting MCF for lagoons accounts for temperature variation throughout the year, residual VS in a system (carry-over), and management and design practices that may reduce the VS available for conversion to CH_4. It is assumed that liquid-slurry systems have a retention time less than 30 days, so the liquid-slurry MCF calculation doesn't reflect the VS carry-over.

The liquid system MCFs are presented in Table A- 197 by state, WMS, and animal group for 2010.

Nitrous Oxide Emission Factors

Direct N_2O emission factors for manure management systems (kg N_2O-N/kg excreted N) were set equal to the most recent default IPCC factors (IPCC 2006), presented in Table A- 198.

Indirect N_2O emission factors account for two fractions of nitrogen losses: volatilization of ammonia (NH_3) and NO_X ($Frac_{gas}$) and runoff/leaching ($Frac_{runoff/leach}$). IPCC default indirect N_2O emission factors were used to estimate indirect N_2O emissions. These factors are 0.010 kg N_2O-N/kg N for volatilization and 0.0075 kg N_2O/kg N for runoff/leaching.

Country-specific estimates of N losses were developed for $Frac_{gas}$ and $Frac_{runoff/leach}$ for the United States. The vast majority of volatilization losses are NH_3. Although there are also some small losses of NO_X, no quantified estimates were available for use and those losses are believed to be small (about 1 percent) in comparison to the NH_3 losses. Therefore, $Frac_{gas}$ values were based on WMS-specific volatilization values estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). To estimate $Frac_{runoff/leach}$, data from EPA's Office of Water were used that estimate the amount of runoff from beef, dairy, and heifer operations in five geographic regions of the country (EPA 2002b). These estimates were used to develop U.S. runoff factors by animal type, WMS, and region. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses; therefore, $Frac_{runoff/leach}$ was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A- 199.

Step 5: CH_4 and N_2O Emission Calculations

To calculate CH_4 emissions for animals other than cattle, first the amount of volatile solids excreted in manure that is managed in each WMS was estimated:

$$\mathrm{VS\ excreted}_{\mathrm{State,\ Animal,\ WMS}} = \mathrm{Population}_{\mathrm{State,\ Animal}} \times \frac{\mathrm{TAM}}{1000} \times \mathrm{VS} \times \mathrm{WMS} \times 365.25$$

Where,

$\text{VS excreted}_{\text{State, Animal, WMS}}$ = Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
$\text{Population}_{\text{State, Animal}}$ = Annual average state animal population by animal type (head)
TAM = Typical animal mass (kg)
VS = Volatile solids production rate (kg VS/1000 kg animal mass/day)
WMS = Distribution of manure by WMS for each animal type in a state (percent)
365.25 = Days per year

Using the CEFM VS data for cattle, the amount of VS excreted was calculated using the following equation:

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{VS} \times \text{WMS}$$

Where,

$\text{VS excreted}_{\text{State, Animal, WMS}}$ = Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
$\text{Population}_{\text{State, Animal}}$ = Annual average state animal population by animal type (head)
VS = Volatile solids production rate (kg VS/animal/year)
WMS = Distribution of manure by WMS for each animal type in a state (percent)

For all animals, the estimated amount of VS was used to calculate CH_4 emissions using the following equation:

$$CH_4 = \sum_{\text{State, Animal, WMS}} \left(\text{VS excreted}_{\text{State, Animal, WMS}} \times B_o \times \text{MCF} \times 0.662 \right)$$

Where,
CH_4 = CH_4 emissions (kg CH_4/yr)
$\text{VS excreted}_{\text{WMS, State}}$ = Amount of VS excreted in manure managed in each WMS (kg/yr)
B_o = Maximum CH_4 producing capacity (m^3 CH_4/kg VS)
$\text{MCF}_{\text{animal, state, WMS}}$ = MCF for the animal group, state and WMS (percent)
0.662 = Density of methane at 25^o C (kg CH_4/m^3 CH_4)

A calculation was developed to estimate the amount of CH_4 emitted from anaerobic digestion (AD) systems utilizing CH_4 capture and combustion technology. First, AD systems were assumed to produce 90 percent of the maximum CH_4 producing capacity. This value is applied for all climate regions and AD system types. However, the actual amount of CH_4 produced by each AD system is very variable and will change based on operational and climate conditions and an assumption of 90 percent is likely overestimating CH_4 production from some systems and underestimating CH_4 production in other systems. The CH_4 production of AD systems is calculated using the equation below:

$$CH_4 \text{ Production AD}_{\text{AD System}} = \text{Population AD}_{\text{AD System}} \times \frac{\text{TAM}}{1000} \times \text{VS} \times B_o \times 0.662 \times 365.25 \times 0.90$$

Where,

CH_4 Production $\text{AD}_{\text{AD system}}$ = CH_4 production from a particular AD system, (kg/yr)
Population AD_{state} = Number of animals on a particular AD system
VS = Volatile solids production rate (kg VS/1000 kg animal mass-day)
TAM = Typical Animal Mass (kg/head)
B_o = Maximum CH_4 producing capacity (CH4 m^3/kg VS)
0.662 = Density of CH_4 at 25^o C (kg CH_4/m^3 CH_4)
365.25 = Days/year
0.90 = CH_4 production factor for AD systems

Next, the collection efficiency (CE) and destruction efficiency (DE) was considered of the AD system. The CE of covered lagoon systems was assumed to be 75 percent, and the CE of complete mix and plug flow AD systems was assumed to be 99 percent (EPA 2008). The CH_4 DE from flaring or burning in an engine was assumed to be 98 percent; therefore, the amount of CH_4 that would not be flared or combusted was assumed to be 2 percent (EPA 2008). The amount of CH_4 produced by systems with anaerobic digestion was calculated with the following equation:

$$CH_4\ \text{Emissions AD} = \sum_{\text{State, Animal, AD Systems}} \begin{pmatrix} \left[CH_4\ \text{Production AD}_{\text{AD system}} \times CE_{\text{AD system}} \times (1 - DE)\right] \\ + \left[CH_4\ \text{Production AD}_{\text{AD system}} \times (1 - CE_{\text{AD system}})\right] \end{pmatrix}$$

Where:

CH_4 Emissions AD = CH_4 emissions from AD systems, (kg/yr)
CH_4 Production $AD_{\text{AD system}}$ = CH_4 production from a particular AD system, (kg/yr)
$CE_{\text{AD system}}$ = Collection efficiency of the AD system, varies by AD system type
DE = Destruction efficiency of the AD system, 0.98 for all systems

In addition to CH_4 emissions, also total N_2O emissions were estimated from manure management systems. Total N_2O emissions were calculated by summing direct and indirect N_2O emissions. The first step in estimating direct and indirect N_2O emissions was calculating the amount of N excreted in manure and managed in each WMS for animals other than cattle using the following equation:

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \frac{\text{TAM}}{1000} \times \text{Nex} \times 365.25$$

Where,

N excreted $_{\text{State, Animal, WMS}}$ = Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{state}}$ = Annual average state animal population by animal type (head)
WMS = Distribution of manure by waste management system for each animal type in a state (percent)
TAM = Typical animal mass (kg)
Nex = Total Kjeldahl nitrogen excretion rate (kg N/1000 kg animal mass/day)
365.25 = Days per year

Using the CEFM Nex data for cattle, the amount of N excreted was calculated using the following equation:

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \text{Nex}$$

Where,

N excreted $_{\text{State, Animal, WMS}}$ = Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{state}}$ = Annual average state animal population by animal type (head)
WMS = Distribution of manure by waste management system for each animal type in a state (percent)
Nex = Total Kjeldahl N excretion rate (kg N/animal/year)

For all animals, direct N_2O emissions were calculated as follows:

$$\text{Direct N2O} = \sum_{\text{State, Animal, WMS}} \left(\text{N excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

Where,

Direct N_2O = Direct N_2O emissions (kg N_2O/yr)

$N\ excreted_{State,\ Animal,\ WMS}$ = Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
EF_{WMS} = Direct N_2O emission factor from IPCC guidelines (kg N_2O-N /kg N)
44/28 = Conversion factor of N_2O-N to N_2O

Indirect N_2O emissions were calculated for all animals with the following equation:

$$\text{Indirect N2O} = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times \text{EF}_{\text{volatilization}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times \text{EF}_{\text{runnoff/leach}} \times \frac{44}{28} \right] \right)$$

Where,

Indirect N_2O = Indirect N_2O emissions (kg N_2O/yr)
$N\ excreted_{State,\ Animal,\ WMS}$ = Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
$Frac_{gas,WMS}$ = Nitrogen lost through volatilization in each WMS
$Frac_{runoff/leach,WMS}$ = Nitrogen lost through runoff and leaching in each WMS; data were not available for leaching so the value reflects only runoff
$EF_{volatilization}$ = Emission factor for volatilization (0.010 kg N_2O-N/kg N)
$EF_{runoff/leach}$ = Emission factor for runoff/leaching (0.0075 kg N_2O-N/kg N)
44/28 = Conversion factor of N_2O-N to N_2O

` Emission estimates of CH_4 and N_2O by animal type are presented for all years of the inventory in Table A- 200 and Table A- 201respectively. Emission estimates for 2010 are presented by animal type and state in Table A- 202 and Table A- 203, respectively.

Table A-190: Livestock Population (1,000 Head)

Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Dairy Cattle	14,144	13,590	13,191	13,217	13,165	13,215	13,021	13,165	13,398	13,487	13,658	13,761	13,608
Dairy Cows	10,015	9,482	9,183	9,172	9,106	9,142	8,988	9,004	9,104	9,145	9,257	9,333	9,086
Dairy Heifer	4,129	4,108	4,008	4,045	4,060	4,073	4,033	4,162	4,294	4,343	4,401	4,429	4,522
Swine[1]	53,941	58,899	58,864	58,913	60,028	59,827	60,735	61,073	61,887	65,417	67,408	65,990	64,693
Market <50 lb.	18,359	19,656	19,574	19,659	19,863	19,929	20,222	20,228	20,514	21,812	19,964	19,444	19,049
Market 50-119 lb.	11,734	12,836	12,926	12,900	13,284	13,138	13,400	13,519	13,727	14,557	17,219	16,995	16,699
Market 120-179 lb.	9,440	10,545	10,748	10,708	11,013	11,050	11,227	11,336	11,443	12,185	12,931	12,567	12,313
Market >180 lb.	7,510	8,937	9,385	9,465	9,738	9,701	9,922	9,997	10,113	10,673	11,193	11,079	10,854
Breeding	6,899	6,926	6,231	6,181	6,129	6,011	5,963	5,993	6,090	6,190	6,102	5,905	5,778
Beef Cattle[2]	87,228	95,683	89,948	89,118	89,102	88,232	86,441	86,954	88,070	87,639	86,450	85,812	85,224
Feedlot Steers	6,357	7,233	8,304	7,932	8,116	8,416	8,018	8,116	8,724	8,674	8,481	8,445	8,603
Feedlot Heifers	3,192	3,831	4,702	4,569	4,557	4,676	4,521	4,536	4,801	4,730	4,589	4,509	4,651
NOF Bulls	2,160	2,385	2,293	2,274	2,244	2,248	2,201	2,214	2,258	2,214	2,207	2,184	2,190
NOF Calves	22,561	23,499	22,569	22,389	22,325	21,997	21,781	21,678	21,621	21,483	21,155	21,001	20,856
NOF Heifers	10,182	11,829	9,781	9,832	9,843	9,564	9,321	9,550	9,716	9,592	9,350	9,447	9,328
NOF Steers	10,321	11,716	8,724	8,724	8,883	8,347	8,067	8,185	8,248	8,302	8,233	8,515	8,226
NOF Cows	32,455	35,190	33,575	33,398	33,134	32,983	32,531	32,674	32,703	32,644	32,435	31,712	31,371
Sheep	11,358	8,989	7,036	6,908	6,623	6,321	6,065	6,135	6,200	6,120	5,950	5,699	5,573
Sheep On Feed	1,180	1,771	2,963	3,256	3,143	3,049	2,923	2,971	3,026	3,000	2,911	2,767	2,739
Sheep NOF	10,178	7,218	4,073	3,652	3,480	3,272	3,142	3,164	3,174	3,120	3,039	2,932	2,834
Goats	2,516	2,357	2,419	2,475	2,530	2,652	2,774	2,897	3,019	3,141	3,141	3,141	3,141
Poultry[3]	1,537,074	1,826,977	2,033,123	2,060,398	2,097,691	2,085,268	2,130,877	2,150,410	2,154,236	2,166,936	2,175,990	2,088,828	2,104,120
Hens >1 yr.	273,467	299,071	333,593	340,317	340,209	340,979	343,922	348,203	349,888	346,613	339,859	341,005	342,451
Pullets	73,167	81,369	95,159	95,656	95,289	100,346	101,429	96,809	96,596	103,816	99,458	102,301	104,665
Chickens	6,545	7,637	8,088	8,126	8,353	8,439	8,248	8,289	7,938	8,164	7,589	8,487	7,390
Broilers	1,066,209	1,331,940	1,506,127	1,525,413	1,562,015	1,544,155	1,589,209	1,613,091	1,612,327	1,619,400	1,638,055	1,554,582	1,568,218
Turkeys	117,685	106,960	90,155	90,887	91,826	91,349	88,069	84,018	87,487	88,943	91,029	82,453	81,396
Horses	5,069	5,130	5,240	5,500	6,000	7,000	8,000	9,200	9,500	9,500	9,500	9,500	9,500

Note: Totals may not sum due to independent rounding.

[1] Prior to 2008, the Market <50 lbs category was <60 lbs and the Market 50-119 lbs category was Market 60-119 lbs; USDA updated the categories to be more consistent with international animal categories.

[2] NOF = Not on Feed

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

Table A- 191: Waste Characteristics Data

Animal Group	TAM (kg)	TAM Source	Total Kjeldahl Nitrogen, N_{ex} (kg/day per 1,000 kg mass)	N_{ex} Source	Maximum Methane Generation Potential, B_o (m^3 CH_4/kg VS added)	B_o Source	Volatile Solids, VS (kg/day per 1,000 kg mass)	VS Source
Dairy Cows	680	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.24	Morris 1976	Table A- 92	Moffroid and Pape, 2011
Dairy Heifers	406-408	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.17	Bryant et. al. 1976	Table A- 92	Moffroid and Pape, 2011
Feedlot Steers	419-457	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.33	Hashimoto 1981	Table A- 92	Moffroid and Pape, 2011
Feedlot Heifers	384-430	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.33	Hashimoto 1981	Table A- 92	Moffroid and Pape, 2011
NOF Bulls	750	Shuyler 2000	Table A- 193	USDA 1996a	0.17	Hashimoto 1981	Table A- 193	USDA 1996a
NOF Calves	118	USDA 1996a	Table A- 193	USDA 1996a, 2008	0.17	Hashimoto 1981	Table A- 193	USDA 1996a, 2008
NOF Heifers	296-406	Enteric Fermentation		Moffroid and Pape, 2011	0.17	Hashimoto 1981		Moffroid and Pape, 2011
NOF Steers	314-335	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.17	Hashimoto 1981	Table A- 92	Moffroid and Pape, 2011
NOF Cows	554-611	Enteric Fermentation	Table A- 92	Moffroid and Pape, 2011	0.17	Hashimoto 1981	Table A- 92	Moffroid and Pape, 2011
Market Swine <50 lbs.	13	ERG 2010a	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Breeding Swine	198	Safley 2000	Table A- 193	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 193	USDA 1996a, 2008
Feedlot Sheep	25	EPA 1992	Table A- 193	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A- 193	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A- 193	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A- 193	ASAE 1998, USDA 2008
Goats	64	ASAE 1999	Table A- 193	ASAE 1998	0.17	EPA 1992	Table A- 193	ASAE 1998
Horses	450	ASAE 1999	Table A- 193	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A- 193	ASAE 1998, USDA 2008
Hens >/= 1 yr	1.8	ASAE 1999	Table A- 193	USDA 1996a, 2008	0.39	Hill 1982	Table A- 193	USDA 1996a, 2008
Pullets	1.8	ASAE 1999	Table A- 193	USDA 1996a, 2008	0.39	Hill 1982	Table A- 193	USDA 1996a, 2008
Other Chickens	1.8	ASAE 1999	Table A- 193	USDA 1996a, 2008	0.39	Hill 1982	Table A- 193	USDA 1996a, 2008
Broilers	0.9	ASAE 1999	Table A- 193	USDA 1996a, 2008	0.36	Hill 1984	Table A- 193	USDA 1996a, 2008
Turkeys	6.8	ASAE 1999	Table A- 193	USDA 1996a, 2008	0.36	Hill 1984	Table A- 193	USDA 1996a, 2008

Table A-192: Estimated Volatile Solids and Nitrogen Excreted Production Rate by year for Animals Other Than Cattle (kg/day/1000 kg animal mass)

Animal Type	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
VS																					
Swine, Market <50 lbs.	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Swine, Market 50-119 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market 120-179lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market >180 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine Breeding	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
NOF Bulls	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
NOF Calves	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.5	6.6	6.7	6.8	6.9	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.7	7.7
Sheep	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.1	9.0	8.9	8.8	8.8	8.7	8.6	8.5	8.4	8.3	8.3	8.3
Goats	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Hens >1yr.	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2
Pullets	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2
Chickens	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.9	10.9	10.9	10.9	10.9	10.9	11.0	11.0	11.0	11.0	11.0	11.0
Broilers	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.2	15.3	15.5	15.7	15.8	16.0	16.2	16.3	16.5	16.7	16.8	17.0	17.0	17.0
Turkeys	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.6	9.5	9.4	9.3	9.2	9.1	9.0	8.9	8.8	8.7	8.6	8.5	8.5	8.5
Horses	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.6	9.2	8.8	8.4	8.1	7.7	7.3	6.9	6.5	6.1	6.1	6.1
Nex																					
Swine, Market <50 lbs.	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.63	0.65	0.68	0.71	0.73	0.76	0.79	0.81	0.84	0.87	0.89	0.92	0.92	0.92
Swine, Market 50-119 lbs.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54
Swine, Market 120-179lbs.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54
Swine, Breeding	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.20	0.20	0.20
NOF Bulls	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
NOF Calves	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.31	0.33	0.34	0.35	0.36	0.38	0.39	0.40	0.41	0.43	0.44	0.45	0.45	0.45
Sheep	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45
Goats	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Hens >1yr.	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.71	0.72	0.73	0.73	0.74	0.75	0.76	0.77	0.77	0.78	0.79	0.79	0.79
Pullets	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.71	0.72	0.73	0.73	0.74	0.75	0.76	0.77	0.77	0.78	0.79	0.79	0.79
Chickens	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.85	0.88	0.90	0.92	0.94	0.97	0.99	1.01	1.03	1.06	1.08	1.10	1.10	1.10
Broilers	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.09	1.08	1.07	1.05	1.04	1.03	1.02	1.01	1.00	0.98	0.97	0.96	0.96	0.96
Turkeys	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.73	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.65	0.64	0.63	0.63	0.63	0.63
Horses	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25	0.25	0.25

Table A-193: Estimated Volatile Solids and Nitrogen Excreted Production Rate by State for Cattle for 2010 (kg/animal/year)

	Volatile Solids							Nitrogen Excreted						
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer
Alabama	2233	1253	1664	1094	971	679	654	134	68.9	120.1	82.7	70.6	56.4	56.1
Alaska	1983	1253	1891	1279	1116	678	655	122	68.9	97.0	69.0	56.9	56.7	56.3
Arizona	2850	1253	1891	1252	1116	679	657	159	68.9	97.0	67.0	56.9	56.4	57.1
Arkansas	2062	1253	1664	1087	971	678	654	125	68.9	120.1	82.1	70.6	56.6	56.3
California	2800	1253	1891	1215	1116	679	657	156	68.9	97.0	64.3	56.9	56.5	56.9
Colorado	2867	1253	1891	1189	1116	679	657	160	68.9	97.0	62.5	56.9	56.4	56.9
Connecticut	2538	1253	1674	1105	977	679	654	146	68.9	127.2	88.1	74.9	56.4	56.2
Delaware	2368	1253	1674	1094	977	678	654	138	68.9	127.2	87.0	74.9	56.6	56.3
Florida	2548	1253	1664	1107	971	679	654	148	68.9	120.1	83.9	70.6	56.6	56.2
Georgia	2490	1253	1664	1088	971	679	654	145	68.9	120.1	82.1	70.6	56.5	56.2
Hawaii	2094	1253	1891	1252	1116	679	654	127	68.9	97.0	67.0	56.9	56.5	56.2
Idaho	2792	1253	1891	1206	1116	679	657	156	68.9	97.0	63.7	56.9	56.4	56.9
Illinois	2531	1253	1589	998	923	679	657	145	68.9	121.4	79.0	71.2	56.4	56.9
Indiana	2617	1253	1589	1014	923	679	656	149	68.9	121.4	80.7	71.2	56.4	56.9
Iowa	2649	1253	1589	980	923	679	656	150	68.9	121.4	77.3	71.2	56.4	56.8
Kansas	2668	1253	1589	976	923	679	657	151	68.9	121.4	76.9	71.2	56.4	56.9
Kentucky	2262	1253	1664	1077	971	678	657	136	68.9	120.1	81.1	70.6	56.6	56.9
Louisiana	1981	1253	1664	1106	971	679	654	122	68.9	120.1	83.9	70.6	56.5	56.2
Maine	2470	1253	1674	1091	977	679	654	143	68.9	127.2	86.6	74.9	56.5	56.1
Maryland	2484	1253	1674	1091	977	679	657	143	68.9	127.2	86.6	74.9	56.3	56.9
Massachusetts	2401	1253	1674	1093	977	679	654	140	68.9	127.2	86.9	74.9	56.5	56.1
Michigan	2837	1253	1589	1004	923	679	656	158	68.9	121.4	79.7	71.2	56.4	56.8
Minnesota	2546	1253	1589	1004	923	679	656	146	68.9	121.4	79.6	71.2	56.5	56.8
Mississippi	2134	1253	1664	1093	971	679	654	130	68.9	120.1	82.6	70.6	56.4	56.2
Missouri	2189	1253	1589	1022	923	679	657	131	68.9	121.4	81.5	71.2	56.4	56.9
Montana	2641	1253	1664	1079	971	679	659	150	68.9	120.1	81.3	70.6	56.3	57.5
Nebraska	2578	1253	1891	1186	1116	679	657	147	68.9	97.0	62.3	56.9	56.4	56.9
Nevada	2753	1253	1589	1027	923	679	655	155	68.9	121.4	82.0	71.2	56.5	56.5
New Hampshire	2583	1253	1891	1233	1116	679	654	148	68.9	97.0	65.6	56.9	56.5	56.1
New Jersey	2406	1253	1674	1083	977	678	654	140	68.9	127.2	85.8	74.9	56.6	56.2
New Mexico	2933	1253	1674	1081	977	679	667	163	68.9	127.2	85.7	74.9	56.4	59.8
New York	2654	1253	1891	1218	1116	679	656	151	68.9	97.0	64.6	56.9	56.4	56.8
North Carolina	2617	1253	1674	1104	977	678	654	151	68.9	127.2	88.0	74.9	56.6	56.2
North Dakota	2465	1253	1664	1065	971	679	656	142	68.9	120.1	80.0	70.6	56.4	56.7
Ohio	2552	1253	1589	1019	923	679	657	146	68.9	121.4	81.2	71.2	56.4	56.9
Oklahoma	2383	1253	1589	1013	923	679	656	139	68.9	121.4	80.6	71.2	56.4	56.8
Oregon	2618	1253	1664	1068	971	679	657	149	68.9	120.1	80.2	70.6	56.4	56.9
Pennsylvania	2581	1253	1891	1226	1116	679	657	147	68.9	97.0	65.1	56.9	56.4	56.9
Rhode Island	2423	1253	1674	1110	977	679	654	141	68.9	127.2	88.5	74.9	56.4	56.2
South Carolina	2489	1253	1674	1104	977	679	654	145	68.9	127.2	87.9	74.9	56.5	56.1
South Dakota	2629	1253	1664	1050	971	679	656	149	68.9	120.1	78.5	70.6	56.4	56.8
Tennessee	2375	1253	1589	1041	923	679	656	140	68.9	121.4	83.5	71.2	56.4	56.7
Texas	2701	1253	1664	1053	971	679	657	153	68.9	120.1	78.8	70.6	56.4	56.9
Utah	2698	1253	1664	1080	971	679	657	152	68.9	120.1	81.4	70.6	56.6	56.9
Vermont	2484	1253	1891	1226	1116	678	654	143	68.9	97.0	65.1	56.9	56.6	56.1
Virginia	2505	1253	1674	1092	977	679	658	146	68.9	127.2	86.8	74.9	56.4	57.3
Washington	2856	1253	1664	1058	971	679	656	159	68.9	120.1	79.3	70.6	56.4	56.8
West Virginia	2272	1253	1891	1247	1116	679	657	134	68.9	97.0	66.6	56.9	56.2	57.1
Wisconsin	2640	1253	1589	1021	923	679	657	150	68.9	121.4	81.4	71.2	56.4	56.9
Wyoming	2598	1253	1891	1233	1116	679	657	148	68.9	97.0	65.6	56.9	56.4	56.9

Source: Moffroid and Pape, 2011.

Table A-194: 2010 Manure Distribution Among Waste Management Systems by Operation (Percent)

	Beef Feedlots		Dairies[1]						Dairy Heifer Facilities				Swine Operations[1]					Layer Operations		Broiler and Turkey Operations	
State	Dry Lot[2]	Liquid/ Slurry[2]	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[2]	Dry Lot[2]	Liquid/ Slurry[2]	Pasture[2]	Pasture	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture	Poultry with Litter
Alabama	100	1	51	16	7	10	16	0	17	38	0	45	5	4	7	54	31	42	58	1	99
Alaska	100	1	5	9	34	19	24	9	6	90	1	4	64	2	10	7	17	25	75	1	99
Arizona	100	0	0	10	9	19	61	0	10	90	0	0	6	3	6	55	29	60	40	1	99
Arkansas	100	1	60	14	10	7	9	0	15	28	0	57	4	4	13	45	35	0	100	1	99
California	100	1	1	11	9	20	59	0	11	88	1	1	10	3	7	50	29	12	88	1	99
Colorado	100	0	1	1	11	23	64	0	1	98	0	1	1	6	26	17	50	60	40	1	99
Connecticut	100	1	6	43	16	20	13	2	43	51	0	6	78	1	6	5	11	5	95	1	99
Delaware	100	1	6	44	19	19	10	2	44	50	0	6	8	5	25	17	46	5	95	1	99
Florida	100	1	13	22	7	15	43	0	22	61	1	17	72	1	8	6	13	42	58	1	99
Georgia	100	1	37	18	9	12	23	0	18	42	0	40	4	4	8	53	31	42	58	1	99
Hawaii	100	1	10	0	9	23	57	0	0	99	1	1	31	3	19	14	32	25	75	1	99
Idaho	100	0	0	0	11	23	65	0	1	99	0	0	12	5	23	15	44	60	40	1	99
Illinois	100	1	4	6	39	31	16	5	8	87	0	5	1	5	29	14	52	2	98	1	99
Indiana	100	1	5	8	29	31	24	3	13	79	0	8	1	5	28	14	52	0	100	1	99
Iowa	100	1	4	8	34	30	20	4	10	83	0	6	1	4	9	54	33	0	100	1	99
Kansas	100	1	2	3	21	37	36	2	5	92	0	3	2	5	28	13	52	2	98	1	99
Kentucky	100	1	60	14	14	7	3	2	14	24	0	61	5	4	10	48	33	5	95	1	99
Louisiana	100	1	59	15	10	7	9	1	14	26	0	60	88	1	3	3	6	60	40	1	99
Maine	100	1	7	45	20	17	10	2	45	48	0	7	65	2	10	7	16	5	95	1	99
Maryland	100	1	7	44	22	16	8	3	44	49	0	7	7	5	25	17	47	5	95	1	99
Massachusetts	100	1	7	44	22	16	8	3	45	47	0	7	56	2	12	9	20	5	95	1	99
Michigan	100	1	2	4	24	38	29	3	6	91	0	3	4	5	26	17	48	2	98	1	99
Minnesota	100	1	5	8	39	28	17	4	10	84	0	6	1	5	26	18	50	0	100	1	99
Mississippi	100	1	54	15	10	8	12	0	15	28	0	57	2	4	6	58	31	60	40	1	99
Missouri	100	1	7	12	42	22	11	5	14	77	0	8	2	5	28	13	52	0	100	1	99
Montana	100	0	2	4	19	28	42	4	4	93	0	3	3	5	25	17	49	60	40	1	99
Nebraska	100	1	2	4	26	35	29	3	6	90	0	4	1	5	28	14	51	2	98	1	99
Nevada	100	0	0	0	10	24	65	0	0	99	0	0	34	3	18	14	31	0	100	1	99
New Hampshire	100	1	7	44	19	18	10	2	44	49	0	7	64	2	10	8	17	5	95	1	99
New Jersey	100	1	7	45	25	13	6	3	45	47	0	8	36	3	18	14	30	5	95	1	99
New Mexico	100	0	0	10	9	19	61	0	10	90	0	0	100	0	0	0	0	60	40	1	99
New York	100	1	6	44	17	18	13	2	45	48	0	7	13	5	23	15	44	5	95	1	99
North Carolina	100	1	46	17	11	15	10	2	15	31	0	54	0	4	7	57	32	42	58	1	99
North Dakota	100	1	7	11	38	26	15	4	11	83	0	6	5	5	25	17	48	2	98	1	99
Ohio	100	1	6	11	38	26	15	4	14	78	0	8	3	5	28	14	51	0	100	1	99
Oklahoma	100	0	0	7	21	22	45	4	6	94	0	0	1	4	6	58	31	60	40	1	99
Oregon	100	1	16	0	11	22	50	1	0	80	1	20	48	2	14	11	24	25	75	1	99
Pennsylvania	100	1	8	46	24	12	6	2	47	44	0	9	4	5	26	18	48	0	100	1	99
Rhode Island	100	1	9	47	25	13	5	2	47	44	0	9	72	1	8	6	13	5	95	1	99

	Beef Feedlots		Dairies[1]						Dairy Heifer Facilities				Swine Operations[1]					Layer Operations		Broiler and Turkey Operations	
State	Dry Lot[2]	Liquid/ Slurry[2]	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[2]	Dry Lot[2]	Liquid/ Slurry[2]	Pasture[2]	Pasture	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture	Poultry with Litter
South Carolina	100	1	47	17	8	11	18	0	15	31	0	54	3	4	7	55	31	60	40	1	99
South Dakota	100	1	3	4	24	36	31	2	8	87	0	5	1	5	26	17	50	2	98	1	99
Tennessee	100	1	58	15	12	9	4	2	15	26	0	59	13	3	11	41	32	5	95	1	99
Texas	100	0	0	9	11	22	58	1	8	92	0	0	3	4	6	57	30	12	88	1	99
Utah	100	0	1	1	15	26	56	2	1	98	0	1	1	6	26	17	51	60	40	1	99
Vermont	100	1	6	44	17	19	13	2	44	49	0	7	63	2	10	8	18	5	95	1	99
Virginia	100	1	56	15	11	10	5	2	15	28	0	57	4	4	7	54	31	5	95	1	99
Washington	100	1	11	0	11	22	56	1	0	83	1	17	43	3	15	11	28	12	88	1	99
West Virginia	100	1	8	46	23	14	7	2	45	48	0	7	59	2	11	7	20	5	95	1	99
Wisconsin	100	1	5	9	38	28	17	4	12	82	0	7	13	4	23	17	42	2	98	1	99
Wyoming	100	0	4	6	19	23	43	4	12	81	0	7	4	5	25	16	49	60	40	1	99

[1] In the methane inventory for manure management, the percent of dairy cows and swine with anaerobic digestion systems is estimated using data from EPA's AgSTAR Program.

[2] Because manure from beef feedlots and 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 A- 195: Manure Management System Descriptions

Manure Management System	Description[1]
Pasture	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed. N_2O emissions from deposited manure are covered under the N_2O from Agricultural Soils category.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. N_2O emissions during storage and treatment are assumed to be zero. N_2O emissions from land application are covered under the Agricultural Soils category.
Solid Storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Dry Lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.
Liquid/ Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds, usually for periods less than one year.
Anaerobic Lagoon	Uncovered anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5 to 15 years, and the sludge is typically applied to agricultural lands. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields. Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of nondegradable material such as straw or other bedding materials.
Anaerobic Digester	Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO2 and CH4, which is captured and flared or used as a fuel.
Deep Pit	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility. Typical storage periods range from 5 to 12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land.
Poultry with Litter	Enclosed poultry houses use bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Litter is typically cleaned out completely once a year. These manure systems are typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.
Poultry without Litter	In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is stored. When designed and operated properly, this high-rise system is a form of passive windrow composting.

[1] Manure management system descriptions are from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Volume 4: Agriculture, Forestry and Other Land Use, Chapter 10: Emissions from Livestock and Manure Management, Tables 10.18 and 10.21) and the *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* (EPA-821-R-03-001, December 2002).

Table A- 196: Methane Conversion Factors (percent) for Dry Systems

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Aerobic Treatment	0	0	0
Cattle Deep Litter (<1 month)	0.03	0.03	0.3
Cattle Deep Litter (>1 month)	0.21	0.44	0.76
Composting - In Vessel	0.005	0.005	0.005
Composting - Static Pile	0.005	0.005	0.005
Composting-Extensive/ Passive	0.005	0.01	0.015
Composting-Intensive	0.005	0.01	0.015
Daily Spread	0.001	0.005	0.01
Dry Lot	0.01	0.015	0.05
Fuel	0.1	0.1	0.1
Pasture	0.01	0.015	0.02
Poultry with bedding	0.015	0.015	0.015

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Poultry without bedding	0.015	0.015	0.015
Solid Storage	0.02	0.04	0.05

Table A- 197: Methane Conversion Factors by State for Liquid Systems for 2010(percent)

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
Alabama	0.77	0.43	0.77	0.42	0.44	0.77
Alaska	0.46	0.14	0.46	0.14	0.14	0.46
Arizona	0.81	0.59	0.79	0.48	0.53	0.76
Arkansas	0.77	0.40	0.77	0.43	0.41	0.77
California	0.75	0.33	0.73	0.31	0.41	0.75
Colorado	0.66	0.22	0.68	0.24	0.24	0.66
Connecticut	0.70	0.27	0.71	0.27	0.27	0.70
Delaware	0.75	0.36	0.75	0.36	0.36	0.75
Florida	0.76	0.53	0.76	0.52	0.52	0.76
Georgia	0.77	0.44	0.76	0.42	0.42	0.76
Hawaii	0.77	0.58	0.77	0.58	0.58	0.77
Idaho	0.66	0.22	0.64	0.21	0.21	0.65
Illinois	0.74	0.33	0.74	0.32	0.31	0.74
Indiana	0.72	0.30	0.73	0.31	0.31	0.73
Iowa	0.71	0.27	0.71	0.28	0.28	0.71
Kansas	0.76	0.35	0.75	0.34	0.34	0.75
Kentucky	0.75	0.35	0.75	0.36	0.35	0.76
Louisiana	0.78	0.48	0.78	0.49	0.50	0.78
Maine	0.66	0.22	0.66	0.22	0.21	0.66
Maryland	0.74	0.32	0.74	0.32	0.34	0.74
Massachusetts	0.69	0.25	0.70	0.26	0.26	0.70
Michigan	0.69	0.26	0.70	0.26	0.26	0.69
Minnesota	0.69	0.25	0.70	0.26	0.25	0.68
Mississippi	0.78	0.45	0.77	0.44	0.45	0.78
Missouri	0.75	0.35	0.75	0.34	0.34	0.75
Montana	0.59	0.18	0.60	0.19	0.20	0.60
Nebraska	0.72	0.28	0.72	0.28	0.28	0.72
Nevada	0.69	0.24	0.71	0.26	0.23	0.69
New Hampshire	0.67	0.23	0.67	0.24	0.22	0.67
New Jersey	0.73	0.32	0.74	0.32	0.31	0.74
New Mexico	0.74	0.32	0.72	0.29	0.31	0.71
New York	0.68	0.24	0.68	0.25	0.25	0.69
North Carolina	0.75	0.36	0.76	0.41	0.33	0.75
North Dakota	0.65	0.22	0.65	0.22	0.22	0.65
Ohio	0.72	0.29	0.72	0.30	0.29	0.72
Oklahoma	0.77	0.42	0.77	0.39	0.39	0.77
Oregon	0.62	0.20	0.63	0.20	0.22	0.64
Pennsylvania	0.71	0.28	0.72	0.30	0.29	0.72
Rhode Island	0.71	0.28	0.71	0.28	0.28	0.71
South Carolina	0.77	0.43	0.77	0.43	0.42	0.77
South Dakota	0.70	0.26	0.70	0.26	0.26	0.70
Tennessee	0.75	0.36	0.76	0.38	0.37	0.76
Texas	0.78	0.42	0.78	0.44	0.38	0.79
Utah	0.67	0.23	0.69	0.24	0.24	0.67
Vermont	0.65	0.22	0.65	0.22	0.22	0.66
Virginia	0.73	0.32	0.75	0.36	0.33	0.74
Washington	0.63	0.21	0.64	0.21	0.22	0.64
West Virginia	0.72	0.29	0.72	0.29	0.29	0.72
Wisconsin	0.68	0.24	0.69	0.26	0.25	0.69
Wyoming	0.62	0.20	0.64	0.21	0.22	0.63

Table A- 198: Direct Nitrous Oxide Emission Factors for 2010 (kg N_2O-N/kg Kjdl N)

Waste Management System	**Direct N_2O Emission Factor**
Aerobic Treatment (forced aeration)	0.005
Aerobic Treatment (natural aeration)	0.01
Anaerobic Digester	0
Anaerobic Lagoon	0
Cattle Deep Bed (active mix)	0.07
Cattle Deep Bed (no mix)	0.01
Composting_in vessel	0.006
Composting_intensive	0.1
Composting_passive	0.01
Composting_static	0.006
Daily Spread	0
Deep Pit	0.002
Dry Lot	0.02
Fuel	0
Liquid/Slurry	0.005
Pasture	0
Poultry with bedding	0.001
Poultry without bedding	0.001
Solid Storage	0.005

Table A- 199: Indirect Nitrous Oxide Loss Factors (percent)

			Runoff/Leaching Nitrogen Loss[1]				
Animal Type	**Waste Management System**	**Volatilization Nitrogen Loss**	**Central**	**Pacific**	**Mid-Atlantic**	**Midwest**	**South**
Beef Cattle	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Beef Cattle	Liquid/Slurry	26	0	0	0	0	0
Beef Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Anaerobic Lagoon	43	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Daily Spread	10	0	0	0	0	0
Dairy Cattle	Deep Pit	24	0	0	0	0	0
Dairy Cattle	Dry Lot	15	0.6	2	1.8	0.9	2.2
Dairy Cattle	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Solid Storage	27	0.2	0	0	0	0
Goats	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Goats	Pasture	0	0	0	0	0	0
Horses	Dry Lot	23	0	0	0	0	0
Horses	Pasture	0	0	0	0	0	0
Poultry	Anaerobic Lagoon	54	0.2	0.8	0.7	0.4	0.9
Poultry	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Poultry	Pasture	0	0	0	0	0	0
Poultry	Poultry with bedding	26	0	0	0	0	0
Poultry	Poultry without bedding	34	0	0	0	0	0
Poultry	Solid Storage	8	0	0	0	0	0
Sheep	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Sheep	Pasture	0	0	0	0	0	0
Swine	Anaerobic Lagoon	58	0.2	0.8	0.7	0.4	0.9
Swine	Deep Pit	34	0	0	0	0	0
Swine	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Swine	Pasture	0	0	0	0	0	0
Swine	Solid Storage	45	0	0	0	0	0

[1] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.

Table A- 200: Methane Emissions from Livestock Manure Management (Gg)[a]

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Dairy Cattle	**599**	**615**	**598**	**623**	**663**	**693**	**702**	**734**	**781**	**854**	**900**	**960**	**997**	**870**	**1000**	**1069**	**1101**	**1224**	**1238**	**1233**	**1239**
Dairy Cows	592	608	591	616	656	686	695	727	774	846	893	952	990	864	993	1062	1094	1216	1230	1225	1231
Dairy Heifer	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	8	8	8	8
Swine	**624**	**676**	**639**	**680**	**741**	**764**	**730**	**783**	**892**	**849**	**834**	**854**	**879**	**860**	**857**	**914**	**901**	**982**	**938**	**896**	**948**
Market Swine	484	524	500	534	585	608	582	626	720	692	680	696	720	706	706	753	741	814	780	748	792
Market <50 lbs.	102	110	104	109	119	121	116	125	141	133	131	134	137	135	135	142	141	155	109	103	110
Market 50-119 lbs.	101	111	105	110	120	124	117	127	144	138	136	138	144	140	141	150	148	163	174	167	177
Market 120-179 lbs.	136	147	140	151	164	170	163	175	201	193	189	192	199	196	196	210	206	227	229	218	231
Market >180 lbs.	145	156	152	165	182	194	185	198	235	229	225	232	240	234	234	251	246	269	268	259	273
Breeding Swine	140	152	139	146	156	155	148	157	172	157	155	158	158	154	151	161	160	168	157	148	156
Beef Cattle	**128**	**128**	**131**	**131**	**137**	**141**	**139**	**136**	**139**	**139**	**133**	**136**	**133**	**133**	**131**	**135**	**138**	**136**	**132**	**131**	**134**
Feedlot Steers	14	14	14	13	14	14	14	13	13	14	15	15	15	16	15	15	16	16	16	16	16
Feedlot Heifers	7	7	7	7	8	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9	9
NOF Bulls	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
NOF Calves	8	8	8	8	9	9	8	8	9	9	9	9	9	9	9	9	10	10	9	9	9
NOF Heifers	12	12	13	14	14	15	15	14	15	14	13	13	13	13	12	13	13	13	13	13	13
NOF Steers	12	12	13	14	13	14	14	13	13	12	11	11	11	10	10	10	10	11	10	11	11
NOF Cows	69	69	70	71	74	76	76	74	76	76	71	73	71	71	71	73	74	73	70	69	71
Sheep	**7**	**7**	**7**	**6**	**6**	**5**	**5**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Goats	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Poultry	**131**	**132**	**127**	**131**	**131**	**128**	**126**	**128**	**130**	**126**	**127**	**131**	**129**	**130**	**129**	**129**	**131**	**134**	**129**	**128**	**129**
Hens >1 yr.	73	72	70	73	72	69	68	67	70	66	67	70	67	68	66	66	66	67	64	64	64
Total Pullets	25	26	23	23	23	22	21	23	23	21	22	22	22	22	23	22	23	25	23	23	24
Chickens	4	4	4	4	4	4	3	3	4	4	3	3	4	4	3	3	3	3	3	4	3
Broilers	19	20	20	21	22	23	24	25	26	27	28	28	29	29	30	31	32	32	33	31	31
Turkeys	10	10	10	10	9	9	9	9	8	7	7	7	7	7	7	7	7	7	7	6	6
Horses	**22**	**22**	**21**	**21**	**21**	**21**	**21**	**21**	**22**	**21**	**20**	**20**	**21**	**24**	**26**	**28**	**27**	**27**	**24**	**24**	**24**

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

Table A- 201: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (Gg)

Animal Type	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Dairy Cattle	**17.1**	**17.01**	**17.03**	**17.27**	**17.4**	**17.7**	**17.7**	**17.9**	**18.0**	**17.6**	**17.9**	**18.2**	**18.5**	**16.6**	**17.8**	**18.3**	**18.9**	**18.9**	**18.6**	**18.8**	**18.9**
Dairy Cows	10.0	10.07	9.97	10.05	10.1	10.3	10.3	10.4	10.5	10.2	10.5	10.5	10.6	9.6	10.3	10.5	10.8	10.8	10.6	10.8	10.7
Dairy Heifer	7.0	6.93	7.06	7.22	7.3	7.4	7.4	7.4	7.5	7.4	7.5	7.7	7.8	7.0	7.5	7.8	8.1	8.1	8.0	8.0	8.2
Swine	**4.0**	**4.18**	**4.33**	**4.37**	**4.6**	**4.5**	**4.4**	**4.7**	**5.1**	**5.0**	**5.0**	**5.1**	**5.3**	**5.4**	**5.6**	**5.7**	**5.9**	**6.3**	**6.5**	**6.3**	**6.2**
Market Swine	3.0	3.11	3.26	3.29	3.5	3.5	3.3	3.6	4.0	4.1	4.1	4.2	4.4	4.5	4.7	4.9	5.0	5.5	5.6	5.5	5.4
Market <50 lbs.	0.6	0.59	0.61	0.60	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.1	0.8	0.8	0.8
Market 50-119 lbs.	0.6	0.67	0.70	0.70	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.3	1.2	1.2
Market 120-179 lbs.	0.9	0.90	0.94	0.95	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.6	1.6	1.6
Market >180 lbs.	0.9	0.95	1.02	1.04	1.1	1.1	1.1	1.2	1.3	1.3	1.3	1.4	1.5	1.5	1.6	1.6	1.6	1.8	1.9	1.9	1.8
Breeding Swine	1.0	1.07	1.08	1.07	1.1	1.1	1.0	1.1	1.1	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8
Beef Cattle	**20.8**	**21.31**	**21.12**	**20.08**	**22.0**	**22.9**	**22.5**	**22.6**	**22.7**	**25.2**	**26.1**	**25.1**	**25.9**	**26.1**	**24.7**	**25.1**	**26.8**	**26.6**	**26.1**	**26.1**	**26.6**
Feedlot Steers	14.0	14.30	14.17	13.45	14.6	15.1	14.7	14.6	14.7	16.2	16.8	16.1	16.7	16.9	15.9	16.2	17.4	17.3	17.1	17.1	17.3
Feedlot Heifers	6.8	7.01	6.95	6.62	7.4	7.8	7.8	8.0	8.0	9.0	9.3	9.1	9.2	9.2	8.8	8.9	9.4	9.3	9.1	9.0	9.3
Sheep	**0.4**	**0.41**	**0.44**	**0.44**	**0.6**	**0.7**	**0.8**	**0.9**	**0.9**	**1.0**	**1.1**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.1**
Goats	**0.1**	**0.07**	**0.07**	**0.07**	**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**	**0.1**	**0.1**	**0.1**	**0.1**
Poultry	**4.7**	**4.79**	**4.88**	**4.96**	**5.1**	**5.1**	**5.3**	**5.3**	**5.3**	**5.3**	**5.3**	**5.3**	**5.4**	**5.3**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**	**5.2**	**5.2**
Hens >1 yr.	1.0	1.02	1.02	1.03	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3
Total Pullets	0.3	0.29	0.29	0.29	0.3	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	0.4	0.4	0.4
Chickens	0.0	0.03	0.03	0.03	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	0.0	0.0	0.0	0.0
Broilers	2.2	2.26	2.36	2.46	2.6	2.7	2.8	2.8	2.9	2.9	2.9	2.9	3.0	2.9	2.9	3.0	2.9	2.9	2.9	2.7	2.8
Turkeys	1.2	1.19	1.18	1.14	1.1	1.1	1.1	1.1	1.0	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.7
Horses	0.7	0.70	0.71	0.71	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.1	1.1	1.1	1.1	1.1

Table A- 202: Methane Emissions by State from Livestock Manure Management for 2010 (Gg)[a]

State	Beef on Feedlots	Beef Not on Feed	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses
Alabama	0.0298	2.5182	0.6928	0.0136	1.8701	0.5777	9.1894	3.7535	0.0249	0.0057	0.0302	0.6750
Alaska	0.0001	0.0196	0.0303	0.0003	0.0028	0.0010	0.2053	+	0.0248	0.0038	0.0001	0.0096
Arizona	0.7219	1.1731	46.2322	0.1298	2.5979	0.7444	0.7530	+	0.0249	0.1128	0.0158	0.5327
Arkansas	0.0128	3.6402	0.4693	0.0161	1.1115	1.9628	0.5386	3.7902	0.7002	0.0057	0.0190	0.6119
California	1.3392	3.9227	398.8200	1.9332	1.4710	0.2431	4.3345	0.2958	0.3801	0.4299	0.0490	1.4005
Colorado	1.5721	2.7044	25.1424	0.1051	4.8514	2.7520	3.2800	+	0.0248	0.1739	0.0122	0.6150
Connecticut	0.0005	0.0199	1.0174	0.0154	0.0073	0.0043	0.2588	+	0.0248	0.0038	0.0011	0.0595
Delaware	0.0005	0.0122	0.3519	0.0049	0.0472	0.0362	0.0844	0.8507	0.0248	0.0038	0.0009	0.0205
Florida	0.0129	3.3950	18.4947	0.0857	0.0577	0.0310	6.7591	0.1878	0.0249	0.0057	0.0216	0.9338
Georgia	0.0210	1.9177	7.1082	0.0682	2.2485	0.9583	14.1289	4.7709	0.0249	0.0057	0.0315	0.5944
Hawaii	0.0041	0.3354	0.3474	0.0029	0.1032	0.0776	0.1272	+	0.0249	0.0057	0.0034	0.0507
Idaho	0.3439	1.5572	110.5599	0.4431	0.1570	0.0904	0.6471	+	0.0248	0.1034	0.0044	0.3824
Illinois	0.2860	1.0820	9.2128	0.0852	42.2081	11.0202	0.2547	+	0.0248	0.0301	0.0084	0.4106
Indiana	0.2029	0.6533	13.8008	0.1134	35.2648	6.3647	0.7928	0.2949	0.3988	0.0244	0.0118	0.4193
Iowa	2.2133	3.0994	21.7330	0.2081	287.9804	31.8492	1.7109	0.2949	0.0248	0.0987	0.0140	0.3719
Kansas	4.0190	5.1050	20.0442	0.1321	20.7780	4.1880	0.0484	+	0.0248	0.0376	0.0124	0.4644
Kentucky	0.0189	2.7618	1.7481	0.0903	5.0253	1.1475	0.5904	1.1219	0.0248	0.0174	0.0245	0.9063
Louisiana	0.0105	1.7711	0.7947	0.0195	0.0180	0.0098	2.2125	0.2958	0.0249	0.0057	0.0081	0.4687
Maine	0.0010	0.0385	1.4476	0.0265	0.0099	0.0070	0.2924	+	0.0248	0.0038	0.0015	0.0628
Maryland	0.0226	0.1253	2.6910	0.0496	0.2783	0.0693	0.2537	1.0878	0.0248	0.0038	0.0042	0.1588
Massachusetts	0.0006	0.0242	0.5744	0.0101	0.0416	0.0193	0.0117	+	0.0248	0.0038	0.0021	0.1062
Michigan	0.2744	0.4604	45.4261	0.2509	9.1758	2.0978	0.6323	0.2949	0.0248	0.0376	0.0070	0.5225
Minnesota	0.4672	1.4349	32.7639	0.4671	64.1196	11.0620	0.3514	0.1524	1.1715	0.0611	0.0092	0.4657
Mississippi	0.0266	1.9164	0.7103	0.0192	6.0816	1.4523	8.3463	2.9341	0.0249	0.0057	0.0115	0.5058
Missouri	0.1016	4.8520	6.7295	0.0745	25.8168	7.8786	0.2609	0.2949	0.4487	0.0371	0.0241	0.7706
Montana	0.0443	3.6022	1.7816	0.0104	1.1638	0.3545	0.3397	+	0.0248	0.1151	0.0031	0.5437
Nebraska	4.0996	6.8716	7.7940	0.0321	26.2769	7.6697	0.5831	0.2949	0.0248	0.0348	0.0086	0.3390
Nevada	0.0131	0.5506	6.2364	0.0151	0.0082	0.0057	0.0243	+	0.0248	0.0352	0.0030	0.0950
New Hampshire	0.0004	0.0153	0.7103	0.0133	0.0112	0.0053	0.0774	+	0.0248	0.0038	0.0010	0.0511
New Jersey	0.0007	0.0273	0.3286	0.0085	0.0567	0.0114	0.0828	+	0.0248	0.0038	0.0027	0.1549
New Mexico	0.0736	1.3638	76.9854	0.2239	0.0003	0.0003	0.7003	+	0.0248	0.0564	0.0089	0.2770
New York	0.0523	0.4456	31.0661	0.5462	0.8699	0.2076	0.4644	0.2949	0.0248	0.0310	0.0100	0.4391
North Carolina	0.0105	0.9732	2.4935	0.0345	145.4239	32.2021	11.7595	2.7748	0.7478	0.0117	0.0246	0.4049
North Dakota	0.1379	2.2333	1.4049	0.0156	0.7630	0.6294	0.0450	+	0.0248	0.0413	0.0011	0.2312
Ohio	0.3228	0.8968	20.8384	0.1934	18.0933	3.5396	0.9602	0.2172	0.1147	0.0601	0.0174	0.6158
Oklahoma	0.8544	8.7531	10.1687	0.0572	33.8643	15.2850	3.7068	0.8172	0.0249	0.0529	0.0470	1.2829
Oregon	0.1367	1.4089	15.8958	0.0932	0.0658	0.0288	0.8805	0.2949	0.0248	0.1057	0.0095	0.4620
Pennsylvania	0.1361	0.7447	17.7220	0.5177	10.9732	2.0770	0.7648	0.5405	0.1844	0.0442	0.0148	0.6010
Rhode Island	0.0001	0.0037	0.0357	0.0009	0.0037	0.0034	0.0808	+	0.0248	0.0038	0.0002	0.0180
South Carolina	0.0080	0.7113	1.3000	0.0217	4.8263	0.5189	4.6927	0.8754	0.2976	0.0057	0.0163	0.3354
South Dakota	0.6473	4.4069	11.7608	0.0556	10.4536	3.2271	0.1467	+	0.1147	0.1527	0.0027	0.3628
Tennessee	0.0093	2.4583	1.5880	0.0634	2.6542	0.4725	0.2554	0.6990	0.0248	0.0148	0.0327	0.7329
Texas	6.3178	21.8135	93.5366	0.5729	10.1295	1.6870	4.6109	2.3736	0.0249	0.5850	0.4273	3.4006
Utah	0.0385	0.8736	15.7574	0.0722	5.8930	1.4093	2.9933	+	0.1147	0.1363	0.0043	0.3088
Vermont	0.0014	0.0628	5.9546	0.0928	0.0075	0.0038	0.0186	+	0.0248	0.0038	0.0016	0.0686
Virginia	0.0402	1.7480	3.0299	0.0883	5.7579	0.8433	0.3936	0.9065	0.4237	0.0418	0.0158	0.4668
Washington	0.3000	0.7167	42.0557	0.2091	0.1083	0.0616	1.1853	0.2949	0.0248	0.0282	0.0082	0.4636
West Virginia	0.0133	0.5407	0.3669	0.0069	0.0216	0.0113	0.1689	0.3171	0.0773	0.0141	0.0070	0.1949
Wisconsin	0.3891	1.1611	94.2525	1.0592	2.5397	0.8072	0.3047	0.1698	0.0248	0.0423	0.0140	0.6197
Wyoming	0.1006	1.9808	0.8084	0.0075	0.2621	0.2870	0.0086	+	0.0248	0.1762	0.0021	0.4158

+ Emission estimate is less than 0.00005 Gg.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

Table A- 203: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2010 (Gg)

State	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses
Alabama	0.0069	0.0130	0.0047	0.0045	0.0092	0.0021	0.0646	0.3321	0.0029	0.0031	0.0024	0.0232
Alaska	+	0.0001	0.0006	0.0004	+	+	0.0036	+	0.0029	0.0010	+	0.0005
Arizona	0.2029	0.3779	0.2023	0.1157	0.0119	0.0026	0.0039	+	0.0029	0.0176	0.0012	0.0183
Arkansas	0.0031	0.0057	0.0043	0.0040	0.0061	0.0078	0.0764	0.3353	0.0811	0.0027	0.0015	0.0210
California	0.3213	0.5986	2.0936	1.5567	0.0082	0.0010	0.0900	0.0262	0.0440	0.0759	0.0039	0.0481
Colorado	0.6894	1.2852	0.1567	0.1605	0.0511	0.0214	0.0195	+	0.0029	0.0408	0.0014	0.0317
Connecticut	0.0002	0.0003	0.0146	0.0108	0.0001	+	0.0110	+	0.0029	0.0031	0.0001	0.0031
Delaware	0.0002	0.0004	0.0044	0.0032	0.0004	0.0002	0.0034	0.0755	0.0029	0.0031	0.0001	0.0011
Florida	0.0029	0.0054	0.0927	0.0432	0.0003	0.0001	0.0472	0.0166	0.0029	0.0031	0.0017	0.0321
Georgia	0.0050	0.0093	0.0473	0.0247	0.0113	0.0036	0.1001	0.4221	0.0029	0.0031	0.0025	0.0204
Hawaii	0.0009	0.0017	0.0018	0.0023	0.0005	0.0003	0.0014	+	0.0029	0.0010	0.0003	0.0017
Idaho	0.1526	0.2846	0.7321	0.6815	0.0018	0.0008	0.0039	+	0.0029	0.0243	0.0005	0.0197
Illinois	0.1163	0.2171	0.1436	0.1058	0.3640	0.0695	0.0181	+	0.0029	0.0210	0.0010	0.0212
Indiana	0.0824	0.1538	0.2291	0.1288	0.3136	0.0414	0.1101	0.0262	0.0464	0.0171	0.0014	0.0216
Iowa	0.9145	1.7064	0.3023	0.2533	1.7100	0.1387	0.2375	0.0262	0.0029	0.0689	0.0017	0.0192
Kansas	1.6072	2.9962	0.1655	0.1718	0.1705	0.0254	0.0034	+	0.0029	0.0262	0.0015	0.0239
Kentucky	0.0068	0.0127	0.0315	0.0287	0.0275	0.0046	0.0241	0.0996	0.0029	0.0141	0.0029	0.0467
Louisiana	0.0024	0.0044	0.0070	0.0043	0.0001	+	0.0112	0.0262	0.0029	0.0027	0.0006	0.0161
Maine	0.0004	0.0007	0.0246	0.0181	0.0001	0.0001	0.0131	+	0.0029	0.0031	0.0002	0.0032
Maryland	0.0082	0.0153	0.0412	0.0322	0.0023	0.0004	0.0104	0.0966	0.0029	0.0031	0.0005	0.0082
Massachusetts	0.0002	0.0004	0.0105	0.0067	0.0004	0.0001	0.0005	+	0.0029	0.0031	0.0002	0.0055
Michigan	0.1146	0.2138	0.5369	0.3347	0.0897	0.0153	0.0463	0.0262	0.0029	0.0262	0.0008	0.0269
Minnesota	0.1955	0.3645	0.6500	0.5794	0.6239	0.0794	0.0488	0.0135	0.1362	0.0426	0.0011	0.0240
Mississippi	0.0061	0.0115	0.0068	0.0046	0.0295	0.0051	0.0429	0.2596	0.0029	0.0031	0.0009	0.0174
Missouri	0.0407	0.0759	0.1177	0.0812	0.2249	0.0499	0.0363	0.0262	0.0522	0.0259	0.0029	0.0397
Montana	0.0198	0.0368	0.0200	0.0152	0.0144	0.0032	0.0022	+	0.0029	0.0270	0.0004	0.0280
Nebraska	1.6949	3.1605	0.0834	0.0422	0.2463	0.0529	0.0418	0.0262	0.0029	0.0243	0.0010	0.0175
Nevada	0.0057	0.0107	0.0371	0.0232	0.0001	+	0.0034	+	0.0029	0.0083	0.0004	0.0049
New Hampshire	0.0002	0.0003	0.0117	0.0092	0.0001	+	0.0034	+	0.0029	0.0031	0.0001	0.0026
New Jersey	0.0003	0.0005	0.0062	0.0053	0.0004	0.0001	0.0034	+	0.0029	0.0031	0.0003	0.0080
New Mexico	0.0326	0.0596	0.3933	0.3049	+	+	0.0039	+	0.0029	0.0132	0.0011	0.0143
New York	0.0204	0.0380	0.4841	0.3673	0.0087	0.0015	0.0201	0.0262	0.0029	0.0252	0.0012	0.0226
North Carolina	0.0038	0.0071	0.0250	0.0136	0.7294	0.1190	0.0844	0.2463	0.0869	0.0095	0.0029	0.0209
North Dakota	0.0586	0.1095	0.0266	0.0193	0.0083	0.0051	0.0034	+	0.0029	0.0289	0.0001	0.0119
Ohio	0.1321	0.2465	0.3581	0.2199	0.1646	0.0236	0.1332	0.0193	0.0133	0.0485	0.0021	0.0317
Oklahoma	0.2475	0.4619	0.0679	0.0546	0.1680	0.0553	0.0190	0.0723	0.0029	0.0245	0.0037	0.0441
Oregon	0.0519	0.0968	0.1276	0.1032	0.0007	0.0002	0.0114	0.0262	0.0029	0.0280	0.0011	0.0238
Pennsylvania	0.0512	0.0955	0.4005	0.3119	0.0982	0.0139	0.1063	0.0480	0.0214	0.0358	0.0018	0.0310
Rhode Island	+	0.0001	0.0008	0.0005	+	+	0.0034	+	0.0029	0.0031	+	0.0009
South Carolina	0.0019	0.0035	0.0086	0.0058	0.0235	0.0019	0.0242	0.0774	0.0345	0.0031	0.0013	0.0115
South Dakota	0.2699	0.5035	0.1304	0.0714	0.1007	0.0229	0.0107	+	0.0133	0.1066	0.0003	0.0187
Tennessee	0.0033	0.0061	0.0223	0.0216	0.0146	0.0019	0.0106	0.0621	0.0029	0.0120	0.0039	0.0378
Texas	1.8362	3.4233	0.4918	0.5369	0.0606	0.0074	0.0921	0.2100	0.0029	0.0915	0.0337	0.1168
Utah	0.0169	0.0315	0.1128	0.1095	0.0599	0.0113	0.0174	+	0.0133	0.0320	0.0005	0.0159
Vermont	0.0006	0.0011	0.1019	0.0644	0.0001	+	0.0008	+	0.0029	0.0031	0.0002	0.0035
Virginia	0.0147	0.0274	0.0429	0.0326	0.0303	0.0033	0.0164	0.0805	0.0493	0.0339	0.0019	0.0241
Washington	0.1134	0.2115	0.3027	0.2411	0.0012	0.0005	0.0283	0.0262	0.0029	0.0075	0.0010	0.0239
West Virginia	0.0050	0.0093	0.0069	0.0045	0.0002	0.0001	0.0073	0.0281	0.0090	0.0114	0.0008	0.0100
Wisconsin	0.1627	0.3034	1.7590	1.2787	0.0241	0.0056	0.0223	0.0151	0.0029	0.0295	0.0017	0.0319
Wyoming	0.0445	0.0830	0.0074	0.0094	0.0049	0.0039	0.0001	+	0.0029	0.0413	0.0002	0.0214

+ Emission estimate is less than 0.00005 Gg.

3.11. Methodology for Estimating N_2O Emissions from Agricultural Soil Management

Nitrous oxide emissions from agricultural soils result from the interaction of the natural processes of denitrification and nitrification with management practices that add or release mineral nitrogen (N) in the soil profile. Emissions can occur directly in the soil where the N is made available or can be transported to another location following volatilization, leaching, or runoff, and then converted into N_2O.

A combination of Tier 1 and Tier 3 approaches was used to estimate direct and indirect N_2O emissions from agricultural soils. The process-based biogeochemical model DAYCENT (a Tier 3 approach) was used to estimate N_2O emissions resulting from croplands on mineral soils that were used to produce major crops, while the IPCC (2006) Tier 1 methodology was applied to estimate N_2O emissions for non-major crop types on mineral soils. The Tier 1 method was also used to estimate direct N_2O emissions due to drainage and cultivation of organic cropland soils. Direct N_2O emissions from grasslands were estimated by using a combination of DAYCENT and IPCC (2006) Tier 1 methods. A combination of DAYCENT and Tier 1 methods was also used to estimate indirect emissions from all managed lands (i.e., croplands, grasslands, forest lands, and settlements). Specifically, the amount of N volatilized from soils, as well as leaching or transport of nitrate (NO_3^-) off-site in surface runoff waters was computed by DAYCENT for the direct emission analyses, while IPCC default factors were used to estimate N transport for the analyses using the Tier 1 methodology. The indirect N_2O emissions resulting from off-site transport of N were then computed using the IPCC (2006) Tier 1 default emission factor. Overall, the Tier 3 approach is used to estimate approximately 86 percent of direct soil emissions and 80 percent of total soil N_2O emissions associated with agricultural soil management in the United States.

DAYCENT (Del Grosso et al. 2001, Parton et al. 1998) simulates biogeochemical N fluxes between the atmosphere, vegetation, and soil, allowing for a more complete estimation of N_2O emissions than IPCC Tier 1 methods by accounting for the influence of environmental conditions including soil characteristics and weather patterns, specific crop and forage qualities that influence the N cycle, and management practices at a daily time step. For example, plant growth is controlled by nutrient availability, water, and temperature stress; moreover, growth removes mineral N from the soil before it can potentially be converted into N_2O. Nutrient supply is a function of external nutrient additions as well as litter and soil organic matter (SOM) decomposition rates, and increasing decomposition can lead to greater N_2O emissions by enhancing mineral N availability in soils. In this model-based assessment framework, daily maximum/minimum temperature and precipitation, timing and description of management events (e.g., fertilization, tillage, harvest), and soil texture data are model inputs to DAYCENT, which form the basis to simulate key processes and generate robust estimates of N_2O emissions from soils. Key processes simulated within sub-models of DAYCENT include plant production, organic matter formation and decomposition, soil water and soil temperature regimes by layer, and nitrification and denitrification processes (Figure A- 7). Comparison of model results and plot level data show that DAYCENT reliably simulates crop yields, soil organic matter levels, and trace gas fluxes for a number of native and managed systems (Del Grosso et al. 2001, 2005). Comparisons with measured data showed that DAYCENT estimated emissions more accurately and precisely than the IPCC Tier 1 methodology (Figure A- 8). The linear regression of simulated vs. measured emissions for DAYCENT had higher r^2 and a fitted line closer to a perfect 1:1 relationship between measured and modeled N_2O emissions (Del Grosso et al. 2005, 2008). This is not surprising, since DAYCENT includes site-specific factors (climate, soil properties, and previous management) that influence N_2O emissions. Furthermore, DAYCENT also simulated NO_3^- leaching (root mean square error = 20 percent) more accurately than IPCC Tier 1 methodology (root mean square error = 69 percent) (Del Grosso et al. 2005). Thus, the Tier 3 approach has reduced uncertainties in the agricultural soil management section relative to earlier Inventory years where the IPCC Tier 1 method was used. The latest operational version of DAYCENT has several improvements, including (1) elimination of the influence of labile (i.e., easily decomposable by microbes) C availability on surface litter denitrification rates, (2) incorporation of precipitation events on surface litter denitrification, and (3) having the wettest soil layer within the rooting zone control plant transpiration.

[Begin Text Box]

Box 1. DAYCENT Model Simulation of Nitrification and Denitrification

The DAYCENT model simulates the two biogeochemical processes, nitrification and denitrification, that result in N_2O emissions from soils (Del Grosso et al. 2000, Parton et al. 2001). Nitrification is calculated for the top 15 cm of soil, while denitrification is calculated for the entire soil profile. The equations and key parameters controlling N_2O emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium (NH_4^+) concentration, water filled pore space (WFPS), temperature (t), and pH according to the following equation:

$$\text{Nit} = NH_4 \times K_{max} \times F(t) \times F(WFPS) \times F(pH)$$

where,

Nit = the soil nitrification rate (g N/m^2/day)
NH_4 = the model-derived soil ammonium concentration (g N/m^2)
K_{max} = the maximum fraction of NH_4^+ nitrified (K_{max} = 0.10/day)
F(t) = the effect of soil temperature on nitrification (Figure A- 5a)
F(WFPS) = the effect of soil water content and soil texture on nitrification (Figure A- 5b)
F(pH) = the effect of soil pH on nitrification (Figure A- 5c)

The current parameterization used in the model assumes that 1.2 percent of nitrified N is converted to N_2O.

N_2O emissions from denitrification are a function of soil NO_3^- concentration, WFPS, heterotrophic (i.e., microbial) respiration, and texture. Denitrification is calculated for each soil layer in the profile, and N_2O emissions from each layer are summed to obtain total soil emissions. The model assumes that denitrification rates are controlled by the availability of soil NO_3^- (electron acceptor), labile C compounds (electron donor) and oxygen (competing electron acceptor). Heterotrophic soil respiration is used as a proxy for labile C availability, while oxygen availability is a function of soil physical properties that influence gas diffusivity, soil WFPS, and oxygen demand. The model selects the minimum of the NO_3^- and CO_2 functions to establish a maximum potential denitrification rate for particular levels of electron acceptor and C substrate and accounts for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

$$\text{Den} = \min[F(CO_2), F(NO_3)] \times F(WFPS)$$

where,

Den = the soil denitrification rate (μg N/g soil/day)
$F(CO_2)$ = a function relating N gas flux to soil respiration (Figure A- 6a)
$F(NO_3)$ = a function relating N gas flux to nitrate levels (Figure A- 5b)
F(WFPS) = a dimensionless multiplier (Figure A- 6c).

The x inflection point of F(WFPS) is a function of respiration and soil gas diffusivity at field capacity (D_{FC}):

$$x \text{ inflection} = 0.90 - M(CO_2)$$

where,

M = a multiplier that is a function of D_{FC}.

Respiration has a much stronger effect on the water curve in clay soils with low D_{FC} than in loam or sandy soils with high D_{FC} (Figure A- 6c). The model assumes that microsites in fine-textured soils can become anaerobic at relatively low water contents when oxygen demand is high.

After calculating total N gas flux, the ratio of N_2/N_2O is estimated so that total N gas emissions can be partitioned between N_2O and N_2:

$$R_{N2/N2O} = F_r(NO_3/CO_2) \times F_r(WFPS).$$

where,

$R_{N2/N2O}$ = the ratio of N_2/N_2O
$F_r(NO_3/CO_2)$ = a function estimating the impact of the availability of electron donor relative to substrate
$F_r(WFPS)$ = a multiplier to account for the effect of soil water on $N_2:N_2O$.

For $F_r(NO_3/CO_2)$, as the ratio of electron donor to substrate increases, a higher portion of N gas is assumed to be in the form of N_2O. For $F_r(WFPS)$, as WFPS increases, a higher portion of N gas is assumed to be in the form of N_2.

[End Box]

Figure A- 5: Effect of Soil Temperature, Water-Filled Pore Space, and pH on Nitrification Rates

Figure A- 6: Effect of Soil Nitrite Concentration, Heterotrophic Respiration Rates, and Water-Filled Pore Space on Denitrification Rates

There are five steps in estimating direct N_2O emissions from cropland and grassland soils, and indirect N_2O emissions from volatilization, leaching, and runoff from all managed lands (i.e., croplands, grasslands, forest lands, and settlements). First, the activity data are derived from a combination of land-use, livestock, crop, and grassland management surveys, as well as expert knowledge. In the second, third, and fourth steps, direct and indirect N_2O emissions are estimated using DAYCENT and/or the Tier 1 method. In the fifth step, total emissions are computed by summing all components. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

The activity data requirements vary for major crops, non-major crops, grasslands, organic cropland soils, settlements and forest lands. Activity data were derived for direct and indirect N_2O emission calculations as described below.

Step 1a: Activity Data for Direct Emissions from Crop Production on Mineral Soils

Nitrous oxide emissions from mineral cropland soils include emissions from both major and non-major cropping systems and were estimated using a Tier 3 and Tier 1 approach, respectively.

Major Crop Types: Tier 3 DAYCENT Simulations

The activity data requirements for estimating N_2O emissions from major crop types (corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton) include the following: (1) crop-specific mineral N fertilizer rates and timing, (2) crop-specific manure amendment N rates and timing, (3) other N inputs, (4) crop-specific land management information, (5) native vegetation, (6) daily weather data for every county, (7) sub-county-level soil texture data, and (8) county-level crop areas. The United States was divided into 63 agricultural regions based on common cropping practices as defined by McCarl et al. (1993), and data were assembled and provided as inputs to the DAYCENT biogeochemical ecosystem model.

Synthetic N Fertilizer Application: Data on N fertilizer rates were obtained primarily from the U.S. Department of Agriculture–Economic Research Service 1995 Cropping Practices Survey (ERS 1997). In this survey, data on inorganic N fertilization rates were collected for major crops (corn, cotton, soybeans, and wheat) in the high production states during 1995. It is assumed that the fertilization rates have not changed much during the Inventory reporting period, which is confirmed by the sales data showing relatively minor change in the amount of fertilizer sold for on-farm use across the time series of this Inventory (Ruddy et al. 2006). The trend and therefore the rates and uncertainties reflected in the 1995 survey data are considered representative for 1990 through 2010 (trends will be re-evaluated when new fertilization data are released by U.S. Department of Agriculture). Note that all wheat data were combined into one category and assumed to represent small grains in aggregate. Estimates for sorghum fertilizer rates were derived from corn fertilizer rates using a ratio of national average corn fertilizer rates to national average sorghum fertilizer rates, which were derived from additional publications (NASS 1992, 1999, 2004; ERS 1988; Grant and Krenz 1985; USDA 1954, 1957, 1966). Alfalfa hay is assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003).

The ERS survey parameter "TOT N" (total amount of N applied per acre), with a small number of records deleted as outliers, was used in determining the fraction of crop acres receiving fertilizer and the average fertilizer rates for each region. Mean fertilizer rates and standard deviations for irrigated and rainfed crops were produced for each state with a minimum of 15 data points for irrigated and rainfed, respectively. If a state was not surveyed for a particular crop or if fewer than 15 data points existed for one of the categories, then data were aggregated to U.S. Department of Agriculture Farm Production Regions in order to estimate a mean and standard deviation for fertilization rates (Farm Production Regions are groups of states in the United States with similar agricultural commodities). If Farm Production Region data were not available, crop data were aggregated to the entire United States (all major states surveyed) to estimate a mean and standard deviation for a particular crop in a state lacking sufficient data. Standard deviations for fertilizer rates were used to construct probability distribution functions (PDFs) with log-normal densities in order to address uncertainties in application rates (see Step 2a for discussion of uncertainty methods). Total fertilizer application data are found in Table A- 204.

Simulations were conducted for the period prior to 1990 in order to initialize the DAYCENT model (see Step 2a), and estimates for crop-specific regional fertilizer rates prior to 1990 were based largely on extrapolation/interpolation of fertilizer rates from the years with available data. For crops in some agricultural regions, little or no data were available, and, therefore, a geographic regional mean was used to simulate N fertilization rates (e.g., no data were available from Alabama during the 1970s and 1980s for corn fertilization rates; therefore, mean values from the southeastern United States were used to simulate fertilization to corn fields in this state).

Managed Livestock Manure[67] *N Amendment Rates and Timing:* County-level manure addition estimates have been derived from manure N addition rates developed by the Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level estimates of manure N applied to cropland and pasture. Edmonds et al. (2003) defined a hierarchy that included 24 crops, cropland used as pasture, and permanent pasture. They estimated the area amended with manure and application rates in 1997 for both manure-producing farms and manure-receiving farms within a county and for two scenarios—before implementation of Comprehensive Nutrient Management Plans (baseline) and after implementation (Edmonds et al. 2003). The goal of nutrient management plans is to apply manure nutrients at a rate meeting plant demand, thus limiting leaching losses of nutrients to groundwater and waterways. For DAYCENT simulations, the baseline scenario estimates have been used as the basis for manure amendment applications under the assumption that Comprehensive Nutrient Management Plans have not been fully implemented. This is a conservative assumption because it allows for higher leaching rates due to some over-application of manure to soils. The rates for manure-producing farms and manure-receiving farms have been area-weighted and combined to produce a single county-level estimate for the amount of land amended with manure and the manure N application rate for each crop in each county. Several of the crops in Edmonds et al. (2003) have been area-weighted and combined into broader crop categories. For example, all small grain crops have been combined into one category. In order to address uncertainty in these data, uniform probability distributions were constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if 20 percent of land producing corn in a county was amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to a simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation (see Step 2a for further discussion of uncertainty methods).

Edmonds et al. (2003) only provides manure application rate data for 1997, but the amount of managed manure available for soil application changes annually, so the area amended with manure was adjusted relative to 1997 to account for all the manure available for application in other years. Specifically, the manure N available for application in other years was divided by the manure N available in 1997. If the ratio was greater than 1, there was more manure N available in that county relative to the amount in 1997, and so it was assumed a larger area was amended with manure. In contrast, ratios less than one implied less area was amended with manure because there was a lower amount available in the year compared to 1997. The amendment area in each county for 1997 was multiplied by the ratio to reflect the impact of manure N availability on the area amended. The amount of managed manure N available for application to soils was calculated by determining the populations of animals that were on feedlots or otherwise housed in order to collect and manage the manure, as described in the Manure Management section (Section 6.2) and annex (Annex 3.10).

To estimate C inputs associated with manure N application rates derived from Edmonds et al. (2003), carbon-nitrogen (C:N) ratios for livestock-specific manure types were adapted from the Agricultural Waste Management Field Handbook (USDA 1996), On-Farm Composting Handbook (NRAES 1992), and recoverability factors provided by Edmonds et al (2003). The C:N ratios were applied to county-level estimates of manure N excreted by animal type and management system to produce a weighted county average C:N ratio for manure amendments. The average C:N ratio was used to determine the associated C input for crop amendments derived from Edmonds et al. (2003).

To account for the common practice of reducing inorganic N fertilizer inputs when manure is added to a cropland soil, crop-specific reduction factors were derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (ERS 1997). Mineral N fertilization rates were reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and

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[67] For purposes of the Inventory, total livestock manure is divided into two general categories: (1) managed manure, and (2) unmanaged manure. Managed manure includes manure that is stored in manure management systems such as pits and lagoons, as well as manure applied to soils through daily spread manure operations. Unmanaged manure encompasses all manure deposited on soils by animals on PRP.

whether it was irrigated or rainfed. The reduction factors were randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

Manure N that was not applied to major crops and grassland was assumed to be applied to non-major crop types. The fate of manure N is summarized in Table A- 205.

Residue N Inputs: Residue N input is estimated as part of the DAYCENT simulation and is not an input to the model. Unlike the Tier 1 approach, N inputs from crop residues are not considered activity data in the DAYCENT simulations because N availability from this source is simulated by the model based on N uptake during crop growth according to environmental and management conditions, such as temperature, precipitation, and edaphic (i.e., soil) characteristics, in combination with the harvest practices. That is, while the model accounts for the contribution of N from crop residues to the soil profile and subsequent N_2O emissions, this source of mineral soil N is not activity data in the sense that it is not a model input. Similarly, N from mineralization of soil organic matter and asymbiotic N fixation are also simulated by the model. The simulated total N inputs of above- and below-ground residue N and fixed N that was not harvested and not burned (the DAYCENT simulations assumed that 3 percent of non-harvested above ground residues for grain crops were burned) are provided in Table A- 206.

Other N Inputs: Other N inputs are estimated within the DAYCENT simulation, and thus input data are not required, including mineralization from decomposition of soil organic matter and asymbiotic fixation of N from the atmosphere. The influence of additional inputs of N are estimated in the simulations so that there is full accounting of all emissions from managed lands, as recommended by IPCC (2006). The simulated total N inputs from other sources are provided in Table A- 206.

Crop Rotation and Land Management Information: Data were obtained on specific timing and type of cultivation, timing of planting/harvest, and crop rotation schedules for the 63 agricultural regions (Hurd 1930, 1929, Latta 1938, Iowa State College Staff Members 1946, Bogue 1963, Hurt 1994, USDA 2000a, 2000b, CTIC 1998, Piper et al. 1924, Hardies and Hume 1927, Holmes 1902, 1929, Spillman 1902, 1905, 1907, 1908, Chilcott 1910, Smith 1911, Kezer ca 1917, Hargreaves 1993, ERS 2002, Warren 1911, Langston et al. 1922, Russell et al. 1922, Elliott and Tapp 1928, Elliott 1933, Ellsworth 1929, Garey 1929, Holmes 1929, Hodges et al. 1930, Bonnen and Elliott 1931, Brenner et al. 2002, 2001, Smith et al. 2002). As with N fertilizer and manure additions, data were not complete, so regional averages were used to fill spatial gaps in the datasets and interpolation/extrapolation was used to fill temporal gaps. The amount of agricultural residue burning was based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

Native Vegetation by County: Pre-agricultural land cover for each county was designated according to the potential native vegetation used in the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP 1995), which was based on the Kuchler (1964) Potential Vegetation Map for the conterminous United States.

Daily Weather Data by County: Daily maximum/minimum temperature and precipitation data were obtained from the DAYMET model, which generates daily surface precipitation, temperature, and other meteorological data at 1 km^2 resolution driven by weather station observations and an elevation model (Thornton et al. 2000 and 1997, Thornton and Running 1999, DAYMET no date). It is necessary to use computer-generated weather data because weather station data do not exist in each county, and moreover weather station data are for a point in space, while the DAYMET uses this information with interpolation algorithms to derive weather patterns for areas between these stations. DAYMET weather data are available for the United States at 1 km^2 resolution for 1980 through 2003. For each county, DAYMET weather data were selected from the 1 km^2 cell that occurred in agricultural lands according the National Land Cover Dataset (Vogelman et al. 2001). The grid cells formed the basis for county-scale PDFs based on the frequency of cells with same weather patterns. Separate PDFs were developed for cropland, pasture/hay land, and rangeland. A weather record was then randomly selected from the PDFs in each iteration of the Monte Carlo analysis to represent variation in precipitation and temperature at the county scale. Weather data were randomly selected from the previous 23 years to represent 2004 through 2009, accounting for uncertainty in the weather during the years that have no data. The time series will be updated when new weather data are available.

Soil Properties by County: Soil texture data required by DAYCENT were obtained from STATSGO (Soil Survey Staff 2005). Observed data for soil hydraulic properties needed for model inputs were not available, so they were calculated from STATSGO (Soil Survey Staff 2005) texture class and Saxton et al.'s (1986) hydraulic properties calculator. Similar to the weather data, soil types within the STATSGO map that occurred in agricultural lands according to the National Land Cover Dataset (Vogelman et al. 2001) were used to form a county-scale PDF. Specifically, the PDFs were an area-weighted proportion for the extent of overlap between STATSGO map units and agricultural land. Separate PDFs were developed for cropland, pasture/hay land, and rangeland. Individual soil types were randomly selected from the PDFs during each iteration of the Monte Carlo analysis to represent variation in soil texture and depth at the county scale.

Crop Areas by County: County-level total crop area data were downloaded from the NASS web site for the years 1990 through 2010 (USDA 2010a, 2010b), and these data formed the basis to scale emissions from individual crop types to an entire county.

Non-Major Crop Types: Tier 1 Method

The activity data required for calculating emissions from non-major crop types include: (1) the amount of mineral N in synthetic fertilizers that are applied annually, (2) managed manure N, (3) the amount of N in other commercial organic fertilizers and (4) the amount of N in the above- and below-ground residue retained on and in soils of all non-major crops.

Application of Synthetic Commercial Fertilizers: A process-of-elimination approach was used to estimate synthetic N fertilizer additions to non-major crop types. The total amount of fertilizer used on farms has been estimated by the USGS from 1990-2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). For 2002-2010, county-level fertilizer used on farms was adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2009). AAPFCO fertilizer data were not yet available for 2010, so 2009 values were used as a placeholder until data become available. In addition, fertilizer application data are available for major crops and grasslands (discussed in Step 1 sections for Major Crops and Grasslands). Thus, the amount of N applied to non-major crops was assumed to be the remainder of the fertilizer used on farms after subtracting the amount applied to major crops and grasslands. The differences were aggregated to the state level and PDFs were derived based on uncertainties in the amount of N applied to major crops and grasslands. Total fertilizer application is found in Table A- 207.

Manure and Other Commercial Organic Fertilizers[68]*:* Manure N applied to non-major crops was estimated using the activity data described for major crops (Table A- 205). Estimates of total national annual N additions from other commercial organic fertilizers were derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2009). AAPFCO fertilizer data were not yet available for 2010, so 2009 values were used as a placeholder until data become available. Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer were subtracted from totals to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands. The organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of N by multiplying the consumption values by the average organic fertilizer N contents provided in the annual fertilizer publications. These N contents are weighted average values, and vary from year to year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2009). The fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but 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 2008 so a "least squares line" statistical extrapolation using the previous 14 years of data was used to arrive at an approximate value. PDFs were derived for the organic fertilizer applications assuming a default ±50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A- 208.

Retention of Crop Residue: Annual crop yield (metric tons per hectare) and area harvested (hectare) statistics for non-major N-fixing crops, including bean and pulse crops, were taken from U.S. Department of Agriculture crop production reports (USDA 1994, 1998, 2003, 2005, 2006, 2008, 2009, 2010a,b). Crop yield per hectare and area planted were multiplied to determine total crop yield for each crop, which was then converted to tons of dry matter product using the residue dry matter fractions shown in

Table A- 209. Dry matter yield was then converted to tons of above- and below-ground biomass N. Above-ground biomass was calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass was calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. N inputs were estimated by multiplying above- and below-ground biomass by respective N concentrations. All ratios and equations used to calculate residue N inputs (shown in Table A- 210) are from IPCC (2006) and Williams (2006). PDFs were derived assuming a ±50 percent uncertainty in the yield estimates (NASS does not provide uncertainty), along with uncertainties provided by the IPCC (2006) for dry matter fractions, above-ground residue, ratio of below-ground to above-ground biomass, and residue N fractions. The resulting annual biomass N inputs are presented in Table A- 210.

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[68] Other commercial organic fertilizers include, dried blood, dried manure, tankage, compost, sewage, and other minor organic fertilizer types, but manure and sewage sludge have been excluded in order to avoid double-counting and ensure consistency across the Inventory as these inputs are calculated using alternative data sources and methods.

Step 1b: Activity Data for Direct Emissions from Drainage and Cultivation of Organic Cropland Soils

Tier 1 Method

Estimates and associated uncertainty for the area of drained and cultivated organic cropland soils in 1992 and 1997 were obtained from the U.S. Department of Agriculture 1997 *National Resources Inventory* (USDA 2000a, as extracted by Eve 2001, and revised by Ogle 2002).[69] These areas were grouped by broad climatic region[70] using temperature and precipitation estimates from Daly et al. (1994, 1998) and then further aggregated to derive total land in temperate and sub-tropical regions. Areas for 1992 were assumed to represent 1990 through 1992 and areas for 1997 were assumed to represent 1993 through 2010 (Table A- 211).

Step 1c: Activity Data for Direct Emissions from Grassland Management

N_2O emissions from non-federal grasslands were estimated using DAYCENT. DAYCENT simulations addressed the influence of legume seeding, managed manure N amendments, unmanaged manure N excreted by livestock and deposited directly onto pasture, range, and paddock (PRP) soils, and synthetic fertilizer applications. N_2O emissions from PRP manure N deposition on federal grasslands and sewage sludge amendments to agricultural soils were addressed using the Tier 1 method.

Tier 3 DAYCENT Simulations

Activity data for DAYCENT simulations of grasslands (i.e., climate, soils, and N inputs) were based on the same sources as those used for major crop types described in Step 1a. In addition to the data sources used for major crops, county-level area data on non-federal pasture and rangeland (i.e., mostly privately-owned) were needed for U.S. grasslands. This information was based on U.S. Land Representation Analysis for Land Use, Land Use Change and Forestry sector (See Section 7.1), and included data compiled from the U.S. Department of Agriculture *National Resources Inventory* (USDA 2000a, Nusser and Goebel 1997, http://www.ncgc.nrcs.usda.gov/products/nri/index.htm), the USDA Forest Service (USFS) Forest Inventory and Analysis Database (FIA, http://fia.fs.fed .us/tools-data/data) and the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD, Vogelman et al. 2001, http://www.mrlc.gov). Grassland on non-federal lands is classified using the NRI and grassland on federal lands is classified using the NLCD. Grassland area data from the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. Another key source of N for grasslands is PRP manure N deposition. Activity data for PRP manure N excretion from dairy cattle, beef cattle, swine, sheep, goats, poultry, and horses were derived from multiple sources as described in the Manure Management section (Section 6.2) and Annex 3.10. The amount of PRP manure N deposited on non-federal grasslands (non-federal grasslands are mostly under private ownership) was based on the relative proportion of federal and non-federal grasslands in each county based on the U.S. Land Representation Analysis (See Section 7.1) . For example, if 75 percent of the grasslands in a county were non-federal then 75 percent of PRP manure N was assumed to be deposited on non-federal grasslands.

Nitrogen fixation by legumes, and N residue inputs from senesced grass litter were included as sources of N to the soil, and were estimated in the DAYCENT simulations as a function of vegetation type, weather, and soil properties. Similar to the methodology for major crops, "other N inputs" were simulated within the DAYCENT model framework in order to estimate all greenhouse gas emissions from managed lands (IPCC 2006), including mineralization from decomposition of soil organic matter and litter, as well as asymbiotic N fixation from the atmosphere. Decomposition rates are a function of litter quality and quantity, soil texture, water content and temperature, and other factors. Total annual amounts of PRP manure N, mineral N fertilizer application, manure N amendments, forage legume N and "other N inputs" can be found in Table A- 212.

Tier 1 Method: Additional Direct Soil N_2O Emissions

The Tier 1 method was used to estimate emissions from PRP manure that were not simulated with DAYCENT, in addition to emissions due to sewage sludge amendments to agricultural soils.

PRP Manure: PRP manure N data were derived using methods described in the Manure Management section (Section 6.2) and Annex 3.10. The amount of PRP manure N deposited on federal grasslands was based on the relative proportion of federal to non-federal grassland area in each county. As discussed in the Tier 3 DAYCENT Simulations

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[69] 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.

[70] The 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.

section, the area data were based on the U.S. Department of Agriculture's *National Resources Inventory* (USDA 2000a) and the National Land Cover Dataset (Vogelman et al. 2001), respectively, and were reconciled with the Forest Inventory and Analysis dataset in order to produce the U.S. Land Representation (See Section 7.1). Soil N_2O emissions from the proportion of PRP manure N deposited on federal grasslands were estimated with the Tier 1 method.

Sewage Sludge Amendments: Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works and is typically used as a soil amendment or is sent to waste disposal facilities such as landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. Estimates of the amounts of sewage sludge N applied to agricultural lands were derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from EPA (1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. Sewage sludge generation data are not available after 2004 (Bastian 2007), so the 1990 through 2004 data were linearly extrapolated for the most recent years. The total sludge generation estimates were then converted to units of N by applying an average N content of 3.9 percent (McFarland 2001), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices were agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal. The resulting estimates of sewage sludge N applied to agricultural land were used here; the estimates of sewage sludge N applied to other land and surface-disposed were used in estimating N_2O fluxes from soils in *Settlements Remaining Settlements* (see section 7.5 of the Land Use, Land-Use Change, and Forestry chapter). Sewage sludge disposal data are provided in Table A- 213.

Step 1d: Activity Data for Indirect N_2O Emissions from Managed Soils of all Land-Use Types and Managed Manure Systems

Volatilization of N that was applied or deposited as synthetic fertilizer, livestock manure, sewage sludge, and other organic amendments leads to emissions of NH_3 and NO_x to the atmosphere. In turn, this N is returned to soils through atmospheric deposition, thereby increasing mineral N availability and enhancing N_2O production. Additional N is lost from soils through leaching as water percolates through a soil profile and through runoff with overland water flow. N losses from leaching and runoff enter groundwater and waterways, from which a portion is emitted as N_2O. However, N leaching was assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. These areas are typically semi-arid to arid, and nitrate leaching to groundwater is a relatively uncommon event; moreover IPCC (2006) recommends limiting the amount of nitrate leaching assumed to be a source of indirect N_2O emissions based on precipitation, irrigation and potential evapotranspiration.

The activity data for synthetic fertilizer, livestock manure, other organic amendments, residue N inputs, sewage sludge N, and other N inputs are the same as those used in the calculation of direct emissions from agricultural mineral soils, and may be found in Table A- 204 through Table A- 208, Table A- 210, and Table A- 213. The activity data for computing direct and indirect N_2O emissions from settlements and forest lands are described in the Land Use, Land-Use Change, and Forestry chapter.

Using the DAYCENT model, volatilization and leaching/surface run-off of N from soils was computed internally for major crop types and non-federal grasslands. DAYCENT simulates the processes leading to these losses of N based on environmental conditions (i.e., weather patterns and soil characteristics), management impacts (e.g., plowing, irrigation, harvest), and soil N availability. Note that the DAYCENT method accounts for losses of N from all anthropogenic activity, not just the inputs of N from mineral fertilization and organic amendments, which are addressed in the Tier 1 methodology. Similarly, the N available for producing indirect emissions resulting from grassland management as well as deposited PRP manure was also estimated by DAYCENT. Estimated leaching losses of N from DAYCENT were not used in the indirect N_2O calculation if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. Volatilized losses of N were summed for each day in the annual cycle to provide an estimate of the amount of N subject to indirect N_2O emissions. In addition, the daily losses of N through leaching and runoff in overland flow were summed for the annual cycle. Uncertainty in the estimates was derived from uncertainties in the activity data for the N inputs (i.e., fertilizer and organic amendments; see Step 1a for further information)

The Tier 1 method was used to estimate N losses from mineral soils due to volatilization and leaching/runoff for non-major crop types, forestland, settlements, sewage sludge applications, and PRP manure on federal grasslands not accounted for by DAYCENT simulations. To estimate volatilized losses, synthetic fertilizers, manure, sewage sludge, and other organic N inputs were multiplied by the fraction subject to gaseous losses using the respective default values of 0.1 kg N/kg N added as mineral fertilizers and 0.2 kg N/kg N added as manure (IPCC 2006). Uncertainty in the volatilized N ranged from 0.03-0.3 kg NH_3-N+NOx-N/kg N for synthetic fertilizer and 0.05-0.5 kg NH_3-N+NOx-N/kg N for organic amendments (IPCC 2006). Leaching/runoff losses of N were estimated by summing the N additions from synthetic and other organic fertilizers, manure, sewage sludge, and above- and below-ground crop residues, and then multiplying by the default fraction subject to leaching/runoff losses of 0.3 kg N/kg N applied, with an uncertainty from 0.1–0.8 kg NO_3-N/kg N (IPCC 2006). However, N leaching was assumed to be an insignificant source of indirect N_2O emissions if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. PDFs were derived for each of the N inputs in the same manner as direct N_2O emissions, discussed in Steps 1a and 1c.

Volatilized N was summed for losses from major crop types, minor crop types, grasslands, settlements, and forest lands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff were summed to obtain the total losses for this pathway.

Step 2: Estimate Direct N_2O Emissions from Cropland Soils

In this step, N_2O emissions were calculated for major crop types and non-major crop types on mineral soils, in addition to emissions associated with drainage and cultivation of organic soils.

Step 2a: Direct N_2O Emissions from Cropland Mineral Soils

Two methods were used to estimate direct N_2O emissions from N additions and crop production on mineral soils. The DAYCENT ecosystem model was used to estimate emissions from major crop types, while the Tier 1 methodology was used to estimate emissions from crops considered non-major types, which are grown on a considerably smaller portion of land than the major types.

Major Crops: Tier 3 DAYCENT Simulations

Simulations were performed over three major time periods for each county in the United States using the DAYCENT model. The first time period was used for simulation of native vegetation up to date of cultivation in the county (1 A.D. to plow out). Plow out was assumed to occur between 1600 and 1850, depending on the state in which the county lies. Simulation of at least 1600 years of native vegetation was needed to initialize soil organic matter (SOM) pools in the model. The second time period of the simulation started at plowout and represents historical agricultural practices up to the modern period (plow out to 1970). Simulation of the historical cropping period was needed to establish modern day SOM levels, which is important because N_2O emissions are sensitive to the amount of SOM. Lastly, simulations were performed for the modern agricultural period (1971 through 2009[71]).

Corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton are defined as major crops and were simulated in every county where they were grown. These crops represent approximately 90 percent of total principal cropland in the United States as defined by the U.S. Department of Agriculture (USDA 2003). Overall, the DAYCENT simulations included approximately 86 percent of total cropland area. For rotations that include a cycle that repeats every two or more years (e.g., corn/soybeans, wheat/corn/fallow), different simulations were performed where each phase of the rotation was simulated every year. For example, 3 rotations were simulated in regions where wheat/corn/fallow cropping is a dominant rotation—one with wheat grown the first year, a second with corn the first year and a third with fallow the first year. This ensured that each crop was represented during each year in one of the three simulations. In cases where the same crop was grown in the same year in two or more distinct rotations for a region, N_2O emissions were averaged across the different rotations to obtain a value for that crop. Emissions from cultivated fallow land were also included. Fallow area was assumed to be equal to winter wheat area in regions where winter wheat/fallow rotations are the dominant land management for winter wheat.

The simulations reported here assumed conventional tillage cultivation, gradual improvement of cultivars, and gradual increases in fertilizer application until 1989. Note that there is a planned improvement to incorporate use of conservation tillage in the United States into this Inventory. The productivity of cultivars (cultivated varieties) has steadily improved over the last century and therefore it is unrealistic to assume that modern varieties of crops, such as corn, are identical to the popular varieties grown in 1900 in terms of yield potential, N demand, etc. Realistic simulations of historical land management and vegetation type are important because they influence present day soil C and N levels, which influence present-day N cycling and associated N_2O emissions.

Uncertainty estimation was an integral part of this analysis; uncertainty in the input data for the county-scale simulations and structural uncertainty associated with the DAYCENT model predictions were both addressed (Del Grosso

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[71] The simulation results for 2010 are not included in this year's report due to pending quality control issues that have not been resolved. The 2010 estimates are based on the 2009 inventory, which is expected to be representative of the 2010 emissions because management of agricultural soils was similar between the two years. The 2010 estimate will be updated in the next NIR.

et al. 2010). In the first step, a Monte Carlo Analysis was used to propagate input data uncertainty through the modeling process. Thus, input data were randomly selected from PDFs for weather records, soil type, mineral N fertilization rate, and organic amendments. See Step 1a for additional discussion about the PDFs. After selecting a set of inputs for a county, DAYCENT was used to simulate each crop and then the process was repeated until 100 iterations were completed. Due to the computationally intensive requirements for DAYCENT, it was not possible to simulate every county with the Monte Carlo Analysis. Two counties were selected from each of the 63 agricultural regions, and additional counties were added based on the variance in N_2O emissions across regions from the past year's Inventory, using a Neyman allocation (Cochran 1977). A Neyman allocation is based on the variance in N_2O emissions across the 63 regions; regions with larger variances were allocated a larger number of counties for the Monte Carlo Analysis. A total of 300 counties were included in the Monte Carlo Analysis, which is approximately 10 percent of all counties with agricultural land. In addition, all counties were simulated once based on the dominant conditions from the PDFs (i.e., most common soil type, weather condition, manure amendment, and mineral fertilizer rate).

In the second step of the uncertainty analysis, a structural uncertainty estimator was developed to account for uncertainty inherent in model formulation and parameterization using an empirically-based procedure described by Ogle et al. (2007). The procedure is based on developing a statistical relationship between modeled results and field measurements. Specifically, DAYCENT was used to simulate 11 agricultural experiments with 108 treatments, and the results were analyzed using a linear-mixed effect model in which measurements were statistically modeled as a function of simulated emissions. Simulated DAYCENT emissions were a highly significant predictor of the measurements, with a p-value of <0.01. Several other variables were tested in the statistical model to evaluate if DAYCENT exhibited bias under certain conditions related to climate, soil types, and management practices. The type of crop or grassland was significant at an alpha level of 0.05, demonstrating that DAYCENT tended to over-estimate emissions for small grains systems and grassland, but was accurate in predicting the N_2O emissions for other crops. Random effects were included in the model to capture the dependence in time series and data collected from the same site, which were needed to estimate appropriate standard deviations for parameter coefficients.

The structural uncertainty estimator accounted for bias and prediction error in the DAYCENT model results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2010. To apply the uncertainty estimator, DAYCENT N_2O emission estimates were used as an input to the linear mixed effect model after randomly selecting statistical parameter coefficients from their joint probability distribution, in addition to random draws from PDFs representing the uncertainty due to site, site by year random effects and the residual error from the linear-mixed effect model (Del Grosso et al. 2010).

In DAYCENT, once N enters the plant/soil system, the model cannot distinguish among the original sources of the N to determine which management activity led to specific N_2O emissions. This means, for example, that N_2O emissions from applied synthetic fertilizer cannot be separated from emissions due to other N inputs, such as crop residues. It is desirable, however, to report emissions associated with specific N inputs. Thus, for each crop in a county, the N inputs in a simulation were determined for anthropogenic practices discussed in IPCC (2006), including synthetic mineral N fertilization, organic amendments, and crop residue N added to soils (including N-fixing crops). The percentage of N input for anthropogenic practices was divided by the total N input, and this proportion was used to determine the amount of N_2O emissions assigned to each of the practices.[72] For example, if 70 percent of the mineral N made available in the soil was due to mineral fertilization, then 70 percent of the N_2O emissions were assigned to this practice. The remainder of soil N_2O emissions is reported under "other N inputs," which includes mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic fixation of mineral N in soils from the atmosphere. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Mineralization of soil organic matter is a more significant source of N, but is still typically less than half of the amount of N made available in the soil compared to fertilization, manure amendments, and symbiotic fixation. Accounting for the influence of "other N inputs" was necessary in order to meet the recommendation of reporting all emissions from managed lands (IPCC 2006). While this method allows for attribution of N_2O emissions to the individual N inputs to the soils, it is important to realize that sources such as synthetic fertilization may have a larger impact on N_2O emissions than would be suggested by the associated level of N input for this source (Delgado et al. 2009). Further research will be needed to improve upon this attribution method, however.

The final N_2O emission estimate was determined by summing the estimates from the single simulation conducted in each county for the dominant condition to the 63 regions. Estimates were then adjusted to account for the difference

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[72] This method is a simplification of reality to allow partitioning of N_2O emissions, as it assumes that all N inputs have an identical chance of being converted to N_2O. This is unlikely to be the case, but DAYCENT does not track N_2O emissions by source of mineral N so this approximation is the only approach that can be used for partitioning N_2O emissions by source of N input. Moreover, this approach is similar to the IPCC Tier 1 method (IPCC 2006), which uses the same direct emissions factor for most N sources (e.g., PRP).

between the emissions estimated in the Monte Carlo analysis and the dominant condition simulation on a region-by-region basis (i.e., if the Monte Carlo mean was slightly higher than the dominant condition among the counties included in the Monte Carlo analysis, the total emission estimate for the region would be raised by the difference) (Del Grosso et al. 2010). In turn, regional values were summed to produce the national total. The uncertainty was based on the variance in simulated N_2O emissions for the iterations in the Monte Carlo Analysis and the variance associated with difference between the means from the Monte Carlo Analysis and the simulated N_2O emissions for the dominant condition, expressed as a 95 percent confidence interval (Del Grosso et al. 2010).

Non-Major Crops: Tier 1 Method

To estimate direct N_2O emissions from N additions to non-major crops, the amount of N in applied synthetic fertilizer, manure and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) was added to N inputs from crop residues, and the resulting annual totals were multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006). The uncertainty was determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranged from 0.3–3.0 kg N_2O-N/kg N (IPCC 2006). Uncertainty in activity data is ± 20 percent for fertilizer additions (Mosier 2004).[73] Uncertainties in the emission factor and fertilizer additions were combined with uncertainty in the equations used to calculate residue N additions from above- and below-ground biomass dry matter and N concentration to derive overall uncertainty.

Step 2b: Direct N_2O Emissions Due to Drainage and Cultivation of Organic Cropland Soils

To estimate annual N_2O emissions from drainage and cultivation of organic soils, the area of cultivated organic soils in temperate regions was multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions was multiplied by the average (12 kg N_2O-N/ha cultivated) of IPCC (2006) default emission factors for temperate (8 kg N_2O-N/ha cultivated) and tropical (16 kg N_2O-N/ha cultivated) organic soils. The uncertainty was determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 2–24 kg N_2O-N/ha (IPCC 2006).

Step 2c: Estimate Total Direct N_2O Emissions from Cropland Soils

In this step, total direct N_2O emissions from cropland soils are calculated by summing direct emissions on mineral soils with emissions resulting from the drainage and cultivation of organic soils (i.e., histosols) (Table A- 214). Uncertainties were combined using the simple error propagation method (IPCC 2006).

Step 3: Estimate Direct N_2O Emissions from Grasslands

DAYCENT was used to estimate direct N_2O emissions from soils in non-federal grasslands (pastures and rangeland), and the Tier 1 method was used for federal grasslands. Managed pastures were simulated with DAYCENT by assuming that the vegetation mix includes forage legumes and grasses, and that grazing intensity was moderate to heavy. Rangelands were simulated without forage legumes and grazing intensity was assumed to be light to moderate. The methodology used to conduct the DAYCENT simulations of grasslands was similar to that for major crop types described above in Step 2a, including the analysis addressing uncertainty in the model inputs and model structure. Carbon and nitrogen additions to grasslands from grazing animals were obtained from county level animal excretion data and area data for federal and non-federal grasslands, as described in Step1c.

The Tier 1 method was used to estimate emissions from N excreted by livestock on federal lands (i.e., PRP manure N). The Tier 1 method was also used to estimate emissions from sewage sludge application to grasslands. These two sources of N inputs to soils were multiplied by the IPCC (2006) default emission factors (0.01 kg N_2O-N/kg N from sludge and horse, sheep, and goat manure, and 0.02 kg N_2O-N/kg N from cattle, swine, and poultry manure) to estimate N_2O emissions. This emission estimate was summed with the DAYCENT simulated emissions to provide the national total for direct N_2O losses from grasslands (Table A- 215). The uncertainty was determined based on the Tier 1 error propagation methods provided by the IPCC (2006) with uncertainty in the default emission factor ranging from 0.007 to 0.06 kg N_2O-N/kg N (IPCC 2006).

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[73] Note that due to lack of data, uncertainties in managed manure N production, PRP manure N production, other commercial organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

Step 4: Estimate Indirect N_2O Emissions for All Land-Use Types

In this step, N_2O emissions were calculated for the two indirect emission pathways (N_2O emissions due to volatilization, and N_2O emissions due to leaching and runoff of N), which were then summed to yield total indirect N_2O emissions from croplands, grasslands, forest lands, and settlements.

Step 4a: Indirect Emissions Due to Volatilization

Indirect emissions from volatilization of N inputs from synthetic and commercial organic fertilizers, and PRP manure, were calculated according to the amount of mineral N that was transported in gaseous forms from the soil profile and later emitted as soil N_2O following atmospheric deposition. See Step 1d for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized for all land-use and livestock activities was multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) to compute total N_2O emissions from volatilization. The resulting estimates are provided in Table A- 216. The uncertainty was determined using simple error propagation methods (IPCC 2006), by combining uncertainties in the amount of N volatilized, with uncertainty in the default emission factor ranging from 0.002–0.05 kg N_2O-N/kg N (IPCC 2006).

Step 4b: Indirect Emissions Due to Leaching and Runoff

The amount of mineral N (i.e., synthetic fertilizers, commercial organic fertilizers, PRP manure, crop residue, N mineralization, asymbiotic fixation) that was transported from the soil profile in aqueous form was used to calculate indirect emissions from (1) leaching of mineral N from soils and (2) losses in runoff of water associated with overland flow. See Step 1d for additional information about the methods used to compute N losses from soils due to leaching and runoff in overland water flows.

The total amount of N transported from soil profiles through leaching and surface runoff was multiplied by the IPCC default emission factor of 0.0075 kg N_2O-N/kg N (IPCC 2006) to estimate emissions for this source. The resulting emission estimates are provided in Table A- 217. The uncertainty was determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 0.0005 to 0.025 kg N_2O-N/kg N (IPCC 2006).

Step 5: Estimate Total N_2O Emissions for U.S. Soils

Total emissions were estimated by adding total direct emissions (from major crop types and non-major crop types on mineral cropland soils, drainage and cultivation of organic soils, and grassland management) to indirect emissions for all land use and management activities. U.S. national estimates for this source category are provided in Table A- 217. Uncertainties in the final estimate were combined using simple error propagation methods (IPCC 2006), and expressed as a 95 percent confidence interval.

Direct and indirect emissions of soil N_2O vary regionally in both croplands and grasslands as a function of N inputs, weather, and soil type. A little more than half of the total N_2O emissions from major crops occur in Iowa, Illinois, Nebraska, Minnesota, Texas, Kansas and Indiana where N inputs associated with corn rotations are high or where large land areas are cropped (Table A- 218). On a per area unit basis, direct N_2O emissions are also high in many of the Mississippi River Basin states where there are also high N input to corn and soybean crops (Figure A- 9). Emissions are also high in some western and New England states. Only a small portion of the land in these regions is used for crop production, but management and conditions lead to higher emissions on a per unit area basis than other regions. For example, emissions are high in California, Arizona, and other western states due to intensive irrigation management systems. For some New England states, emissions are high on a per unit area because subsurface soil layers remain frozen when surface soil layers thaw in spring. This creates saturated conditions near the surface that facilitate denitrification and N_2O emissions. Indirect emissions tend to be high on an area basis in the central and eastern United States because relatively high rainfall facilitates N losses from leaching and runoff and in some western states where irrigation can contribute to leaching and runoff (Figure A- 10).

Direct and indirect emissions from grasslands are typically lower than those from croplands (Table A- 218, Figure A- 11, and Figure A- 12) because N inputs tend to be lower, particularly from synthetic fertilizer. Texas was by far the highest emitter for this category, followed by Nebraska, Montana, Oklahoma, New Mexico Colorado and South Dakota. On a per area unit basis, emissions are lower in the western United States because grasslands in the East and Central regoins are more intensively managed (legume seeding, fertilization) while western rangelands receive few, if any, N inputs. Also, rainfall is limited in most of the western United States, and grasslands are not typically irrigated so minimal leaching and runoff of N occurs in these grasslands.

Figure A- 7: DAYCENT Model Flow Diagram

Figure A- 8: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N_2O Emissions

Figure A- 9: Major Crops, Average Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2010 (Metric Tons CO_2 Eq./ha/year)

Figure A- 10: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2010 (kg N/ha/year)

Figure A- 11: Grasslands, Average Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2010 (Metric Tons CO_2 Eq./ha/year)

Figure A- 12: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2010 (kg N/ha/year)

Table A- 204: Synthetic Fertilizer N Added to Major Crops (Gg N)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Fertilizer N	7,468	7,307	7,915	7,705	7,641	7,412	7,575	7,450	7,547	7,370	7,355	7,000	6,855	7,428	6,663	6,194	6,194

Note: The estimate for 2010 is based on the estimate from 2009 due to quality control issues in the compilation of the inventory for 2010. The estimates will be updated in the NIR.

Table A- 205: Fate of Livestock Manure Nitrogen (Gg N)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Managed Manure N Applied to Major Crops and Grasslands[a,b]	993	968	1,038	1,063	1,116	1,103	1,099	1,086	1,164	1,079	1,077	1,036	847	1,195	1,110	948	948
Managed Manure N Applied to Non-Major Crops[b]	1,446	1,588	1,522	1,522	1,504	1,511	1,548	1,575	1,561	1,489	1,551	1,634	1,864	1,588	1,614	1,741	1,741
Managed Manure N Applied to Grasslands	446	515	514	503	542	478	463	466	470	470	472	475	479	475	474	462	462
Pasture, Range, & Paddock Manure N	6,994	7,559	7,532	7,426	7,414	7,300	7,204	7,177	7,268	7,171	7,223	7,355	7,413	7,527	7,403	7,255	7,255
Total	9,878	10,630	10,606	10,514	10,577	10,392	10,313	10,304	10,463	10,209	10,322	10,500	10,603	10,785	10,602	10,405	10,405

[a] Accounts for N volatilized and leached/runoff during treatment, storage and transport before soil application.

[b] Includes managed manure and daily spread manure amendments

[c] Totals may not sum exactly due to rounding.

Table A- 206: Crop Residue N and Other N Inputs to Major Crops as Simulated by DAYCENT (Gg N)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Residue N[a]	2,982	3,305	3,322	3,329	3,099	3,659	3,450	3,151	3,253	3,407	3,231	3,041	3,186	3,164	3,210	2,996	2,996
Mineralization & Asymbiotic Fixation	12,406	12,010	12,590	12,811	14,166	12,926	13,548	13,520	13,238	13,216	13,361	12,740	12,800	13,084	12,943	12,345	12,345

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: The estimate for 2010 is based on the estimate from 2009 due to quality control issues in the compilation of the inventory for 2010. The estimates will be updated in the NIR.

Table A- 207: Synthetic Fertilizer N Added to Non-Major Crops (Gg N)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Fertilizer N	1,116	1,924	1,364	1,673	1,707	1,880	1,584	1,610	1,578	1,875	1,942	2,192	2,076	1,742	2,286	2,710	3,075

Table A- 208: Other Organic Commercial Fertilizer Consumption on Agricultural Lands (Gg N)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Other Commercial Organic Fertilizer N[a]	4	10	13	14	12	11	9	7	8	8	9	10	12	15	12	10	11

[a] Includes dried blood, tankage, compost, other. Excludes dried manure and sewage sludge used as commercial fertilizer to avoid double counting.

Table A- 209: Key Assumptions for Production of Non-Major Crops and Retention of Crop Residues

Crop	Dry Matter Fraction of Harvested Product	Above-ground Residue Slope	Above-ground Residue Intercept	Ratio of Below-ground Residue to Above-ground Biomass	Residue N Fraction Above-ground	Residue N Fraction Below-ground
Peanuts for Nuts	0.94	1.07	1.54	0.20	0.016	0.014
Dry Edible Beans	0.90	0.36	0.68	0.19	0.010	0.010
Dry Edible Peas	0.91	1.13	0.85	0.19	0.008	0.008
Austrian Winter Peas	0.91	1.13	0.85	0.19	0.008	0.008
Lentils	0.91	1.13	0.85	0.19	0.008	0.008
Wrinkled Seed Peas	0.91	1.13	0.85	0.19	0.008	0.008
Barley	0.89	0.98	0.59	0.22	0.007	0.014
Oats	0.89	0.91	0.89	0.25	0.007	0.008
Rye	0.88	1.09	0.88	0.22	0.005	0.011
Millet	0.90	1.43	0.14	0.22	0.007	0.009
Rice	0.89	0.95	2.46	0.16	0.007	0.009

Table A- 210: Nitrogen in Crop Residues Retained on Soils Producing Non-Major Crops (Gg N)

Crop	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Peanuts for Nuts	64	63	65	64	68	66	61	71	61	69	71	77	63	65	79	65	70
Dry Edible Beans	16	16	15	16	16	16	15	13	16	14	13	15	14	15	15	15	16
Dry Edible Peas	9	11	9	11	11	10	10	10	10	11	14	15	8	8	14	17	15
Austrian Winter Peas	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Lentils	9	9	9	9	9	9	10	10	9	9	10	11	10	10	9	11	12
Wrinkled Seed Peas	9	9	8	8	8	8	8	8	8	8	9	8	8	8	8	9	8
Barley	112	96	105	96	94	74	86	68	63	76	76	59	51	59	66	63	51
Oats	55	29	28	30	30	27	28	24	23	27	23	23	20	20	20	20	19
Rye	9	9	9	8	9	9	9	8	8	9	8	8	8	8	8	8	8
Millet	7	7	7	7	7	7	3	7	2	5	6	5	4	6	6	4	5
Rice	80	87	86	91	91	99	94	103	101	97	109	106	95	96	99	105	114
Total	**378**	**343**	**349**	**348**	**352**	**336**	**331**	**330**	**311**	**333**	**347**	**336**	**290**	**304**	**333**	**324**	**327**

.

Table A- 211: Drained and Cultivated Organic Soil Area (Thousand Hectares)

Year	Temperate Area	Sub-Tropical Area
1990	444	194
1995	450	196
1996	450	196
1997	450	196
1998	450	196
1999	450	196
2000	450	196
2001	450	196
2002	450	196
2003	450	196
2004	450	196
2005	450	196
2006	450	196
2007	450	196
2008	450	196
2009	450	196
2010	450	196

Table A- 212: Synthetic Fertilizer N, PRP Manure N, Organic Manure N Amendment, Forage Legume N, and Other N Inputs Simulated with the DAYCENT Model (Gg N)

N Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Fertilizer N	9,678	9,662	10,245	9,973	9,891	9,628	9,747	9,620	9,723	9,553	9,536	9,213	9,088	9,656	8,871	8,385	8,385
PRP Manure N	3,718	4,065	4,021	3,906	3,856	3,787	3,697	3,688	3,701	3,728	3,731	3,806	3,856	3,850	3,819	3,781	3,781
Managed Manure	1,438	1,483	1,552	1,566	1,658	1,581	1,561	1,552	1,634	1,549	1,549	1,511	1,326	1,670	1,584	1,410	1,410
Residue N[a]	11,164	11,560	11,054	11,069	10,667	12,264	11,056	11,078	10,631	11,234	10,855	10,731	10,840	10,875	10,890	10,577	10,577
Mineralization & Asymbiotic Fixation	23,864	23,237	23,649	24,172	25,721	23,703	24,190	24,412	23,731	23,942	24,175	23,635	23,549	23,830	23,731	23,285	23,285

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: The estimates for 2010 are based on the estimates from 2009 due to quality control issues in the compilation of the inventory for 2010. The estimates will be updated in the NIR.

Table A- 213: Sewage Sludge Nitrogen by Disposal Practice (Gg N)

Disposal Practice	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Applied to Agricultural Soils	52	69	72	75	78	81	30	86	89	91	94	98	101	104	106	109	112
Other Land Application	25	28	29	29	29	30	30	30	30	30	30	31	31	32	32	32	32
Surface Disposal	20	16	15	14	13	12	10	9	8	6	5	5	4	4	3	3	3
Total	**98**	**113**	**116**	**118**	**121**	**122**	**124**	**125**	**127**	**128**	**130**	**134**	**136**	**139**	**141**	**144**	**147**

Note: Totals may not sum due to independent rounding.

Table A- 214: Direct N_2O Emissions from Cropland Soils (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Mineral Soils	**100.1**	**107.1**	**115.5**	**112.9**	**116.6**	**111.1**	**112.7**	**120.3**	**112.6**	**109.6**	**116.2**	**115.1**	**112.8**	**114.9**	**115.1**	**109.5**	**109.5**
Major Crops	**85.8**	**88.3**	**99.6**	**95.6**	**99.2**	**92.9**	**95.7**	**103.1**	**95.7**	**91.5**	**97.4**	**94.8**	**92.1**	**97.1**	**94.4**	**86.1**	**86.1**
Synthetic Fertilizer	27.1	27.4	31.7	29.6	29.4	27.4	28.4	30.4	28.8	27.0	28.7	28.1	26.7	29.1	26.5	23.9	23.9
Managed Manure	3.6	3.6	4.2	4.1	4.1	4.0	4.0	4.4	4.3	3.9	4.1	4.1	3.3	4.6	4.4	3.6	3.6
Residue N[a]	10.6	12.4	13.5	12.8	11.6	13.7	12.7	12.7	12.4	12.4	12.6	12.1	12.4	12.4	12.6	11.5	11.5
Mineralization and Asymbiotic Fixation	44.6	44.8	50.2	49.0	54.0	47.7	50.6	55.5	50.2	48.3	52.1	50.5	49.7	50.9	50.9	47.1	47.1
Non-Major Crops	**14.3**	**18.8**	**15.8**	**17.3**	**17.4**	**18.2**	**16.9**	**17.2**	**16.8**	**18.0**	**18.7**	**20.3**	**20.7**	**17.8**	**20.7**	**23.3**	**23.3**
Synthetic Fertilizer	5.4	9.4	6.6	8.2	8.3	9.2	7.7	7.8	7.7	9.1	9.5	10.7	10.1	8.5	11.1	13.2	13.2
Managed Manure and Other Organic Commercial Fertilizer	7.1	7.8	7.5	7.5	7.4	7.4	7.6	7.7	7.6	7.3	7.6	8.0	9.1	7.8	7.9	8.5	8.5
Residue N	1.8	1.7	1.7	1.7	1.7	1.6	1.6	1.6	1.5	1.6	1.7	1.6	1.4	1.5	1.6	1.6	1.6
Organic Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Total*	**103.0**	**110.0**	**118.4**	**115.8**	**119.5**	**114.0**	**115.6**	**123.2**	**115.5**	**112.5**	**119.1**	**118.0**	**115.7**	**117.8**	**118.0**	**112.4**	**112.4**

+ Less than 0.05 Tg CO_2 Eq.

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: The major crop estimates for 2010 are based on the emissions from 2009 due to quality control issues in the compilation of the inventory for 2010. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of the emissions in 2010. The estimates will be updated in the next NIR.

Table A- 215: Direct N_2O Emissions from Grasslands (Tg CO_2 Eq.)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
DAYCENT	**47.1**	**45.2**	**49.4**	**46.2**	**47.3**	**42.9**	**43.3**	**47.3**	**47.5**	**42.6**	**44.5**	**45.6**	**44.3**	**43.4**	**44.9**	**44.4**	**44.4**
Synthetic Fertilizer	2.7	2.8	3.0	2.8	2.9	2.6	2.7	2.9	2.9	2.6	2.7	2.8	2.8	2.7	2.8	2.8	2.8
PRP Manure	16.1	16.9	18.6	17.0	17.4	15.5	15.9	17.0	17.4	15.3	16.0	16.6	16.2	15.5	16.0	15.7	15.7
Managed Manure	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Residue N[a]	12.0	10.9	11.6	10.9	10.8	11.2	10.3	11.7	11.5	10.6	10.8	11.1	10.8	10.7	11.0	10.8	10.8
Mineralization and Asymbiotic Fixation	16.3	14.6	16.2	15.6	16.3	13.7	14.4	15.7	15.6	14.1	15.0	15.1	14.6	14.5	15.1	15.1	15.1
Tier 1	**5.7**	**6.1**	**6.1**	**6.0**	**6.0**	**5.9**	**5.7**	**5.6**	**5.6**	**5.5**	**5.4**	**5.5**	**5.6**	**5.6**	**5.6**	**5.5**	**5.5**
PRP Manure	5.4	5.8	5.7	5.6	5.6	5.5	5.3	5.2	5.2	5.0	5.0	5.1	5.1	5.1	5.1	4.9	4.9
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total	**52.8**	**51.3**	**55.5**	**52.2**	**53.3**	**48.8**	**49.0**	**52.9**	**53.1**	**48.1**	**49.9**	**51.1**	**49.9**	**49.0**	**50.5**	**49.9**	**49.9**

+ Less than 0.05 Tg CO_2 Eq.

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: The estimates for 2010 are based on the emissions from 2009 due to quality control issues in the compilation of the inventory for 2010. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of the emissions in 2010. The estimates will be updated in the next NIR.

Table A- 216: Indirect N_2O Emissions (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Volatilization and Atm. Deposition	**17.0**	**18.3**	**17.5**	**17.9**	**17.9**	**17.8**	**17.7**	**17.9**	**17.6**	**17.5**	**17.8**	**18.2**	**19.5**	**17.7**	**18.1**	**18.8**	**19.0**
Croplands	11.5	12.7	12.1	12.4	12.3	12.4	12.6	12.6	12.5	12.3	12.6	13.0	14.3	12.6	13.0	13.7	13.9
Settlements	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Forest Land	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Grasslands	5.3	5.4	5.2	5.4	5.4	5.2	4.9	5.1	4.9	5.0	5.0	5.0	5.0	4.9	4.9	4.9	4.8
Surface Leaching & Run-off	**27.1**	**30.3**	**29.8**	**25.8**	**29.2**	**24.5**	**26.6**	**28.8**	**24.9**	**25.9**	**26.7**	**25.7**	**26.0**	**26.6**	**26.3**	**26.2**	**26.5**
Croplands	25.9	29.1	28.1	24.4	27.5	23.0	25.0	27.3	23.2	24.0	24.9	23.7	24.4	24.9	24.6	24.2	24.5
Settlements	0.2	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	0.4	0.4	0.4
Forest Land	+	+	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	0.1	0.1
Grasslands	1.0	0.9	1.4	0.9	1.3	1.1	1.2	1.2	1.2	1.4	1.3	1.5	1.1	1.2	1.2	1.5	1.5
Total	**44.1**	**48.6**	**47.4**	**43.7**	**47.1**	**42.3**	**44.2**	**46.7**	**42.5**	**43.4**	**44.5**	**43.9**	**45.5**	**44.3**	**44.4**	**45.0**	**45.5**

+ Less than 0.05 Tg CO_2 Eq.

Table A- 217: Total N_2O Emissions from Agricultural Soil Management (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Direct	**155.8**	**161.3**	**173.8**	**168.0**	**172.8**	**162.8**	**164.5**	**176.1**	**168.5**	**160.6**	**169.0**	**169.1**	**165.6**	**166.8**	**168.5**	**162.2**	**162.3**
Direct Emissions from Mineral Cropland Soils	**100.1**	**107.1**	**115.5**	**112.9**	**116.6**	**111.1**	**112.7**	**120.3**	**112.6**	**109.6**	**116.2**	**115.1**	**112.8**	**114.9**	**115.1**	**109.5**	**109.5**
Synthetic Fertilizer	32.5	36.8	38.4	37.8	37.7	36.6	36.2	38.2	36.5	36.1	38.1	38.8	36.8	37.6	37.6	37.1	37.2
Organic Amendment[a]	10.6	11.4	11.7	11.6	11.5	11.5	11.6	12.1	12.0	11.2	11.7	12.1	12.4	12.5	12.4	12.2	12.2
Residue N[b]	12.4	14.0	15.2	14.5	13.4	15.3	14.3	14.3	13.9	14.0	14.3	13.7	13.8	13.9	14.3	13.1	13.1
Mineralization and Asymbiotic Fixation	44.6	44.8	50.2	49.0	54.0	47.7	50.6	55.5	50.2	48.3	52.1	50.5	49.7	50.9	50.9	47.1	47.1
Direct Emissions from Drained Organic Cropland Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Direct Emissions from Grasslands*	**52.8**	**51.3**	**55.5**	**52.2**	**53.3**	**48.8**	**49.0**	**52.9**	**53.1**	**48.1**	**49.9**	**51.1**	**49.9**	**49.0**	**50.5**	**49.9**	**49.9**
Synthetic Mineral Fertilizer	2.7	2.8	3.0	2.8	2.9	2.6	2.7	2.9	2.9	2.6	2.7	2.8	2.8	2.7	2.8	2.8	2.8
PRP Manure*	21.6	22.6	24.3	22.6	23.0	20.9	21.2	22.2	22.6	20.4	20.9	21.6	21.2	20.6	21.0	20.6	20.6
Managed Manure	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Residue[b]	12.0	10.9	11.6	10.9	10.8	11.2	10.3	11.7	11.5	10.6	10.8	11.1	10.8	10.7	11.0	10.8	10.8
Mineralization and Asymbiotic Fixation	16.3	14.6	16.2	15.6	16.3	13.7	14.4	15.7	15.6	14.1	15.0	15.1	14.6	14.5	15.1	15.1	15.1
Total Indirect	**44.1**	**48.6**	**47.4**	**43.7**	**47.1**	**42.3**	**44.2**	**46.7**	**42.5**	**43.4**	**44.5**	**43.9**	**45.5**	**44.3**	**44.4**	**45.0**	**45.5**
Volatilization	17.0	18.3	17.5	17.9	17.9	17.8	17.7	17.9	17.6	17.5	17.8	18.2	19.5	17.7	18.1	18.8	19.0
Leaching/Runoff	27.1	30.3	29.8	25.8	29.2	24.5	26.6	28.8	24.9	25.9	26.7	25.7	26.0	26.6	26.3	26.2	26.5
Total Emissions	**200.0**	**209.8**	**221.2**	**211.7**	**219.9**	**205.1**	**208.8**	**222.8**	**211.0**	**204.0**	**213.5**	**213.1**	**211.1**	**211.1**	**212.9**	**207.3**	**207.8**

+ Less than 0.05 Tg CO_2 Eq.

[a] Organic amendment inputs include managed manure amendments, daily spread manure and other commercial organic fertilizer (i.e., dried blood, tankage, compost, and other).

[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 218: Total 2010 N_2O Emissions (Direct and Indirect) from Agricultural Soil Management by State (Tg CO_2 Eq.)

State	Croplands[1]	Grasslands[2]	Settlements[3]	Forest Lands[4]	Total	Lower Bound	Upper Bound
AL	0.84	0.71	0.03	n.e.	1.59	1.02	2.91
AR	3.47	0.76	0.02	n.e.	4.25	2.81	8.00
AZ	0.78	0.96	0.02	n.e.	1.76	0.87	4.44
CA	7.07	2.19	0.19	n.e.	9.45	6.09	18.23
CO	1.60	2.55	0.02	n.e.	4.17	2.71	7.04
CT	0.12	0.03	0.02	n.e.	0.16	0.12	0.30
DE	0.24	0.01	0.01	n.e.	0.26	0.18	0.74
FL	2.23	1.02	0.22	n.e.	3.47	2.44	5.90
GA	1.55	0.33	0.01	n.e.	1.89	1.21	3.96
HI[5]	0.00	n.e.	n.e.	n.e.	1.89	1.21	3.96
IA	16.02	0.82	0.07	n.e.	16.92	12.20	34.23
ID	2.01	1.71	0.02	n.e.	3.74	2.37	7.51
IL	11.86	0.37	0.12	n.e.	12.34	8.81	19.28
IN	7.56	0.30	0.07	n.e.	7.94	5.05	12.77
KS	6.55	2.23	0.07	n.e.	8.86	6.32	13.79
KY	2.19	1.14	0.03	n.e.	3.36	2.10	5.94
LA	1.58	0.54	0.04	n.e.	2.16	1.65	3.45
MA	0.13	0.02	0.04	n.e.	0.19	0.13	0.76
MD	0.74	0.09	0.05	n.e.	0.89	0.37	2.20
ME	0.22	0.02	0.01	n.e.	0.25	0.17	1.36
MI	4.60	0.37	0.08	n.e.	5.05	3.60	8.62
MN	10.13	0.79	0.03	n.e.	10.95	7.73	17.15
MO	6.13	1.81	0.07	n.e.	8.01	5.39	12.71
MS	2.59	0.42	0.03	n.e.	3.05	1.84	6.56
MT	1.53	3.23	0.01	n.e.	4.77	2.91	7.69
NC	2.69	0.80	0.05	n.e.	3.54	2.38	7.17
ND	5.33	1.24	0.03	n.e.	6.61	4.43	10.51
NE	7.54	3.02	0.07	n.e.	10.62	7.65	16.76
NH	0.06	0.01	0.01	n.e.	0.08	0.06	0.41
NJ	0.19	0.02	0.07	n.e.	0.28	0.15	0.91
NM	0.88	3.04	0.01	n.e.	3.93	2.15	6.77
NV	0.32	0.72	0.01	n.e.	1.05	0.08	9.17
NY	3.19	0.33	0.07	n.e.	3.59	2.34	7.01
OH	7.40	0.48	0.11	n.e.	7.99	5.68	12.58
OK	1.78	3.03	0.03	n.e.	4.84	2.51	8.64
OR	1.12	1.62	0.01	n.e.	2.75	1.74	5.72
PA	1.82	0.13	0.06	n.e.	2.01	0.91	5.17
RI	0.02	0.00	0.01	n.e.	0.03	0.02	0.58
SC	0.66	0.14	0.03	n.e.	0.83	0.14	2.00
SD	3.62	2.65	0.02	n.e.	6.29	4.38	10.15
TN	1.74	0.77	0.05	n.e.	2.56	1.53	6.42
TX	7.38	8.98	0.09	n.e.	16.45	10.13	26.22
UT	0.64	1.09	0.01	n.e.	1.73	1.16	3.53
VA	0.91	0.82	0.06	n.e.	1.79	0.95	4.14
VT	0.46	0.06	0.00	n.e.	0.52	0.37	1.11
WA	2.29	1.01	0.03	n.e.	3.32	1.25	7.95
WI	7.07	0.77	0.04	n.e.	7.88	5.57	13.03
WV	0.44	0.21	0.01	n.e.	0.66	0.36	1.62
WY	0.38	2.10	0.01	n.e.	2.49	1.68	4.11

[1] Emissions from non-manure organic N inputs for minor crops were not estimated (n.e.) at the state level.

[2] Emissions from sewage sludge applied to grasslands and were not estimated (n.e.) at the state level

[3] Emissions from sewage sludge applied to settlements were not estimated (n.e.) at the state level.

[4] Forestland emissions were not estimated (n.e.) at the state level.

[5] N_2O emissions are not reported for Hawaii except from cropland organic soils.

3.12. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands

This sub-annex expands on the methodology used to calculate net changes in carbon (C) stocks in forest ecosystems and in harvested wood products. Some of the details of C conversion factors and procedures for calculating net CO_2 flux for forests are provided below; full details of selected topics may be found in the cited references.

Carbon Stocks and Net Changes in Forest Ecosystem Carbon Stocks

At least two forest inventories exist for most forest land in the United States. C stocks are estimated based on data from each inventory, at the level of permanent inventory plots. C per hectare (for a sample location) is multiplied by the total number of hectares that the plot represents, and then totals are summed for an area of interest, such as the state of Maine. Net annual C stock changes are calculated by taking the difference between the inventories and dividing by the number of years between the inventories for a selected state or sub-state area.

Forest inventory data

The estimates of forest C stocks are based on data derived from forest inventory surveys. Forest inventory data were obtained from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (Frayer and Furnival 1999, USDA Forest Service 2011a, USDA Forest Service 2011b). FIA data include remote sensing information and collection of measurements in the field at sample locations called plots. Tree measurements include diameter and species. On a subset of plots, additional measurements or samples are taken of down dead wood, litter, and soil C; however, these are not yet available nationwide for C estimation. The field protocols are thoroughly documented and available for download from the USDA Forest Service (2011c). Bechtold and Patterson (2005) provide the estimation procedures for standard forest inventory results. The data are freely available for download at USDA Forest Service (2011b) as the Forest Inventory and Analysis Database (FIADB) Version 4.0 (Woudenberg et al. 2010); these data are the primary sources of forest inventory used to estimate forest C stocks.

Forest surveys have begun in the U.S. territories and in Hawaii. Meanwhile this inventory assumes that these areas account for a net C change of zero. Survey data are available for the temperate oceanic ecoregion of Alaska (southeast and south central). Inventory data are publicly available for 6 million hectares of forest land, and these inventoried lands, comprising 12 percent of the total forest land in Alaska, contribute to the forest carbon stocks presented here.

Agroforestry systems are also not currently accounted for in the U.S. inventory, since they are not explicitly inventoried by either of the two primary national natural resource inventory programs: the FIA program of the USDA Forest Service and the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005). The majority of these tree-based practices do not meet the size and definitions for forests within each of these resource inventories. The size characteristics that exclude them from inventories also allow these systems to provide their many services without taking the land out of agricultural production, making them an appealing C sequestration option. Agroforestry in the United States has been defined as "intensive land-use management that optimizes the benefits (physical, biological, ecological, economic, social) from bio-physical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Gold et al. 2000). In the United States, there are six categories of agroforestry practices: riparian forest buffers, windbreaks, alley cropping, silvopasture, forest farming and special applications.[74] These practices are used to address many issues facing agricultural lands, such as economic diversification, habitat fragmentation, and water quality. While providing these services and regardless of intent, these tree-based plantings will also reduce atmospheric CO_2. This occurs directly through CO_2 sequestration into woody biomass, and indirectly through enhancement of agricultural production, trapping wind-blown and surface runoff sediments, and/or reducing CO_2 emissions through fuel-use savings (Quam et al. 1992). The effects of these individual practices can potentially be quite large when taken into account within a whole-farm or within an aggregating larger entity (i.e., state-level) (Quam et al. 1992, Schoeneberger 2006). One estimate of the sequestration potential through agroforestry practices in the United States is 90.3 Mt C/year by 2025 (Nair and Nair 2003).

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[74] More information on agroforestry practices can be found online at <http://www.unl.edu/nac>.

Summing state-level C stocks to calculate United States net C flux in forest ecosystems

The overall approach for determining forest C stocks and stock change is essentially based on methodology and algorithms coded into the computer tool described in Smith et al. (2010). A significant change in methods for the present inventory involves a new approach to estimates of standing C stock in live and standing dead trees, which has been incorporated in the current version of the Smith et al. (2010) C calculator. The carbon calculation tool focuses on estimating forest C stocks based on data from two or more forest surveys conducted several years apart for each state or sub-state. There are generally two or more surveys available for download for each state. C stocks are calculated separately for each state based on available inventories conducted since 1990 and for the inventory closest to, but prior to, 1990 if such data are available and consistent with these methods. This approach ensures that the period 1990 (the base year) to present can be adequately represented. Surveys conducted prior to and in the early to mid 1990s focused on land capable of supporting timber production (timberland).[75] As a result, information on less productive forest land or lands reserved from harvest was limited. Inventory field crews periodically measured all the plots in a state at a frequency of every 5 to 14 years. Generally, forests in states with fast-growing (and therefore rapidly changing) forests tended to be surveyed more often than states with slower-growing (and therefore slowly changing) forests. Older surveys for some states, particularly in the West, also have National Forest System (NFS) lands or reserved lands that were surveyed at different times than productive, privately-owned forest land in the state. Periodic data for each state thus became available at irregular intervals and determining the year of data collection associated with the survey can sometimes be difficult.

Table A-219: Source of Unique Forest Inventory and Average Year of Field Survey Used to Estimate Statewide Carbon Stocks

State/Substate[a]	Source of Inventory Data, Report/Inventory Year[b]	Average Year Assigned to Inventory[c]
Alabama	FIADB 4.0, 1982	1982
	FIADB 4.0, 1990	1990
	FIADB 4.0, 2000	1999
	FIADB 4.0, 2005	2003
	FIADB 4.0, 2010	2007
Alaska, non-reserved Southcentral	FIADB 4.0, 2003	2001
	FIADB 4.0, 2009	2007
Alaska, non-reserved Southeast	FIADB 4.0, 2003	1997
	FIADB 4.0, 2009	2007
Alaska, reserved Southcentral	FIADB 4.0, 2009	2006
Alaska, reserved Southeast	FIADB 4.0, 2009	2006
Arizona, NFS non-woodlands	1987 RPA	1985
	FIADB 4.0, 1999	1996
	FIADB 4.0, 2009	2005
Arizona, NFS woodlands	1987 RPA	1984
	FIADB 4.0, 1999	1996
	FIADB 4.0, 2009	2005
Arizona, non-NFS non-woodlands	FIADB 4.0, 1985	1986
	FIADB 4.0, 1999	1996

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[75] Forest land is defined as land at least 120 feet wide and 1 acre in size with at least 10 percent cover (or equivalent stocking by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between forest and nonforest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet and continuous length of at least 363 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet wide or an acre in size. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land (Smith et al. 2009). Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. Productivity is at a minimum rate of 20 cubic feet of industrial wood per acre per year (Woudenberg and Farrenkopf 1995). There are about 203 million hectares of timberland in the conterminous United States, which represents 81 percent of all forest lands over the same area (Smith et al. 2009).

	FIADB 4.0, 2009	2006
Arizona, non-NFS woodlands	FIADB 4.0, 1999	1990
	FIADB 4.0, 2009	2006
Arkansas	FIADB 4.0, 1988	1988
	FIADB 4.0, 1995	1996
	FIADB 4.0, 2005	2003
	FIADB 4.0, 2010	2008
California, NFS	IDB, 1990s	1997
	FIADB 4.0, 2009	2006
California, non-NFS	IDB, 1990s	1993
	FIADB 4.0, 2009	2006
Colorado, NFS non-woodlands	1997 RPA	1981
	FIADB 4.0, 2009	2006
Colorado, NFS woodlands	1997 RPA	1975
	FIADB 4.0, 1984	1997
	FIADB 4.0, 2009	2006
Colorado, non-NFS non-woodlands	Westwide, 1983	1980
	FIADB 4.0, 2009	2006
Colorado, non-NFS woodlands	Westwide, 1983	1983
	FIADB 4.0, 2009	2006
Connecticut	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2007	2006
	FIADB 4.0, 2010	2009
Delaware	FIADB 4.0, 1986	1986
	FIADB 4.0, 1999	1999
	FIADB 4.0, 2008	2007
Florida	FIADB 4.0, 1987	1987
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2007	2005
Georgia	FIADB 4.0, 1989	1989
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2004	2002
	FIADB 4.0, 2009	2007
Idaho, Caribou-Targhee NF	Westwide, 1991	1992
	FIADB 4.0, 2009	2007
Idaho, Kootenai NF	1987 RPA	1988
	FIADB 4.0, 1991	1995
	FIADB 4.0, 2009	2007
Idaho, Payette NF	1987 RPA	1982
	FIADB 4.0, 2009	2007
Idaho, Salmon-Challis NF	1987 RPA	1978
	FIADB 4.0, 2009	2007
Idaho, Sawtooth NF	Westwide, 1991	1983
	FIADB 4.0, 1991	1996
	FIADB 4.0, 2009	2007
Idaho, non-NFS non-woodlands	FIADB 4.0, 1991	1990
	FIADB 4.0, 2009	2007

Idaho, non-NFS woodlands	FIADB 4.0, 1991	1982
	FIADB 4.0, 2009	2007
Idaho, other NFS	Westwide, 1991	1988
	FIADB 4.0, 1991	2000
	FIADB 4.0, 2009	2007
Illinois	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2009	2007
Indiana	FIADB 4.0, 1986	1986
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2003	2001
	FIADB 4.0, 2008	2007
Iowa	FIADB 4.0, 1990	1990
	FIADB 4.0, 2003	2002
	FIADB 4.0, 2008	2006
Kansas	FIADB 4.0, 1981	1981
	FIADB 4.0, 1994	1994
	FIADB 4.0, 2005	2003
	FIADB 4.0, 2009	2007
Kentucky	FIADB 4.0, 1988	1987
	FIADB 4.0, 2004	2002
	FIADB 4.0, 2009	2008
Louisiana	FIADB 4.0, 1984	1984
	FIADB 4.0, 1991	1991
	FIADB 4.0, 2005	2004
Maine	Eastwide, 1982	1983
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2003	2002
	FIADB 4.0, 2008	2007
Maryland	FIADB 4.0, 1986	1986
	FIADB 4.0, 1999	2000
	FIADB 4.0, 2008	2007
Massachusetts	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2007	2006
	FIADB 4.0, 2010	2009
Michigan	FIADB 4.0, 1980	1980
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2009	2007
Minnesota	FIADB 4.0, 1990	1989
	FIADB 4.0, 2003	2001
	FIADB 4.0, 2008	2006
Mississippi	FIADB 4.0, 1987	1987
	FIADB 4.0, 1994	1994
	FIADB 4.0, 2006	2007
Missouri	FIADB 4.0, 1989	1988
	FIADB 4.0, 2003	2002

	FIADB 4.0, 2008	2006
Montana, NFS	1987 RPA	1988
	FIADB 4.0, 1989	1996
	FIADB 4.0, 2009	2007
Montana, non-NFS non-reserved	FIADB 4.0, 1989	1989
	FIADB 4.0, 2009	2006
Montana, non-NFS reserved	1997 RPA	1990
	FIADB 4.0, 2009	2007
Nebraska	FIADB 4.0, 1983	1983
	FIADB 4.0, 1994	1995
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2010	2008
Nevada, NFS non-woodlands	1987 RPA	1974
	FIADB 4.0, 1989	1997
	FIADB 4.0, 2005	2005
Nevada, NFS woodlands	1987 RPA	1978
	FIADB 4.0, 1989	1997
	FIADB 4.0, 2005	2005
Nevada, non-NFS non-woodlands	1997 RPA	1985
	FIADB 4.0, 2005	2005
Nevada, non-NFS woodlands	FIADB 4.0, 1989	1980
	FIADB 4.0, 2005	2005
New Hampshire	FIADB 4.0, 1983	1983
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2007	2005
	FIADB 4.0, 2010	2009
New Jersey	FIADB 4.0, 1987	1987
	FIADB 4.0, 1999	1999
	FIADB 4.0, 2008	2007
New Mexico, NFS non-woodlands	1987 RPA	1986
	FIADB 4.0, 1999	1997
New Mexico, NFS woodlands	1987 RPA	1986
	FIADB 4.0, 1999	1997
New Mexico, non-NFS non-woodlands	FIADB 4.0, 1987	1987
	FIADB 4.0, 1999	1999
New Mexico, non-NFS woodlands	FIADB 4.0, 1999	1989
New York, non-reserved	Eastwide, 1980	1981
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2007	2005
New York, reserved	1987 RPA	1988
	FIADB 4.0, 2007	2005
North Carolina	FIADB 4.0, 1984	1984
	FIADB 4.0, 1990	1990
	FIADB 4.0, 2002	2001
	FIADB 4.0, 2007	2006
North Dakota	FIADB 4.0, 1980	1979
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2005	2003

	FIADB 4.0, 2010	2009
Ohio	FIADB 4.0, 1991	1991
	FIADB 4.0, 2006	2005
	FIADB 4.0, 2009	2008
Oklahoma, Central & West	FIADB 4.0, 2010	2010
Oklahoma, East	FIADB 4.0, 1986	1986
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2008	2008
Oregon, NFS East	IDB, 1990s	1995
	FIADB 4.0, 2009	2006
Oregon, NFS West	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Oregon, non-NFS East	Westwide, 1992	1991
	IDB, 1990s	1999
	FIADB 4.0, 2009	2005
Oregon, non-NFS West	Westwide, 1992	1989
	IDB, 1990s	1997
	FIADB 4.0, 2009	2006
Pennsylvania	FIADB 4.0, 1989	1990
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2009	2008
Rhode Island	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1999
	FIADB 4.0, 2007	2006
	FIADB 4.0, 2010	2009
South Carolina	FIADB 4.0, 1986	1986
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2001	2001
	FIADB 4.0, 2006	2005
	FIADB 4.0, 2010	2008
South Dakota, NFS	1997 RPA	1986
	FIADB 4.0, 1995	1999
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2010	2009
South Dakota, non-NFS	1987 RPA	1986
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2010	2008
Tennessee	FIADB 4.0, 1989	1989
	FIADB 4.0, 1999	1998
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2009	2008
Texas, Central & West	FIADB 4.0, 2009	2007
Texas, East	FIADB 4.0, 1986	1986
	FIADB 4.0, 1992	1992
	FIADB 4.0, 2003	2003
	FIADB 4.0, 2008	2006
Utah, non-woodlands	FIADB 4.0, 1993	1993
	FIADB 4.0, 2009	2005

Utah, woodlands	FIADB 4.0, 1993	1994
	FIADB 4.0, 2009	2005
Vermont	FIADB 4.0, 1983	1983
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2007	2006
	FIADB 4.0, 2010	2009
Virginia	FIADB 4.0, 1985	1985
	FIADB 4.0, 1992	1991
	FIADB 4.0, 2001	2000
	FIADB 4.0, 2007	2005
	FIADB 4.0, 2010	2009
Washington, NFS East	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Washington, NFS West	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Washington, non-NFS East	IDB, 1990s	1992
	FIADB 4.0, 2009	2006
Washington, non-NFS West	IDB, 1990s	1990
	FIADB 4.0, 2009	2006
West Virginia	FIADB 4.0, 1989	1988
	FIADB 4.0, 2000	2001
	FIADB 4.0, 2008	2007
Wisconsin	FIADB 4.0, 1983	1982
	FIADB 4.0, 1996	1995
	FIADB 4.0, 2004	2002
	FIADB 4.0, 2009	2007
Wyoming, NFS	1997 RPA	1982
	FIADB 4.0, 2000	2000
Wyoming, non-NFS non-reserved non-woodlands	FIADB 4.0, 1984	1984
	FIADB 4.0, 2000	2002
Wyoming, non-NFS non-reserved woodlands	FIADB 4.0, 1984	1984
	FIADB 4.0, 2000	2002
Wyoming, non-NFS reserved	1997 RPA	1985
	FIADB 4.0, 2000	2000

[a] Substate areas (Smith et al. 2010) include National Forests (NFS), all forest ownerships except National Forest (non-NFS), woodlands (forest land dominated by woodland species, such as pinyon and juniper, where stocking cannot be determined (USDA Forest Service 2011c)), non-woodlands (used for clarity to emphasize that woodlands are classified separately), reserved (forest land withdrawn from timber utilization through statute, administrative regulation, or designation, Smith et al. (2009)), and non-reserved (forest land that is not reserved, used for clarity). Some National Forests are listed individually by name, e.g., Payette NF. Oregon and Washington were divided into eastern and western forests (east or west of the crest of the Cascade Mountains). Oklahoma and Texas are divided into East versus Central & West according to forest inventory survey units (USDA Forest Service 2011d). Alaska is represented by a portion of forest land, in the southcentral and southeast part of the state.

[b] FIADB 4.0 is the current, publicly available, format of FIA inventory data, and these files were downloaded from the Internet 17 August 2011 (USDA Forest Service 2011b). IDB (Integrated Database) data are a compilation of periodic inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). Eastwide (Hansen et al. 1992) and Westwide (Woudenberg and Farrenkopf 1995) inventory data are formats that predate the FIADB data. RPA data are periodic national summaries. The year is the nominal, or reporting, year associated with each dataset.

[c] Average year is based on average measurement year of forest land survey plots and rounded to the nearest integer year.

A new national plot design and annualized sampling (USDA Forest Service 2011a) was introduced by FIA with most new surveys beginning after 1998. These surveys include sampling of all forest land including reserved and lower productivity lands. Most states have annualized inventory data available as of August 2011. Annualized sampling means that a portion of plots throughout the state is sampled each year, with the goal of measuring all plots once every 5 to 10 years, depending on the region of the United States. The full unique set of data with all measured plots, such that each plot has been measured one time, is called a cycle. Sampling is designed such that partial inventory cycles provide usable, unbiased samples of forest inventory, but with higher sampling errors than the full cycle. After all plots have been measured once, the sequence continues with remeasurement of the first year's plots, starting the next new cycle. Most Eastern states have completed one or two cycles of the annualized inventories and are providing annual updates to the state's forest inventory with each year's remeasurements, such that one plot's measurements are included in subsequent year's annual updates. Thus, annually updated estimates of forest C stocks are accurate, but estimates of stock change cannot utilize the annually updated inventory measurements directly, as there is redundancy in the data used to generate the annual updates of C stock. For example, a typical annual inventory update for an eastern state will include new data from remeasurement on 20 percent of plots; data from the remaining 80 percent of plots is identical to that included in the previous year's annual update. The interpretation and use of the sequence of annual inventory updates can affect trends in annualized stock and stock change. In general, the C stock and stock change calculations use annual inventory summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update is the exception because it is included in stock change calculations if at least half of the plots in a state include new measurements. Table A-219 lists the specific surveys used in this report, and this list can be compared with the full set of summaries available for download (USDA Forest Service 2011b).

For each pool in each state in each year, C stocks are estimated by linear interpolation between survey years. Similarly, fluxes, or net stock changes, are estimated for each pool in each state by dividing the difference between two successive stocks by the number of intervening years between surveys. Thus, the number of separate stock change estimates for each state or sub-state is one less than the number of available inventories. Annual estimates of stock and net change since the most recent survey are based on linear extrapolation. C stock and flux estimates for each pool are summed over all forest land in all states as identified in to form estimates for the United States. Summed net annual stock change and stock are presented in Table A-219 and Table A-220 , respectively. Table A-221 also provides an estimate of forest area based on the interpolation and extrapolation procedure described above. Estimated net stock change of non-soil forest ecosystem carbon for each of the states is shown in Table A-222, which also includes estimated forest area and total non-soil forest carbon stock. The state-level forest areas and carbon stocks are from the most recent inventory available (USDA Forest Service 2011a), and the estimate for net stock change is the mean of the 2000 through 2010 estimates from the carbon calculator (Smith et al. 2010).

Table A-220: Net Annual Changes in Carbon Stocks (Tg C yr^{-1}) in Forest and Harvested Wood Pools, 1990–2010

Carbon Pool	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest	(155.3)	(154.8)	(152.6)	(145.6)	(153.0)	(149.5)	(148.2)	(137.6)	(122.7)	(104.2)	(100.5)	(140.4)	(183.9)	(215.6)	(223.8)	(227.9)	(233.2)	(233.5)	(233.5)	(233.5)	(233.5)
Live, aboveground	(94.3)	(94.1)	(94.8)	(95.3)	(99.3)	(100.3)	(98.7)	(99.9)	(94.5)	(90.7)	(90.1)	(103.2)	(110.6)	(116.5)	(118.5)	(121.4)	(123.2)	(123.3)	(123.3)	(123.3)	(123.3)
Live, belowground	(18.5)	(18.5)	(18.6)	(18.8)	(19.6)	(19.8)	(19.5)	(19.8)	(18.7)	(18.1)	(17.9)	(20.4)	(21.8)	(23.0)	(23.4)	(23.9)	(24.3)	(24.3)	(24.3)	(24.3)	(24.3)
Dead Wood	(15.9)	(16.1)	(15.9)	(14.6)	(14.7)	(10.4)	(15.2)	(12.2)	(11.7)	(11.3)	(11.6)	(13.7)	(18.4)	(19.5)	(19.6)	(19.5)	(20.0)	(20.1)	(20.1)	(20.1)	(20.1)
Litter	(6.0)	(5.9)	(5.9)	(5.0)	(4.5)	(2.9)	(3.3)	(3.6)	0.3	4.0	5.9	0.6	(6.1)	(10.3)	(12.1)	(12.7)	(14.1)	(14.2)	(14.2)	(14.2)	(14.2)
Soil Organic Carbon	(20.7)	(20.3)	(17.4)	(11.9)	(14.9)	(16.1)	(11.3)	(2.1)	1.9	11.8	13.2	(3.6)	(26.9)	(46.3)	(50.2)	(50.4)	(51.6)	(51.6)	(51.6)	(51.6)	(51.6)
Harvested Wood	(35.9)	(33.8)	(33.8)	(32.9)	(33.4)	(32.3)	(30.6)	(32.0)	(31.1)	(32.5)	(30.8)	(25.5)	(26.8)	(25.9)	(28.7)	(28.7)	(29.6)	(28.1)	(22.4)	(14.8)	(17.9)
Products in Use	(17.7)	(14.9)	(16.3)	(15.0)	(15.9)	(15.1)	(14.1)	(14.7)	(13.4)	(14.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.4)	(12.3)	(10.7)	(5.2)	1.8	(1.2)
SWDS	(18.3)	(18.8)	(17.4)	(17.9)	(17.5)	(17.2)	(16.5)	(17.3)	(17.7)	(18.4)	(18.0)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)	(16.7)
Total Net Flux	(191.3)	(188.6)	(186.3)	(178.5)	(186.4)	(181.8)	(178.8)	(169.6)	(153.8)	(136.7)	(131.3)	(165.9)	(210.6)	(241.4)	(252.6)	(256.6)	(262.8)	(261.6)	(255.9)	(248.3)	(251.4)

Table A-221: Carbon Stocks (Tg C) in Forest and Harvested Wood Pools, 1990–2011

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Forest Area (1000 ha)	271,866	272,509	273,157	273,778	274,358	274,932	275,500	276,014	276,484	276,957	277,317	277,622	277,997	278,518	279,211	279,954	280,697	281,451	282,205	282,959	283,713	284,467
Carbon Pool																						
Forest	39,108	39,263	39,418	39,571	39,716	39,869	40,019	40,167	40,304	40,427	40,531	40,632	40,772	40,956	41,172	41,395	41,623	41,857	42,090	42,324	42,557	42,791
Live, aboveground	12,426	12,520	12,614	12,709	12,804	12,904	13,004	13,103	13,203	13,297	13,388	13,478	13,581	13,692	13,808	13,927	14,048	14,171	14,295	14,418	14,541	14,665
Live, belowground	2,458	2,476	2,495	2,514	2,532	2,552	2,572	2,591	2,611	2,630	2,648	2,666	2,686	2,708	2,731	2,755	2,778	2,803	2,827	2,851	2,876	2,900
Dead Wood	2,307	2,322	2,338	2,354	2,369	2,384	2,394	2,409	2,422	2,433	2,444	2,456	2,470	2,488	2,508	2,527	2,547	2,567	2,587	2,607	2,627	2,647
Litter	4,817	4,823	4,829	4,835	4,840	4,845	4,847	4,851	4,854	4,854	4,850	4,844	4,844	4,850	4,860	4,872	4,885	4,899	4,913	4,927	4,941	4,955
Soil Organic Carbon	17,100	17,121	17,141	17,159	17,170	17,185	17,201	17,213	17,215	17,213	17,201	17,188	17,192	17,218	17,265	17,315	17,365	17,417	17,469	17,520	17,572	17,624
Harvested Wood	1,859	1,895	1,963	1,996	2,029	2,061	2,092	2,124	2,155	2,187	2,218	2,244	2,271	2,296	2,325	2,354	2,383	2,412	2,434	2,449	2,466	2,487
Products in Use	1,231	1,249	1,280	1,295	1,311	1,326	1,340	1,355	1,368	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,460	1,471	1,476	1,474	1,475	1,479
SWDS	628	646	683	701	718	735	752	769	787	805	823	840	857	873	890	906	923	941	958	974	991	1,008
Total Carbon Stock	40,967	41,158	41,381	41,566	41,745	41,930	42,111	42,291	42,459	42,615	42,750	42,876	43,043	43,252	43,497	43,749	44,007	44,268	44,524	44,772	45,023	45,278

Table A-222: State-level forest area, carbon stock, and net annual stock change. Estimates are forest ecosystem carbon and do not include harvested wood

State	Mean year of field data collection	Forest area (1000 ha)	Nonsoil C stock (Tg C)	Mean net annual nonsoil stock change 2000–2010 (Tg C/yr)
Alabama	2007	9,233	656	(5.7)
Alaska	2007	6,039	963	(3.6)
Arizona	2006	7,572	392	0.4
Arkansas	2008	7,576	566	(4.7)
California	2006	13,333	1,816	(9.9)
Colorado	2006	9,294	758	(2.7)
Connecticut	2009	683	82	(0.1)
Delaware	2008	138	16	(0.2)
Florida	2008	7,010	436	(2.7)
Georgia	2008	10,030	771	(6.4)
Idaho	2007	8,656	918	0.3
Illinois	2007	1,968	168	(3.3)
Indiana	2009	1,932	183	(3.1)
Iowa	2008	1,225	88	(2.2)
Kansas	2007	922	59	(1.1)
Kentucky	2009	5,023	450	(4.1)
Louisiana	2004	5,722	411	(2.3)
Maine	2009	7,149	620	(1.1)
Maryland	2008	993	122	(1.1)
Massachusetts	2009	1,220	151	(0.9)
Michigan	2008	8,095	687	(5.9)
Minnesota	2008	6,997	437	(3.8)
Mississippi	2008	7,921	571	(8.0)
Missouri	2008	6,270	470	(8.8)
Montana	2007	10,356	973	(8.3)
Nebraska	2008	615	38	(1.0)
Nevada	2005	4,520	192	(1.3)
New Hampshire	2009	1,953	223	(1.0)
New Jersey	2008	803	79	(0.5)
New Mexico	1994	6,753	380	(0.3)
New York	2008	7,674	853	(6.9)
North Carolina	2007	7,528	674	(3.8)
North Dakota	2009	313	16	(0.1)
Ohio	2008	3,246	328	(3.5)
Oklahoma	2009	5,104	236	(1.4)
Oregon	2006	12,163	1,798	(9.5)
Pennsylvania	2008	6,774	739	(6.2)
Rhode Island	2009	142	16	(0.2)
South Carolina	2008	5,302	431	(6.1)
South Dakota	2009	762	43	(0.6)
Tennessee	2009	5,647	535	(4.3)
Texas	2007	25,621	852	(2.2)
Utah	2005	7,396	425	(4.5)
Vermont	2009	1,854	222	(0.9)
Virginia	2009	6,422	618	(4.6)
Washington	2006	9,057	1,563	(8.9)
West Virginia	2008	4,889	546	(8.6)
Wisconsin	2008	6,828	515	(5.3)
Wyoming	2001	4,633	415	(1.1)

Table A-223 shows average C density values for forest ecosystem C pools according to region and forest types based on forest lands in this Inventory. These values were calculated by applying plot-level C estimation procedures as described below to the most recent inventory per state as available 17 August 2011 (USDA Forest Service 2011b). C density values reflect the most recent survey for each state as available in the FIADB, not potential maximum C storage. C densities are affected by the distribution of stand sizes within a forest type, which can range from regenerating to mature stands. A large proportion of young stands in a particular forest type are likely to reduce the regional average for C density.

Table A-223: Average carbon density (Mg C/ha) by carbon pool and forest area (1000 ha) according to region and forest type, based on the most recent inventory survey available for each state from FIA, corresponding to an average year of 2007

Region (States) Forest Types	**Aboveground Biomass**	**Belowground Biomass**	**Dead Wood**	**Litter**	**Soil Organic Carbon**	**Forest Area**
		Carbon Density (Mg C/ha)				**(1,000 ha)**
Northeast						
(CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV)						
White/Red/Jack Pine	77.7	16.0	9.0	13.7	78.1	1,619
Spruce/Fir	38.6	8.1	9.1	30.7	98.0	3,023
Oak/Pine	70.2	13.8	7.7	27.8	66.9	1,230
Oak/Hickory	76.9	14.5	8.5	8.1	53.1	13,013
Elm/Ash/Cottonwood	53.3	10.1	7.3	6.9	111.7	1,450
Maple/Beech/Birch	70.3	13.5	8.9	27.2	69.6	13,683
Aspen/Birch	40.4	7.9	7.2	8.6	87.4	1,647
Minor Types and Nonstocked	45.2	8.9	8.5	11.0	73.7	1,854
All	67.1	12.9	8.6	17.9	69.0	37,519
Northern Lake States						
(MI,MN,WI)						
White/Red/Jack Pine	45.3	9.4	7.3	12.4	120.8	1,852
Spruce/Fir	28.7	6.0	6.3	33.2	261.8	3,195
Oak/Hickory	54.1	10.2	9.1	8.0	97.1	3,902
Elm/Ash/Cottonwood	41.6	7.9	6.3	7.6	179.9	2,196
Maple/Beech/Birch	58.3	11.1	8.8	27.6	134.3	4,358
Aspen/Birch	31.4	6.0	6.9	8.3	146.1	5,269
Minor Types and Nonstocked	28.0	5.5	7.5	17.9	121.0	1,148
All	42.4	8.2	7.6	16.5	151.8	21,921
Northern Prairie States						
(IA,IL,IN,KS,MO,ND,NE,SD)						
Ponderosa Pine	34.0	7.1	5.6	14.4	48.5	554
Oak/Pine	40.0	7.7	6.0	25.8	40.5	567
Oak/Hickory	52.2	9.8	7.9	7.8	49.4	9,539
Elm/Ash/Cottonwood	54.8	10.2	8.8	6.9	83.2	2,014
Minor Types and Nonstocked	30.9	6.0	6.7	17.9	60.3	1,334
All	49.3	9.3	7.7	9.6	54.9	14,008
South Central						
(AL,AR,KY,LA,MS,OK,TN,TX)						
Loblolly/Shortleaf Pine	47.2	9.7	6.4	9.6	41.9	13,437
Pinyon/Juniper	12.0	2.2	2.3	12.3	37.7	3,976
Oak/Pine	43.5	8.5	5.6	9.3	41.7	5,142
Oak/Hickory	47.5	8.9	6.0	6.4	38.6	25,400
Oak/Gum/Cypress	63.9	12.2	7.2	6.5	52.8	5,159
Elm/Ash/Cottonwood	38.1	7.2	5.0	5.9	49.9	4,093
Woodland Hardwoods	9.8	1.6	1.2	5.0	65.0	9,698
Minor Types and Nonstocked	28.2	5.5	5.2	6.9	54.1	4,940
All	39.4	7.6	5.2	7.4	45.7	71,845
Southeast						
(FL,GA,NC,SC,VA)						
Longleaf/Slash Pine	40.5	8.3	6.1	9.9	110.0	4,173
Loblolly/Shortleaf Pine	51.7	10.7	7.6	9.6	72.9	9,170
Oak/Pine	49.9	9.8	6.0	9.3	61.4	4,095
Oak/Hickory	64.1	12.1	7.4	6.5	45.3	11,877
Oak/Gum/Cypress	63.8	12.4	7.6	6.5	158.0	4,658
Elm/Ash/Cottonwood	48.2	9.1	6.3	5.6	95.7	866
Minor Types and Nonstocked	31.9	6.1	8.0	5.7	110.6	1,452
All	54.9	10.7	7.2	7.9	79.8	36,292

Coastal Alaska (approximately 12 percent of forest land in Alaska)						
Spruce/Fir	15.3	3.0	7.6	33.8	62.1	364
Fir/Spruce/Mountain Hemlock	64.3	13.5	16.6	43.2	62.1	2,168
Hemlock/Sitka Spruce	116.1	24.4	27.2	50.6	116.3	2,753
Aspen/Birch	26.9	5.0	8.6	10.7	42.5	302
Minor Types and Nonstocked	25.3	4.8	8.6	20.1	74.9	452
All	80.1	16.8	19.9	42.7	86.8	6,039
Pacific Northwest, Westside (Western OR and WA)						
Douglas-fir	137.8	28.9	31.4	32.0	94.8	5,937
Fir/Spruce/Mountain Hemlock	131.4	27.7	31.8	38.4	62.1	1,176
Hemlock/Sitka Spruce	173.0	36.5	40.5	37.8	116.3	1,566
Alder/Maple	77.2	15.0	16.6	7.6	115.2	1,187
Minor Types and Nonstocked	57.9	11.4	16.1	13.4	85.6	1,248
All	126.6	26.4	29.4	28.8	95.5	11,114
Pacific Northwest, Eastside (Eastern OR and WA)						
Douglas-fir	62.9	13.1	15.5	36.3	94.8	2,064
Ponderosa Pine	40.8	8.4	9.9	22.5	50.7	2,709
Fir/Spruce/Mountain Hemlock	76.1	16.0	25.0	38.0	62.1	1,766
Lodgepole Pine	36.9	7.8	12.2	21.1	52.0	1,036
Western Larch	69.8	14.6	18.4	35.7	45.1	204
Other Western Softwoods	11.6	2.1	3.8	36.2	78.8	1,249
Minor Types and Nonstocked	27.5	5.4	14.2	24.5	81.2	1,077
All	46.6	9.7	13.8	30.1	68.4	10,106
Pacific Southwest (CA)						
Pinyon/Juniper	14.5	2.7	2.9	21.1	26.3	675
Douglas-fir	143.4	29.7	28.3	35.7	40.1	440
Ponderosa Pine	53.5	11.1	12.4	22.4	41.3	897
Fir/Spruce/Mountain Hemlock	110.6	23.3	33.5	38.3	51.9	818
Redwood	241.6	50.4	58.9	60.5	53.8	299
Other Western Softwoods	24.6	4.7	7.1	37.7	49.8	764
California Mixed Conifer	104.5	21.9	23.9	37.9	49.8	3,155
Western Oak	51.0	9.7	5.2	29.7	27.6	3,690
Tanoak/Laurel	119.7	23.5	11.3	28.0	27.6	829
Minor Types and Nonstocked	39.0	7.7	17.6	24.0	36.8	1,767
All	74.1	15.0	15.8	31.7	38.7	13,333
Rocky Mountain, North (ID,MT)						
Douglas-fir	51.5	10.8	11.3	37.0	38.8	5,587
Ponderosa Pine	31.2	6.4	6.9	22.9	34.3	1,865
Fir/Spruce/Mountain Hemlock	54.2	11.4	19.5	37.4	44.1	4,471
Lodgepole Pine	47.0	10.0	14.6	23.1	37.2	2,761
Western Larch	67.3	14.2	14.2	36.3	34.2	492
Other Western Softwoods	29.9	6.2	11.3	39.3	31.4	649
Aspen/Birch	23.1	4.3	13.3	26.8	56.6	533
Minor Types and Nonstocked	24.1	4.8	17.2	22.5	42.9	2,655
All	44.5	9.3	14.2	31.4	40.1	19,012
Rocky Mountain, South (AZ,CO,NM,NV,UT,WY)						
Pinyon/Juniper	15.6	3.1	1.7	21.1	19.7	18,738
Douglas-fir	49.7	10.5	11.9	38.1	30.9	1,797
Ponderosa Pine	35.5	7.4	6.5	23.6	24.1	3,570
Fir/Spruce/Mountain Hemlock	56.8	12.0	18.8	38.8	31.5	4,262
Lodgepole Pine	47.9	10.2	18.4	24.0	27.0	2,024
Aspen/Birch	40.8	7.8	10.3	28.5	58.8	2,555
Woodland Hardwoods	16.7	3.0	4.9	28.2	25.9	4,135
Minor Types and Nonstocked	12.9	2.4	8.9	22.6	25.4	3,088
All	26.4	5.3	6.6	25.4	25.8	40,168
United States (forest land	**50.5**	**10.0**	**9.1**	**17.4**	**62.0**	**281,356**

included in Inventory)

Note: The forest area values in this table do not equal the forest area values reported in Table A-221, because the forest area values in this table are estimated using the most recent dataset per state, with an average year of 2007. The time series of forest area values reported in Table A-221, in contrast, is constructed following the CCT methods used to construct the carbon stock series. The forest area values reported in Table A-221 and Table A-223 would only be identical if all states were measured simultaneously or they all had identical rates of change.

The Inventory is derived primarily from the current FIADB 4.0 data (USDA Forest Service 2011b), but it also draws on older FIA survey data where necessary. The Resources Planning Act Assessment (RPA) database, which includes periodic summaries of state inventories, is one example. Information about the RPA data is available on the Internet (USDA Forest Service 2011a, see Program Features), and compilations of analytical estimates based on these databases are found in Waddell et al. (1989) and Smith et al. (2001). The basic difference between the RPA database and the FIADB is that the FIADB includes some informative additional details such as individual-tree data. Having only plot-level information (such as volume per hectare) limits the conversion to biomass. This does not constitute a substantial difference for the overall state-wide estimates, but it does affect plot-level precision (Smith et al. 2004). In the past, FIA made their data available in tree-level Eastwide (Hansen et al. 1992) or Westwide (Woudenberg and Farrenkopf 1995) formats, which included inventories for Eastern and Western states, respectively. The current Inventory estimates rely in part on older tree-level data that are not available on the current FIADB site. The Integrated Database (IDB) is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). These data were identified by Heath et al. (2011) as the most appropriate non-FIADB sources for these three states.

An historical focus of the FIA program was to provide information on timber resources of the United States. For this reason, prior to 1998, some forest land, which were less productive or reserved (i.e., land where harvesting was prohibited by law), were less intensively surveyed. This generally meant that on these less productive lands, forest type and area were identified but data were not collected on individual tree measurements. The practical effect that this evolution in inventories has had on estimating forest C stocks from 1990 through the present is that some older surveys of lands do not have the individual-tree data or even stand-level characteristics such as stand age. Any data gaps identified in the surveys taken before 1998 were filled by assigning average C densities calculated from the more complete, later inventories from the respective states. The overall effect of this necessary approach to generate estimates for C stock is that no net change in C density occurs on those lands with gaps in past surveys. This approach to filling gaps in older data also extends to timberlands where individual-tree data as not available (e.g., standing dead trees).

Estimating C stocks from forest inventory data

For each inventory summary in each state, data are converted to C units or augmented by other ecological data. Most of the conversion factors and models used for inventory-based forest carbon estimates (Smith et al. 2010, Heath et al. 2011) were intitially developed as an offshoot of the forest carbon simulation model FORCARB (Heath et al. 2010) and are incorporated into a number of applications (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004, Hoover and Rebain 2008). The conversion factors and model coefficients are usually categorized by region, and forest type. Classifications for both region and forest type are subject to change depending on the particular coefficient set. Thus, region and type are specifically defined for each set of estimates. Factors are applied to the survey data at the scale of FIA inventory plots. The results are estimates of C density (Mg per hectare) for the various forest pools. C density for live trees, standing dead trees, understory vegetation, down dead wood, litter, and soil organic matter are estimated. All non-soil pools except litter can be separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass in this inventory. Similarly, standing dead trees and down dead wood are pooled as dead wood in this inventory. C stocks and fluxes for *Forest Land Remaining Forest Land* are reported in pools following IPCC (2003).

Live tree C pools

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. The value for sound volume provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree. The estimated volumes of wood and bark are converted to biomass based on density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates of Jenkins et al. (2003). Live trees with d.b.h of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process. An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. C is calculated by multiplying biomass by 0.5 because biomass is 50 percent of dry weight (IPCC/UNEP/OECD/IEA 1997). Further discussion and example calculations are provided in Woodall et al. 2011.

Some of the older forest inventory data in use for these estimates do not provide measurements of individual trees. Examples of these data include plots with incomplete or missing tree data (e.g., some of the non-timberland plots in older surveys) or the RPA plot-level summaries. The C estimates for these plots are based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 5 percent of the forest land inventory-plot-to-carbon conversions within the 177 state-level surveys utilized here.

Understory vegetation

Understory vegetation is a minor component of biomass. Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch d.b.h. In this inventory, it is assumed that 10 percent of understory C mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in IPCC (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter.

Estimates of C density are based on information in Birdsey (1996), which was applied to FIA permanent plots. These were fit to the equation:

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density}))}$$

In this equation, “ratio” is the ratio of understory C density (Mg C/ha) to live tree C density (above- and belowground) according to Jenkins et al. (2003) and expressed in Mg C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients is in Table A-224. Regions and forest types are the same classifications described in Smith et al. (2003). As an example, the basic calculation for understory C in aspen-birch forests in the Northeast is:

$$\text{Understory (Mg C/ha)} = (\text{live tree C density}) \times e^{(0.855 - 1.03 \times \ln(\text{tree C density}))}$$

This calculation is followed by three possible modifications. First, the maximum value for the ratio is set to 2.02 (see value in column “maximum ratio”); this also applies to stands with zero tree C, which is undefined in the above equation. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked and pinyon/juniper stands are set to coefficient A, which is a C density (Mg C/ha) for these types only.

Table A-224: Coefficients for estimating the ratio of carbon density of understory vegetation (above- and belowground, MgC/ha)[a] by region and forest type. The ratio is multiplied by tree carbon density on each plot to produce understory vegetation

Region[b]	Forest Type[b]	A	B	Maximum ratio[c]
NE	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
	Oak-Hickory	0.842	1.053	2.057
	Oak-Pine	1.960	1.235	4.203
	Other Pine	2.149	1.268	4.191
	Spruce-Fir	0.825	1.121	2.140
	White-Red-Jack Pine	1.000	1.116	2.098
	Nonstocked	2.020	2.020	2.060
NLS	Aspen-Birch	0.777	1.018	2.023
	Lowland Hardwood	0.650	0.997	2.037
	Maple-Beech-Birch	0.863	1.120	2.129
	Oak-Hickory	0.965	1.091	2.072
	Pine	0.740	1.014	2.046
	Spruce-Fir	1.656	1.318	2.136
	Nonstocked	1.928	1.928	2.117
NPS	Conifer	1.189	1.190	2.114
	Lowland Hardwood	1.370	1.177	2.055
	Maple-Beech-Birch	1.126	1.201	2.130
	Oak-Hickory	1.139	1.138	2.072
	Oak-Pine	2.014	1.215	4.185
	Nonstocked	2.052	2.052	2.072

PSW	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
	Other Conifer	4.032	1.785	4.768
	Pinyon-Juniper	4.430	4.430	4.820
	Redwood	2.513	1.312	4.698
	Nonstocked	4.431	4.431	4.626
PWE	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
	Lodgepole Pine	1.790	1.257	4.823
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	1.768	1.213	4.768
	Nonstocked	4.315	4.315	4.626
PWW	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
	Other Hardwoods	2.157	1.220	4.745
	Red Alder	2.094	1.230	4.745
	Western Hemlock	2.081	1.218	4.693
	Nonstocked	4.401	4.401	4.589
RMN	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
	Lodgepole Pine	2.571	1.500	4.773
	Other Conifer	2.614	1.518	4.821
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	2.099	1.344	4.776
	Nonstocked	4.430	4.430	4.773
RMS	Douglas-fir	5.145	2.232	4.829
	Fir-Spruce	2.861	1.568	4.822
	Hardwoods	1.858	1.110	4.745
	Lodgepole Pine	3.305	1.737	4.797
	Other Conifer	2.134	1.382	4.821
	Pinyon-Juniper	2.757	2.757	4.820
	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
SC	Bottomland Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
	Oak-Pine	1.903	1.190	4.173
	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
SE	Bottomland Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
	Oak-Pine	1.642	1.117	4.195
	Planted Pine	1.470	1.036	4.141
	Upland Hardwood	1.903	1.191	4.182
	Nonstocked	4.033	4.033	4.182

[a] Prediction of ratio of understory C to live tree C is based on the equation: Ratio=exp(A − B × ln(tree_carbon_tph)), where “ratio” is the ratio of understory C density to live tree (above-and below- ground) C density, and “tree_carbon_density” is live tree (above-and below- ground) C density in Mg C/ha.

[b] Regions and types as defined in Smith et al. (2003).

[c] Maximum ratio: any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio.

Dead Wood

The standing dead tree C pools include aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm d.b.h. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can significantly affect C mass are decay, which affects density and thus specific C content (Domke et al.

2011, Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). Dry weight to C mass conversion is by multiplying by 0.5.

Some of the older forest inventory data in use for these estimates do not provide measurements of individual standing dead trees. In addition to the RPA data, which are plot-level summaries, some of the older surveys that otherwise include individual-tree data may not completely sample dead trees on non-timberlands and in some cases timberlands. The C estimates for these plots are based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 26 percent of the forest land inventory-plot-to-carbon conversions within the 177 state-level surveys utilized here.

Down dead wood, inclusive of logging residue, are currently sampled on a subset of FIA plots. However, population estimation algorithms for these data are still in development. Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. Down dead wood includes stumps and roots of harvested trees. Ratio estimates of down dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for down dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in . An additional component of down dead wood is a regional average estimate of logging residue based on Smith et al. (2006) applied at the plot level. These are based on a regional average C density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-225. These amounts are added to explicitly account for down dead wood following harvest. In practice, this modification resulted in minor changes to the estimates. Example calculations of the two components for down dead wood in 25-year-old aspen-birch forests in the Northeast are:

C density (Mg C/ha) = (live tree C density, above- and below-ground) × (0.078) = 7.8% of live tree C

Conversion to C units is not necessary because the live tree value is already in terms of C.

C density additional for logging residue (Mg C/ha) = $13.9 \times e^{(-25/12.1)} = 1.8$ (Mg C/ha)

Where live tree C density is according to Jenkins et al. (2003) and expressed as Mg C/ha.

Table A-225: Ratio for estimating down dead wood by region and forest type. The ratio is multiplied by the live tree carbon density on a plot to produce down dead wood carbon density (MgC/ha)

Region[a]	Forest type[a]	Ratio	Region (cont'd)	Forest type (cont'd)	Ratio (cont'd)
NE	Aspen-Birch	0.078	PWW	Douglas-fir	0.100
	MBB/Other Hardwood	0.071		Fir-Spruce	0.090
	Oak-Hickory	0.068		Other Conifer	0.073
	Oak-Pine	0.061		Other Hardwoods	0.062
	Other Pine	0.065		Red Alder	0.095
	Spruce-Fir	0.092		Western Hemlock	0.099
	White-Red-Jack Pine	0.055		Nonstocked	0.020
	Nonstocked	0.019	RMN	Douglas-fir	0.062
NLS	Aspen-Birch	0.081		Fir-Spruce	0.100
	Lowland Hardwood	0.061		Hardwoods	0.112
	Maple-Beech-Birch	0.076		Lodgepole Pine	0.058
	Oak-Hickory	0.077		Other Conifer	0.060
	Pine	0.072		Pinyon-Juniper	0.030
	Spruce-Fir	0.087		Ponderosa Pine	0.087
	Nonstocked	0.027		Nonstocked	0.018
NPS	Conifer	0.073	RMS	Douglas-fir	0.077
	Lowland Hardwood	0.069		Fir-Spruce	0.079
	Maple-Beech-Birch	0.063		Hardwoods	0.064
	Oak-Hickory	0.068		Lodgepole Pine	0.098
	Oak-Pine	0.069		Other Conifer	0.060
	Nonstocked	0.026		Pinyon-Juniper	0.030
PSW	Douglas-fir	0.091		Ponderosa Pine	0.082
	Fir-Spruce	0.109		Nonstocked	0.020
	Hardwoods	0.042	SC	Bottomland Hardwood	0.063
	Other Conifer	0.100		Misc. Conifer	0.068
	Pinyon-Juniper	0.031		Natural Pine	0.068
	Redwood	0.108		Oak-Pine	0.072
	Nonstocked	0.022		Planted Pine	0.077
PWE	Douglas-fir	0.103		Upland Hardwood	0.067
	Fir-Spruce	0.106		Nonstocked	0.013

	Hardwoods	0.027	SE	Bottomland Hardwood	0.064
	Lodgepole Pine	0.093		Misc. Conifer	0.081
	Pinyon-Juniper	0.032		Natural Pine	0.081
	Ponderosa Pine	0.103		Oak-Pine	0.063
	Nonstocked	0.024		Planted Pine	0.075
				Upland Hardwood	0.059
				Nonstocked	0.012

[a] Regions and types as defined in Smith et al. (2003).

Table A-226: Coefficients for estimating logging residue component of down dead wood.

Region[a]	Forest Type Group[b] (softwood/hardwood)	Initial Carbon Density (Mg/ha)	Decay Coefficient
Alaska	hardwood	6.9	12.1
Alaska	softwood	8.6	32.3
NE	hardwood	13.9	12.1
NE	softwood	12.1	17.9
NLS	hardwood	9.1	12.1
NLS	softwood	7.2	17.9
NPS	hardwood	9.6	12.1
NPS	softwood	6.4	17.9
PSW	hardwood	9.8	12.1
PSW	softwood	17.5	32.3
PWE	hardwood	3.3	12.1
PWE	softwood	9.5	32.3
PWW	hardwood	18.1	12.1
PWW	softwood	23.6	32.3
RMN	hardwood	7.2	43.5
RMN	softwood	9.0	18.1
RMS	hardwood	5.1	43.5
RMS	softwood	3.7	18.1
SC	hardwood	4.2	8.9
SC	softwood	5.5	17.9
SE	hardwood	6.4	8.9
SE	softwood	7.3	17.9

[a] Regions are defined in Smith et al. (2003) with the addition of coastal Alaska.
[b] Forest types are according to majority hardwood or softwood species.

Litter carbon

C of the litter layer is currently sampled on a subset of the FIA plots. However, these data are not yet available electronically for general application to all inventories in Table A-1. Litter C is the pool of organic C (including material known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates therefore continue to be based on equations of Smith and Heath (2002) and applied at the plot level. The equations describe processes for decay or loss of forest floor following harvest and the net accumulation of new forest floor material following stand growth. For example, total forest floor C at a given number of years after a clearcut harvest for aspen-birch forests in the North is:

$$\text{Total forest floor C (Mg C/ha)} = (18.4 \times \text{years})/(53.7 + \text{years}) + 10.2 \times e^{(-\text{years} \div 9.2)}$$

See Table 4 of Smith and Heath (2002) for the complete set of coefficients. Note that these are direct estimates of C density; the 0.5 conversion does not apply to litter.

Soil organic carbon

Soil organic carbon (SOC) is currently sampled to a 20 cm depth on subsets of FIA plots, however, these data are not available for the entire United States. Thus, estimates of SOC are based on the national STATSGO spatial database (USDA 1991), and the general approach described by Amichev and Galbraith (2004). In their procedure, SOC was calculated for the conterminous United States using the STATSGO database, and data gaps were filled by representative values from similar soils. Links to region and forest type groups were developed with the assistance of the USDA Forest

Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. The average SOC densities are provided in .

Carbon in Harvested Wood Products

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP carbon. The 2006 IPCC Guidelines provide methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change, and atmospheric flow, as well as a default method. The various approaches are described below. The approaches differ in how HWP Contribution is allocated based on production or consumption as well as what processes (atmospheric fluxes or stock changes) are emphasized.

- **Production approach**: Accounts for the net changes in carbon stocks in forests and in the wood products pool, but attributes both to the producing country.
- **Stock change approach**: Accounts for changes in the product pool within the boundaries of the consuming country.
- **Atmospheric flow approach**: Accounts for net emissions or removals of carbon to and from the atmosphere within national boundaries. C removal due to forest growth is accounted for in the producing country while C emissions to the atmosphere from oxidation of wood products are accounted for in the consuming country.
- **Default approach**: Assumes no change in C stocks in HWP. IPCC (2006) requests that such an assumption be justified if this is how a Party is choosing to report.

The United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-230). Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches—the stock change and atmospheric flow approaches—are also presented for comparison (see Table A-231). Annual estimates of change are calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Estimates of five HWP variables that can be used to calculate HWP contribution for the stock change and atmospheric flow approaches for imports and exports are provided in Table A-230. The HWP variables estimated are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

Table A-227: Harvested wood products from wood harvested in United States—Annual additions of carbon to stocks and total stocks

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Net carbon additions per year (Tg C per year)																						
Total Harvested wood carbon	(35.9)	(33.8)	(33.8)	(32.9)	(33.4)	(32.3)	(30.6)	(32.0)	(31.1)	(32.5)	(30.8)	(25.5)	(26.8)	(25.9)	(28.7)	(28.7)	(29.6)	(28.1)	(22.4)	(14.8)	(17.9)	
Products in use	(17.7)	(14.9)	(16.3)	(15.0)	(15.9)	(15.1)	(14.1)	(14.7)	(13.4)	(14.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.4)	(12.3)	(10.7)	(5.2)	1.8	(1.2)	
Solid wood products	(14.4)	(11.9)	(12.6)	(12.2)	(12.1)	(11.2)	(11.5)	(11.8)	(11.4)	(12.1)	(11.9)	(10.1)	(10.7)	(10.1)	(11.6)	(11.9)	(10.6)	(8.7)	(4.4)	0.6	(1.2)	
Paper products	(3.3)	(3.1)	(3.7)	(2.8)	(3.8)	(3.8)	(2.6)	(3.0)	(2.0)	(2.0)	(1.0)	1.4	1.1	0.4	(0.8)	(0.5)	(1.7)	(2.0)	(0.8)	1.2	0.0	
Products in SWDS	(18.3)	(18.8)	(17.4)	(17.9)	(17.5)	(17.2)	(16.5)	(17.3)	(17.7)	(18.4)	(18.0)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)	(16.7)	
Solid wood products	(9.9)	(11.1)	(9.5)	(9.7)	(9.8)	(10.7)	(10.6)	(10.3)	(10.2)	(10.6)	(10.7)	(10.7)	(11.1)	(11.1)	(11.3)	(11.5)	(11.6)	(11.7)	(11.5)	(11.2)	(11.4)	
Paper products	(8.3)	(7.7)	(7.9)	(8.3)	(7.7)	(6.5)	(6.0)	(6.9)	(7.5)	(7.8)	(7.3)	(6.0)	(6.1)	(5.1)	(5.0)	(4.8)	(5.7)	(5.7)	(5.7)	(5.4)	(5.3)	
Total Carbon stocks (Tg C)																						
Total Harvested wood carbon	1,859	1,895	1,963	1,996	2,029	2,061	2,092	2,124	2,155	2,187	2,218	2,244	2,271	2,296	2,325	2,354	2,383	2,412	2,434	2,449	2,467	2,487
Products in use	1,231	1,249	1,280	1,295	1,311	1,326	1,340	1,355	1,368	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,460	1,471	1,476	1,474	1,475	1,479
Products in SWDS	628	646	683	701	718	735	752	769	787	805	823	840	857	873	890	906	923	941	958	974	991	1,008

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Net carbon additions per year (Tg C per year)																						
Total Harvested wood carbon	(35.9)	(33.8)	(33.8)	(32.9)	(33.4)	(32.3)	(30.6)	(32.0)	(31.1)	(32.5)	(30.8)	(25.5)	(26.8)	(25.9)	(28.7)	(28.7)	(29.6)	(28.1)	(22.4)	(14.8)	(17.9)	(35.9)
Products in use	(17.7)	(14.9)	(16.3)	(15.0)	(15.9)	(15.1)	(14.1)	(14.7)	(13.4)	(14.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.4)	(12.3)	(10.7)	(5.2)	1.8	(1.2)	(17.7)
Solid wood products	(14.4)	(11.9)	(12.6)	(12.2)	(12.1)	(11.2)	(11.5)	(11.8)	(11.4)	(12.1)	(11.9)	(10.1)	(10.7)	(10.1)	(11.6)	(11.9)	(10.6)	(8.7)	(4.4)	0.6	(1.2)	(14.4)
Paper products	(3.3)	(3.1)	(3.7)	(2.8)	(3.8)	(3.8)	(2.6)	(3.0)	(2.0)	(2.0)	(1.0)	1.04	1.1	0.4	(0.8)	(0.5)	(1.7)	(2.0)	(0.8)	1.2	0.0	(3.3)
Products in SWDS	(18.3)	(18.8)	(17.4)	(17.9)	(17.5)	(17.2)	(16.5)	(17.3)	(17.7)	(18.4)	(18.0)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)	(16.7)	(18.3)
Solid wood products	(9.9)	(11.1)	(9.5)	(9.7)	(9.8)	(10.7)	(10.6)	(10.3)	(10.2)	(10.6)	(10.7)	(10.7)	(11.1)	(11.1)	(11.3)	(11.5)	(11.6)	(11.7)	(11.5)	(11.2)	(11.4)	(9.9)
Paper products	(8.3)	(7.7)	(7.9)	(8.3)	(7.7)	(6.5)	(6.0)	(6.9)	(7.5)	(7.8)	(7.3)	(6.0)	(6.1)	(5.1)	(5.0)	(4.8)	(5.7)	(5.7)	(5.7)	(5.4)	(5.3)	(8.3)
Total Carbon stocks (Tg C)																						
Total Harvested wood carbon	1,859	1,895	1,963	1,996	2,029	2,061	2,092	2,124	2,155	2,187	2,218	2,244	2,271	2,296	2,325	2,354	2,383	2,412	2,434	2,449	2,467	2,487
Products in use	1,231	1,249	1,280	1,295	1,311	1,326	1,340	1,355	1,368	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,460	1,471	1,476	1,474	1,475	1,479
Products in SWDS	628	646	683	701	718	735	752	769	787	805	823	840	857	873	890	906	923	941	958	974	991	1,008

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-228: Comparison of Net Annual Change in Harvested Wood Products Carbon Stocks Using Alternative Accounting Approaches

	HWP Contribution to LULUCF Emissions/ removals (Tg CO_2 Eq.)		
Inventory Year	**Stock Change Approach**	**Atmospheric Flow Approach**	**Production Approach**
1990	(129.6)	(138.4)	(131.8)
1991	(116.3)	(131.4)	(123.8)

1992	(120.0)	(131.6)	(123.8)
1993	(126.8)	(127.8)	(120.7)
1994	(130.0)	(129.9)	(122.5)
1995	(126.0)	(128.0)	(118.4)
1996	(122.3)	(122.5)	(112.2)
1997	(131.4)	(127.4)	(117.3)
1998	(139.8)	(122.7)	(114.1)
1999	(149.4)	(127.3)	(119.1)
2000	(143.2)	(120.3)	(112.9)
2001	(128.3)	(100.3)	(93.4)
2002	(135.6)	(103.1)	(98.2)
2003	(134.6)	(99.2)	(94.8)
2004	(163.0)	(109.1)	(105.3)
2005	(161.4)	(109.0)	(105.4)
2006	(138.6)	(114.2)	(108.6)
2007	(115.4)	(112.1)	(103.0)
2008	(78.4)	(94.3)	(82.1)
2009	(41.2)	(69.4)	(54.4)
2010	(54.9)	(84.6)	(65.6)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-229: Harvested Wood Products Sectoral Background Data for LULUCF—United States (production approach)

Inventory year	**1A Annual Change in stock of HWP in use from consumption**	**1B Annual Change in stock of HWP in SWDS from consumption**	**2A Annual Change in stock of HWP in use produced from domestic harvest**	**2B Annual Change in stock of HWP in SWDS produced from domestic harvest**	**3 Annual Imports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips**	**4 Annual Exports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips**	**5 Annual Domestic Harvest**	**6 Annual release of carbon to the atmosphere from HWP consumption (from fuelwood and products in use and products in SWDS)**	**7 Annual release of carbon to the atmosphere from HWP (including firewood) where wood came from domestic harvest (from products in use and products in SWDS)**	**8 HWP Contribution to AFOLU CO_2 emissions/ removals**
	$\Delta C_{HWP\ IU\ DC}$	**$\Delta C_{HWP\ SWDS\ DC}$**	**$\Delta C_{HWP\ IU\ DH}$**	**$\Delta C_{HWP\ SWDS\ DH}$**	**P_{IM}**	**P_{EX}**	**H**	**$\uparrow C_{HWP\ DC}$**	**$\uparrow C_{HWP\ DH}$**	
									Gg C/yr	**Gg CO_2/yr**
1990	17,044	18,308	17,659	18,278	12,680	15,078	142,297	104,547	106,359	(131,772)
1991	13,129	18,602	14,940	18,812	11,552	15,667	144,435	108,588	110,682	(123,758)
1992	15,718	17,006	16,334	17,427	12,856	16,032	139,389	103,489	105,627	(123,791)
1993	16,957	17,627	14,971	17,949	14,512	14,788	134,554	99,694	101,633	(120,708)
1994	18,221	17,221	15,930	17,479	15,685	15,665	134,750	99,328	101,342	(122,498)
1995	17,307	17,051	15,065	17,229	16,712	17,266	137,027	102,115	104,733	(118,411)
1996	17,018	16,348	14,092	16,513	16,691	16,733	134,477	101,069	103,872	(112,219)
1997	18,756	17,090	14,740	17,263	17,983	16,877	135,439	100,699	103,436	(117,344)

1998	20,311	17,818	13,376	17,735	19,722	15,057	135,021	101,558	103,911	(114,071)
1999	22,035	18,714	14,123	18,353	21,266	15,245	134,939	100,211	102,464	(119,078)
2000	20,491	18,560	12,828	17,962	22,426	16,185	134,458	101,648	103,667	(112,898)
2001	17,295	17,691	8,711	16,774	22,975	15,336	128,621	101,274	103,136	(93,447)
2002	18,629	18,357	9,570	17,207	24,604	15,744	127,567	99,441	100,791	(98,179)
2003	19,180	17,532	9,676	16,186	25,962	16,303	124,949	97,896	99,086	(94,828)
2004	26,384	18,077	12,429	16,298	31,650	16,948	130,460	100,700	101,733	(105,332)
2005	25,777	18,249	12,394	16,347	31,714	17,423	131,711	101,976	102,971	(105,382)
2006	19,010	18,780	12,308	17,302	25,485	18,836	127,064	95,922	97,454	(108,567)
2007	12,999	18,497	10,673	17,409	21,603	20,670	120,922	90,360	92,840	(102,967)
2008	3,589	17,786	5,203	17,188	16,822	21,156	108,339	82,630	85,948	(82,101)
2009	(5,581)	16,812	(1,827)	16,656	12,811	20,509	95,143	76,213	80,314	(54,373)
2010	(1,629)	16,589	1,213	16,673	13,748	21,874	98,196	75,110	80,310	(65,583)

Note: $\uparrow C_{HWP\ DC} = H + P_{IM} - P_{EX} - \Delta C_{HWP\ IU\ DC} - \Delta C_{HWP\ SWDS\ DC}$ AND $\uparrow C_{HWP\ DH} = H - \Delta C_{HWP\ IU\ DH} - \Delta C_{HWP\ SWDS\ DH}$. Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere)..

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and removals from the pool of products held in end uses (e.g., products in uses such as housing or publications) and the pool of products held in SWDS. In the case of variables 2A and 2B, the pools include products exported and held in other countries and the pools in the United States exclude products made from wood harvested in other countries. Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003).

The rate of removals from products in use and the rate of decay of products in SWDS are specified by first order (exponential) decay curves with given half-lives (time at which half of amount placed in use will have been discarded from use). Half-lives for products in use, determined after calibration of the model to meet two criteria, are shown in Table A-233. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needed to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needed to match EPA estimates of discards over the period 1990 to 2000. This calibration strongly influences the estimate of variable 1A, and to a lesser extent variable 2A. The calibration also determines the amounts going to SWDS. In addition ,WOODCARB II landfill decay rates have been validated by making sure that estimates of methane emissions from landfills based on EPA data are reasonable in comparison to methane estimates based on WOODCARB II landfill decay rates.

Decay parameters for products in SWDS are shown in Table A-231. Estimates of 1B and 2B also reflect the change over time in the fraction of products discarded to SWDS (versus burning or recycling) and the fraction of SWDS that are sanitary landfills versus dumps.

Variables 2A and 2B are used to estimate HWP contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS. Summaries of net fluxes and stocks for harvested wood in products and SWDS are in Table A-220 and Table A-221. The decline in net additions to HWP carbon stocks continued though 2009 from the recent high point in 2006. This is due to sharp declines in U.S. production of solidwood and paper products in 2009 primarily due to the decline in housing construction. The low level of gross additions to solidwood and paper products in use in 2009 was exceeded by discards from uses. The result is a net reduction in the amount of HWP carbon that is held in products in use during 2009. For 2009 additions to landfills still exceeded emissions from landfills and the net additions to landfills have remained relatively stable. Overall, there were net carbon additions to HWP in use and in landfills combined.

Table A-230: Half-life of solidwood and paper products in end uses

Parameter	Value	Units
Half life of wood in single family housing 1920 and before	78.0	Years
Half life of wood in single family housing 1920–1939	78.0	Years
Half life of wood in single family housing 1940–1959	80.0	Years
Half life of wood in single family housing 1960–1979	81.9	Years
Half life of wood in single family housing 1980 +	83.9	Years
Ratio of multifamily half live to single family half life	0.61	
Ratio of repair and alterations half life to single family half life	0.30	
Half life for other solidwood product in end uses	38.0	Years
Half life of paper in end uses	2.54	Years

Source: Skog, K.E. (2008) " Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56–72.

Table A-231: Parameters determining decay of wood and paper in SWDS

Parameter	Value	Units
Percentage of wood and paper in dumps that is subject to decay	100	Percent
Percentage of wood in landfills that is subject to decay	23	Percent
Percentage of paper in landfills that is subject to decay	56	Percent
Half life of wood in landfills / dumps (portion subject to decay)	29	Years
Half life of paper in landfills/ dumps (portion subject to decay)	14.5	Years

Source: Skog, K.E. (2008) " Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56–72

Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see uncertainty table in LULUCF chapter) are consistent with the IPCC-recommended Tier 2 methodology (IPCC 2006). Separate analyses are produced for forest ecosystem and HWP flux. The uncertainty estimates are from Monte Carlo simulations of the respective models and input data. Methods generally follow those described in Heath and Smith (2000), Smith and Heath (2000), and Skog et al. (2004). Uncertainties surrounding input data or model processes are quantified as probability distribution functions (PDFs), so that a series of sample values can be randomly selected from the distributions. Model simulations are repeated a large number of times to numerically simulate the effect of the random PDF selections on estimated total C flux. The separate results from the ecosystem and HWP simulations are pooled for total uncertainty (see uncertainty table in LULUCF chapter).

Uncertainty surrounding current net C flux in forest ecosystems is based on the value for 2010 as obtained from the Monte Carlo simulation. C stocks are based on forest condition level (plot-level) calculations, and, therefore, uncertainty analysis starts probabilistic sampling at the plot level. Uncertainty surrounding C density (Mg/ha) is defined for each of six C pools for each inventory plot. Live and standing dead tree C pools are generally assigned normal PDFs that represent total uncertainty of all trees measured on the plot, which varies according to species, number of trees, and per area representation. Error estimates for volume and the component ratio method of estimating biomass are not available, so an assumed 10 percent error on biomass from volume is applied to the volume portion of the estimate and error information in Jenkins et al. (2003) is applied to uncertainty about the additional components (e.g., top, leaves, and roots). Uniform PDFs with a range of ±90 percent of the average are used for those plots where C densities from similarly classified forest stands were applied.

Distributions for the remaining C pools are triangular or uniform, which partly reflects the lower level of information available about these estimates. The PDFs defined for these four pools were sampled as marginal distributions. Down dead wood, understory, and litter are assigned triangular distributions with the mean at the expected value for each plot and the minimum and mode at 10 percent of the expected value. The use of these PDFs skewed to the right reflects the assumption that a small proportion of plots will have relatively high C densities. Soil organic C is defined as a uniform PDF at ±50 percent of the mean. Sub-state or state total carbon stocks associated with each survey are the cumulative sum of random samples from the plot-level PDFs, which are then appropriately expanded to population estimates. These expected values for each carbon pool include uncertainty associated with sampling, which is also incorporated in the Monte Carlo simulation. Sampling errors are determined according to methods described for the FIADB (Bechtold and Patterson 2005), are normally distributed, and are assigned a slight positive correlation between successive surveys for Monte Carlo sampling. More recent annual inventories are assigned higher sampling correlation between successive surveys based on the proportion of plot data jointly included in each. Errors for older inventory data are not available, and these surveys are assigned values consistent with those obtained from the FIADB.

Uncertainty about net C flux in HWP is based on Skog et al. (2004) and Skog (2008). Latin hypercube sampling is the basis for the HWP Monte Carlo simulation. Estimates of the HWP variables and HWP Contribution under the production approach are subject to many sources of uncertainty. An estimate of uncertainty is provided that evaluated the effect of uncertainty in 13 sources, including production and trade data and parameters used to make the estimate. Uncertain data and parameters include data on production and trade and factors to convert them to C, the Census-based estimate of C in housing in 2001, the EPA estimate of wood and paper discarded to SWDS for 1990 to 2000, the limits on decay of wood and paper in SWDS, the decay rate (half-life) of wood and paper in SWDS, the proportion of products produced in the United States made with wood harvested in the United States, and the rate of storage of wood and paper C in other countries that came from United States harvest, compared to storage in the United States.

A total of ten thousand samples are drawn from the PDF input to separately determine uncertainties about forest ecosystem and HWP flux before they are combined for a quantitative estimate of total forest carbon uncertainty (see uncertainty table in LULUCF chapter). Again this year, true Monte Carlo sampling is used for the forest ecosystem estimates (in contrast to Latin hypercube sampling, which was used in some previous estimates), and a part of the QA/QC process includes verifying that the PDFs are adequately sampled.

Emissions from Fires

CO_2

As stated in other sections, the forest inventory approach implicitly accounts for emissions due to disturbances. Net C stock change is estimated by subtracting consecutive C stock estimates. A disturbance removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss because only C remaining in the forest is estimated. Estimating the CO_2 emissions from a disturbance such as fire and adding those emissions to the net CO_2 change in forests would result in double-counting the loss from fire because the inventory data already reflect the loss. There is interest, however, in the size of the CO_2 emissions from disturbances such as fire. The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate emissions from forest fires.

The same methodology was used to estimate emissions from both wildfires and prescribed fires occurring in the lower 48 states. Wildfire area statistics are available, but they include non-forest land, such as shrublands and grasslands. It was thus necessary to develop a rudimentary estimate of the percent of area burned in forest by multiplying the reported area burned by a ratio of total forest land area to the total area considered to be under protection from fire. Data on total area of forest land were obtained from FIA (USDA Forest Service 2010b**)**. Data on "total area considered to be under protection from fire" were available at the state level and obtained for the year 1990 from 1984-1990 Wildfire Statistics prepared by the USDA Forest Service (USDA Forest Service 1992). Data for years 1998, 2002, 2004, 2006, and 2008 were obtained from the National Association of State Foresters (NASF 2011, 2008, 2007a, 2007b, 2007c). For states where data were available for all five years, the 1990 value was assumed for years 1990 to 1994, values for 1998 were assumed for years 1995 to 1998, values for 2002 were assumed for years 1999 to 2002, values for 2004 were assumed for years 2003 and 2004, values for 2006 were assumed for years 2005 and 2006, and values for 2008 were assumed for years 2008 to 2010. For states where data were available for all years except 2002, 2004 data were assumed for years 1999 to 2004. For states where data were available for all years except 2004, 2006 data were assumed for 2003 through 2008. For years where data were available for all years except 2006, 2004 data were assumed for years 2003 to 2008. Since both the 1998 and 2006 values are missing from the NASF data for Alaska, the 1990 value was assumed for years 1990 to 1997, the 2002 value was assumed for years 1998 to 2002, the 2004 value was assumed for years 2003 to 2006, and the 2008 value was assumed for 2007 to 2010. Similarly, since the NASF data for New Mexico lacks values for 2002 and 2004, the 1990 value was assumed for years 1990–1995, while the 1998 value was assumed for year 1996 through 2001, the 2006 data were assumed for 2002 to 2006, and the 2008 value was assumed for all remaining years. Illinois has not reported data on wildland since 2002, so the 1990 value was assumed for years 1990–1995, while the 1998 value was assumed for years 1995 through 2001, and the 2002 value was assumed for all remaining years. Total forestland area for the lower 48 states was divided by total area considered to be under protection from wildfire for the lower 48 states across the 1990 to 2010 time series to create ratios that were then applied to reported area burned to estimate the area of forestland burned for the lower 48 states. The ratio was applied to area burned from wildland fires and prescribed fires occurring in the lower 48 states. Reported area burned data for prescribed fires was available from 1998 to 2010 from the National Interagency Fire Center (NIFC 2011**)**. Data for the year 1998 was assumed for years 1990 to 1997.

Forest area burned data for Alaska are from the Alaska Department of Natural Resources (Alaska Department of Natural Resources 2008) or the Alaska Interagency Coordination Center (Alaska Interagency Coordination Center 2011). Data are acres of land which experienced fire activity on forest service land. Based on personal communication with the USDA Forest Service, forest areas under the protection of the USDA Forest Service serve as a proxy for coastal areas, which is where the majority of forest fires in Alaska occur (Heath 2008). According to expert judgment, the coastal area of Alaska included in this Inventory is mostly temperate rainforest and, therefore, there is little call for prescribed burns (Smith 2008a). It was, thus, assumed that reported area burned for prescribed fires covers only prescribed fires in the lower 48 states.

The average C density in the lower 48 states for aboveground biomass C, dead wood C, and litter layer varied between 70.4 and 76.5 Mg/ha, according to annual (1990–2010) data from FIA. In order to estimate these annual C densities in the lower 48 states, the C contained in the aboveground, deadwood, and litter C pools was first summed for each state and year. The methodology assumes that wildfires burn only those pools, and leaves the belowground carbon and soil carbon un-burnt. The methodology estimates the C density value by taking a weighted average of these summed C pools in each state and year. The states' C values are weighted according to area of forestland present in each state and year compared with the total A default value of 0.45 from IPCC (2006) was assumed for the amount of biomass burned by wildfire (combustion factor value). According to the estimates, wildfires in the lower 48 states emit between 31.7 and 34.4 Mg C/ha. For Alaska, the average C density reported by the USDA Forest Service varies between 140.6 and 143.0 Mg/ha, based on data from FIA. In the case of wildfires in Alaska, Alaska's C pool values are used instead of a weighted average for states. These values translate into 63.3 to 64.4 Mg C/ha emitted. Based on data from the USDA Forest Service, the average C density for prescribed fires varied between 25.4 and 25.9 Mg C/ha. For prescribed fires, the methodology assumes that only the litter and deadwood carbon pools burn. The weighted average C densities estimated for prescribed fires therefore only include the sum of these two pools, and excludes aboveground biomass. It is assumed that prescribed fires only occur in the lower 48 states (Smith 2008a). The default value of 0.45 from IPCC (2006) for wildfires was also assumed for the amount of biomass burned by prescribed fires (combustion factor value). As a result, prescribed fires are estimated to emit between 11.4 and 11.7 Mg C/ha.

Estimates for Mg C/ha were multiplied by estimates of forest area burned by year; the resulting estimates are displayed in . C estimates were multiplied by 92.8 percent to account for the proportion of carbon emitted as CO_2 and by

3.67 (i.e., 44/12) to yield CO_2 units. Total CO_2 emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2010 were estimated to be 77.0 Tg/yr.

Table A-232: Areas (hectares) from wildfire statistics and corresponding estimates of carbon and CO_2 (Tg/yr) emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska[1]

	Lower 48 States								Alaska			
	Wildfires				Prescribed Fires				Wildfires			
Year	**Reported area burned[2] (ha)**	**Forest area burned[3] (ha)**	**Carbon emitted (Tg/yr)**	**CO_2 emitted (Tg/yr)**	**Reported area burned[2] (ha)**	**Forest area burned[3] (ha)**	**Carbon emitted (Tg/yr)**	**CO_2 emitted (Tg/yr)**	**Forest area burned[4] (acres)**	**Forest area burned (ha)**	**Carbon emitted (Tg/yr)**	**CO_2 emitted (Tg/yr)**
1990	579,589	306,750	10	33	355,432	188,114	2	7	8	3	0.000	0.001
1991	486,807	258,267	8	28	355,432	188,568	2	7	557	225	0.014	0.049
1992	785,892	417,954	13	45	355,432	189,026	2	7	47	19	0.001	0.004
1993	438,865	233,940	7	26	355,432	189,466	2	7	110	45	0.003	0.010
1994	1,540,987	823,217	26	90	355,432	189,877	2	7	23	9	0.001	0.002
1995	727,051	424,593	14	47	355,432	207,570	2	8	7	3	0.000	0.001
1996	2,212,309	1,331,322	43	147	355,432	213,891	2	8	103	42	0.003	0.009
1997	335,914	202,533	7	22	355,432	214,301	2	8	33	13	0.001	0.003
1998	489,246	295,499	10	33	355,432	214,677	2	8	2	1	0.000	0.000
1999	1,869,918	1,137,763	37	127	806,780	490,890	6	19	7	3	0.000	0.001
2000	2,685,981	1,636,500	54	183	77,789	47,395	1	2	1	1	0.000	0.000
2001	1,356,830	827,629	27	93	667,428	407,113	5	16	2,078	841	0.054	0.183
2002	2,023,976	1,231,995	41	139	1,086,503	661,355	8	26	28	11	0.001	0.002
2003	1,358,986	726,504	24	82	1,147,695	613,549	7	24	17	7	0.000	0.001
2004	637,258	346,919	12	40	996,453	542,462	6	21	23	9	0.001	0.002
2005	1,629,067	951,201	32	109	934,965	545,919	6	21	353	143	0.009	0.031
2006	3,888,011	2,276,326	77	262	1,100,966	644,586	7	25	8	3	0.000	0.001
2007	3,512,122	1,795,086	61	207	1,274,383	651,352	8	26	2	1	0.000	0.000
2008	2,099,984	1,067,696	36	124	783,068	398,135	5	16	1	0	0.000	0.000
2009	1,201,995	613,384	21	72	1,024,306	522,708	6	21	22	9	0.001	0.002
2010	929,687	484,412	17	57	980,903	511,098	6	20	12	5	0.000	0.001

[1] Note that these emissions have already been accounted for in the estimates of net annual changes in carbon stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

[2] National Interagency Fire Center (2011).

[3] Ratios calculated using forest land area estimates from FIA (USDA Forest Service 2011b) and wildland area under protection estimates from USDA Forest Service (1992) and the National Association of State Foresters (2007).

[4] 1990–2007 Alaskan forest fires data are from the Alaska Department of Natural Resources (2008). 2008–2010 data are from Alaska Interagency Coordination Center (2011).

Non-CO_2

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology, IPCC (2006) emission ratios, and default IPCC (2006) combustion factor for wildfires. Emissions estimates for CH_4 and N_2O are calculated by multiplying the total estimated CO_2 emitted from forest burned by gas-specific emissions ratios and conversion factors. The equations used are:

$$CH_4 \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

The resulting estimates are presented in Table A-233.

Table A-233: Estimated carbon released and estimates of non-CO_2 emissions (Tg/yr) for U.S. forests[1]

Year	C emitted (Tg/yr)	CH_4 emitted (Tg/yr)	N_2O (Tg/yr)
1990	11.872	0.121	0.007
1991	10.387	0.106	0.006
1992	15.508	0.158	0.009
1993	9.670	0.099	0.005
1994	28.654	0.292	0.016
1995	16.091	0.164	0.009
1996	45.599	0.465	0.026
1997	9.051	0.092	0.005
1998	12.119	0.124	0.007
1999	42.938	0.438	0.024

2000	54.386	0.554	0.031
2001	32.053	0.327	0.018
2002	48.450	0.494	0.027
2003	31.262	0.319	0.018
2004	17.860	0.182	0.010
2005	38.292	0.390	0.022
2006	84.352	0.860	0.048
2007	68.477	0.698	0.039
2008	41.035	0.418	0.023
2009	27.097	0.276	0.015
2010	22.631	0.231	0.013

[1] Calculated based on C emission estimates in and default factors in IPCC (2003, 2006)

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3.13. Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils on Cropland and Grassland

This sub-annex describes the methodologies used to calculate annual carbon (C) stock changes from mineral and organic soils under agricultural management, including *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Three types of methodologies were applied: (1) a Tier 3 approach, employing the Century simulation model, (2) Tier 2 methods with country-specific stock change and emission factors; and (3) Tier 2 methods for estimating additional changes in mineral soil C stocks due to sewage sludge additions to soils and enrollment changes in the Conservation Reserve Program (CRP) after 2003.

The Inventory uses a Tier 3 approach to estimate soil C stock changes for the majority of agricultural lands. This approach has several advantages over the IPCC Tier 1 or 2 approaches:

- It utilizes actual weather data at county scales, rather than a broad climate region classification, enabling quantification of inter-annual variability in C fluxes at finer spatial scales;
- The model uses a more detailed characterization of spatially-mapped soil properties that influence soil C dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
- The simulation approach provides a more detailed representation of management influences and their interactions than are represented by a discrete factor-based approach in the Tier 1 and 2 methods; and
- Soil C changes are estimated on a more continuous basis (monthly) as a function of the interaction of climate, soil, and land management, compared with the linear change between the start and end of the inventory that is used with the Tier 1 and 2 methods.

The Century model was chosen as an appropriate tool for a Tier 3 approach based on several criteria:

- The model was developed in the United States and has been extensively tested and verified for U.S. conditions. In addition, the model has been widely used by researchers and agencies in many other parts of the world for simulating soil C dynamics at local, regional and national scales (e.g., Brazil, Canada, India, Jordan, Kenya, Mexico).
- The model is capable of simulating cropland, grassland, forest, and savanna ecosystems, and land-use transitions between these different land uses. It is, thus, well suited to model land-use change effects.
- The model was designed to simulate all major types of management practices that influence soil C dynamics, with the exception of cultivated organic soils and a few crops that have not been parameterized for Century simulations (e.g., rice, perennial/horticultural crops, and tobacco). For these latter cases, an IPCC Tier 2 method has been used.
- Much of the data needed for the model was obtainable from existing national databases. The exceptions are CRP enrollment after 2003 and sewage sludge amendments to soils, which are not known at a sufficient resolution to use the Tier 3 model. Soil C stock changes associated with these practices are addressed with a Tier 2 method.

Century Model Description

The Century model simulates C (and also N, P, and S) dynamics, soil temperature, and water dynamics for cropland, grassland, forest, and savanna (mixed forest-grassland) systems. For this analysis, only C and N dynamics have been included for several reasons: to simplify the analysis and reduce data requirements, and because P and S interactions are less important as determinants of land-use- and management-induced changes in soil C stocks for U.S. agricultural systems.

The model has four main components: (1) soil organic matter and nutrient dynamics; (2) plant growth processes; (3) water and temperature dynamics; and (4) management practices. The model was designed to work with readily available input data: monthly weather data (e.g., temperature and precipitation); soil physical properties (e.g., soil texture, drainage condition, rooting depth); and information about land use/land cover (e.g., vegetation attributes) and management activities (see below). The model operates on a monthly time step (with weekly time steps used for soil water dynamics).

Dynamics of organic C and N (Figure A-13) are simulated for the surface and subsurface litter pools and the top 20 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N stocks are represented by two plant litter pools (labelled metabolic and structural) and three soil organic matter (SOM) pools (labelled active, slow, and passive). The metabolic litter pool represents the easily decomposable constituents of plant residues, while the structural litter pool is composed of more recalcitrant, ligno-cellulose plant materials. The three SOM pools represent a gradient in decomposability, from active SOM (representing microbial biomass and associated metabolites) having a rapid turnover (months to years), to passive SOM (representing highly processed, humified, condensed decomposition products), which is highly recalcitrant, with mean residence times on the order of several hundred years. The slow pool represents decomposition products of intermediate stability, having a mean residence time on the order of decades and is the fraction that tends to change the most in terms of C content in response to changes in land use and management. Soil texture influences turnover rates of the slow and passive pools The clay and silt-sized mineral fraction of the soil provides physical protection from microbial attack, leading to slower decomposition and greater SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence the decomposition and loss of C from the soil organic matter pools.

Figure A-13: Flow diagram of Carbon submodel (A) and Nitrogen submodel (B)

The plant-growth submodel simulates C assimilation through photosynthesis, N uptake, dry matter production, partitioning of C within the crop or forage, senescence, and mortality. The primary function of the growth submodel is to estimate the amount, type, and timing of organic matter inputs to soil and to represent the influence of the plant on soil water, temperature, and N balance. Yield and removal of harvested biomass are also simulated. Separate submodels are designed to simulate herbaceous plants (i.e., agricultural crops and grasses) and woody vegetation (i.e., trees and scrub). Only the herbaceous plant submodel is currently used in the Inventory. Maximum monthly net primary production (NPP) rate (a parameter of crop and forage species/variety, specified in the model input files) is modified by air temperature and available water to estimate a potential monthly NPP, which is then further subject to nutrient limitations in order to estimate actual NPP and biomass allocation.

The soil-water balance submodel calculates water balance components and changes in soil water availability, which influences both plant growth and decomposition/nutrient cycling processes. The moisture content of soils are simulated through a multi-layer profile based on precipitation, snow accumulation and melting, interception, soil and canopy evaporation, transpiration, soil water movement, runoff, and drainage.

The final main component of the model is the management submodel, which includes options for specifying crop type, crop sequence (e.g., rotation), tillage, fertilization, organic matter addition (e.g., manure amendments), harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity. An input "schedule" file is used to simulate the timing of management activities and temporal trends; schedules can be organized into discrete time blocks to define a repeated sequence of events (e.g., a crop rotation or a frequency of disturbance such as a burning cycle for perennial grassland). Management options can be specified for any month of a year within a scheduling block, where management codes point to operation-specific parameter files (referred to as *.100 files), which contain the information used to simulate management effects within the model process algorithms. User-specified management activities can be defined by adding to or editing the contents of the *.100 files. Additional details of the model formulation are given in Parton et al. (1987, 1988, 1994) and Metherell et al. (1993), and archived copies of the model source code are available.

The model has been tested for application in U.S. agricultural lands and has been shown to capture the general trends in C storage across approximately 870 field plots from 47 experimental sites (Figure A-14). Some biases and imprecision were found in predictions of soil organic C, which is reflected in the uncertainty associated with Century model results as described in Step 2b of this sub-annex. Additional discussion is provided in Ogle et al. (2007, 2010)

Figure A-14: Comparison of Measured Soil Organic C from Experimental Sites to Modeled Soil Organic C Using the Century Model

IPCC Tier 2 Method Description

The IPCC Tier 2 method has been developed to estimate C stock changes and CO_2 fluxes between soils and the atmosphere based on land-use and management activity (IPCC 2003, 2006; Ogle et al. 2003). For mineral soils (i.e., all soil orders from the USDA taxonomic classification except Histosols), the Tier 2 method uses reference C values to establish baseline C stocks that are modified based on agricultural activities using land-use change, tillage, and input factors. The standard IPCC approach was modified to use agricultural SOC 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. In addition, country-specific factors were derived for land-use change, tillage, and input factors.

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 crop production or grazing (IPCC 2006). The IPCC approach uses an emission factor to estimate annual losses of CO_2 from cultivated organic soils, rather than an explicit stock change approach.

Methodological Steps for Derivation of Soil Organic C Stock Change Estimates

The inventory of soil C stock changes in U.S. agricultural land combines Tier 2 and 3 approaches. A simulation-based Tier 3 approach was used to estimate soil C changes for most agricultural land (approximately 90 percent of total cropland and grassland) comprising the dominant cropping and grazing systems in the United States, for which the model has been well-tested. Estimates for the remaining area, comprising less-common crop systems (e.g., horticultural, vegetable, tobacco, rice), land converted between non-agricultural and agricultural uses, and all agricultural land occurring on drained organic soils, were developed using the Tier 2 approach. Tier 2 methods were also used to estimate additional changes in mineral soil C stocks due to sewage sludge additions to soils, and enrollment changes in the Conservation Reserve Program after 2003. Most of the activity data sources were common to the Tier 2 and Tier 3 approaches, and, hence, they are described in an integrated manner below. Additional activity data required for the methods are described in adjoining sections, followed by the computation steps.

Step 1: Derive Activity Data

Activity data were compiled for the Tier 3 Century biogeochemical model and Tier 2 IPCC methods, including climate data, soil characteristics, and land-use/management activity data. The first step was to obtain land-use/management activity data, and determine the land base for areas under agricultural management. The areas modeled with Century and those estimated with the Tier 2 IPCC method were also subdivided. Finally, additional data, specific to each method, were collected on other key management activities (e.g., tillage management, fertilizer and manure addition rates) and environmental conditions (e.g., climate and soil characteristics).

Step 1a: Determine the Land Base and Classify Management Systems

Land Base—The *National Resources Inventory* (NRI) provided the basis for identifying the U.S. agricultural land base on non-federal lands, and classifying parcels into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland* (USDA-NRCS 2000). Note that the Inventory does not include estimates of C stock changes for grasslands and a minor amount of croplands on federal lands, even though these areas are part of the managed land base for the United States. C stock changes on federal croplands and grasslands will be further evaluated and included in future inventories. The NRI has a stratified multi-stage sampling 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). In principle, the expansion factors represent the amount of area with the land use and land use change history that is the same as the point location. It is important to note that the NRI is a sampling of land use, and therefore there is some uncertainty associated with scaling the point data to a region or the country using the expansion factors. In general, those uncertainties decline at larger scales, such as states compared to smaller county units, because of a larger sample size. An extensive amount of soils, land-use, and land management data have been collected through the survey, which occurs every five years (Nusser et al. 1998).[76] Primary sources for data include aerial photography and remote sensing imagery as well as field visits and county office records. The annual NRI data product provides crop data for most years between 1979 and 2003, with the exception of 1983, 1988, and 1993. These years were gap-filled using an automated set of rules so that cropping sequences were filled with the most likely crop type given the historical cropping pattern at each NRI point location. Grassland data were reported on 5-year increments prior to 1998, but it was assumed that the land use was also grassland between the years of data collection (see Easter et al. 2008 for more information).

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[76] In the current Inventory, NRI data only provide land-use and management statistics through 2003, but additional data will be incorporated in the future to extend the time series of land use and management data.

NRI points were included in the land base for the agricultural soil C inventory if they were identified as cropland or grassland[77] between 1990 and 2003 (Table A-234). The most recent national-level data for this inventory were for 2003; and so the designation for 2003 was extended to 2010 in order to provide C stock changes over the entire time series. An additional modification was made to the time series from 2004 to 2010 for *Grassland Remaining Grassland* and *Land Converted to Grassland* associated with the modification of NRI data with the Forest Inventory and Analysis Dataset. Overall, more than 260,000 NRI points were included in the inventory calculations, and the total agricultural land base varied from 370 to 367 million hectares from 1990 through 2010. Each NRI point represents a specific land parcel based upon the weighted expansion factors.

For each year, land parcels were subdivided into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Land parcels under cropping management in a specific year were classified as *Cropland Remaining Cropland* if they had been cropland for at least 20 years. Similarly land parcels under grassland management in a specific year of the inventory were classified as *Grassland Remaining Grassland* if they had been designated as grassland for at least 20 years.[78] Otherwise, land parcels were classified as *Land Converted to Cropland* or *Land Converted to Grassland* based on the most recent use in the inventory time period. Lands are retained in the land-use change categories (i.e., *Land Converted to Cropland* and *Land Converted to Grassland*) for 20 years as recommended by the IPCC guidelines (IPCC 2006).

Table A-234: Total Land Areas for the Agricultural Soil C Inventory, Subdivided by Land Use Categories (Million Hectares)

	Land Areas (10^6 ha)									
Category	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Mineral Soils										
Cropland Remaining Cropland	166.38	166.14	165.89	163.32	162.27	161.95	161.61	161.26	158.40	158.67
Land Converted to Cropland	14.01	14.24	14.41	14.23	15.71	15.88	16.24	16.37	17.79	17.43
Grassland Remaining Grassland	176.03	175.67	175.38	172.75	171.52	171.43	171.20	171.12	169.79	169.70
Land Converted to Grassland	10.10	10.23	10.44	9.94	10.51	10.77	10.91	11.27	13.73	13.90
Non-Agricultural Uses[a]	2.46	2.46	2.46	8.08	8.08	8.08	8.08	8.08	8.08	8.08
Organic Soils										
Cropland Remaining Cropland	0.70	0.70	0.70	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Land Converted to Cropland	0.07	0.07	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Grassland Remaining Grassland	0.50	0.50	0.50	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Land Converted to Grassland	0.04	0.04	0.04	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Non-Agricultural Uses[a]	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total	**370.32**	**370.10**	**369.93**	**369.66**	**369.43**	**369.45**	**369.40**	**369.44**	**369.13**	**369.12**

Category	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils											
Cropland Remaining Cropland	158.83	158.87	159.56	160.72	160.72	160.72	160.72	160.72	160.72	160.72	160.72
Land Converted to Cropland	17.09	16.83	16.09	14.87	14.87	14.87	14.87	14.87	14.87	14.87	14.87
Grassland Remaining Grassland	169.65	169.50	169.97	170.26	170.04	169.78	169.52	169.25	168.99	168.73	168.73
Land Converted to Grassland	14.24	14.64	14.28	13.98	13.91	13.83	13.74	13.66	13.58	13.50	13.50
Non-Agricultural Uses[a]	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08
Organic Soils											
Cropland Remaining Cropland	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Land Converted to Cropland	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Grassland Remaining Grassland	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Land Converted to Grassland	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Non-Agricultural Uses[a]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total	**369.24**	**369.27**	**369.32**	**369.25**	**368.95**	**368.62**	**368.27**	**367.93**	**367.58**	**367.23**	**367.23**

[a] The non-agricultural uses were converted to or from cropland or grassland between 1990 and 2003.

Note: These data differ from the estimates provided in the Land Representation Section of this NIR, which were updated with the latest NRI activity data. The data for this portion of the inventory will be updated by the next NIR as a planned improvement. The data were not updated in this report due to quality control issues.

Subdivide Land Base for Tier 2 and 3 Inventory Approaches–The Tier 3 method based on application of the Century model was used to model NRI points on most mineral soils. Parcels of land that were not simulated with Century

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[77] Includes non-federal lands only, because federal lands are not classified into land uses as part of the NRI survey (i.e, they are only designated as federal lands).

[78] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifcations were based on less than 20 years from 1990 to 2001.

were allocated to the Tier 2 approach, including (1) land parcels occurring on organic soils; (2) land parcels that included non-agricultural uses such as forest and federal lands in one or more years of the inventory;[79] (3) land parcels on mineral soils that were very gravelly, cobbly, or shaley (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale); or (4) land parcels that were used to produce vegetables, perennial/horticultural crops, tobacco or rice, which was either grown continuously or in rotation with other crops. Century has not been fully tested for non-major crops, horticultural or perennial crops, rice and agricultural use of organic soils. In addition, Century has not been adequately tested for soils with a high gravel, cobble, or shale content, or fully tested for the transitions between agricultural and non-agricultural uses.

Table A-235: Total Land Area Estimated with Tier 2[a] and 3 Inventory Approaches (Million Hectares)

	Land Areas (10^6 ha)		
Year	**Tier 2***	**Tier 3**	**Total**
1990	47.27	323.05	370.32
1991	47.27	322.83	370.10
1992	47.27	322.66	369.93
1993	47.25	322.41	369.66
1994	47.25	322.17	369.43
1995	47.25	322.19	369.45
1996	47.25	322.14	369.40
1997	47.25	322.19	369.44
1998	47.25	321.88	369.13
1999	47.25	321.87	369.12
2000	47.25	321.98	369.24
2001	47.25	322.01	369.27
2002	47.25	322.07	369.32
2003	47.25	321.99	369.25
2004	47.25	321.70	368.95
2005	47.25	321.36	368.62
2006	47.25	321.02	368.27
2007	47.25	320.67	367.93
2008	47.25	320.32	367.58
2009	47.25	319.98	367.23
2010	47.25	319.98	367.23

[a] Land use data for 1998-2003 are based on the Revised 1997 NRI data product for the Tier 2 method. Consequently, area data estimates in this table are not used for the Tier 2 portion of the Inventory.

Management System Classification—NRI points on mineral soils were classified into specific crop rotations, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis based on the survey data (Table A-236). NRI points were assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and interseeding of legumes. In order to estimate uncertainties, PDFs for the NRI land-use data were constructed as multivariate normal based on the total area estimates for each land-use/management category and associated covariance matrix. Through this approach, dependencies in land use were taken into account resulting from the likelihood that current use is correlated with past use.

For the Tier 3 inventory estimates, the actual cropping and grassland histories were simulated with the Century model so it was not necessary to classify NRI points into management systems. Uncertainty in the areas associated with each management system was determined from the estimated sampling variance from the NRI survey (Nusser and Goebel 1997). See Step 2b for additional discussion.

Table A-236: Total Land Areas by Land-Use and Management System for the Tier 2 Approach (Million Hectares)

	Land Areas (10^6 ha)	
Land-Use/Management System	**1990-92 (Tier 2)**	**1993-2010 (Tier 2)**
Cropland Systems	**31.53**	**29.25**
Irrigated Crops	7.27	6.91
Continuous Row Crops	4.12	3.63
Continuous Small Grains	1.25	1.04
Continuous Row Crops and Small Grains	2.30	1.95

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[79] Federal land is treated as forest or nominal grassland for purposes of these calculations, although the specific use is not identified in the NRI survey (USDA-NRCS 2000). Future inventories will include C estimation for the disaggregated land use and land use change categories on federal lands.

Row Crops in Rotation with Hay and/or Pasture	0.30	0.23
Small Grains in Rotation with Hay and/or Pasture	0.06	0.06
Row Crops and Small Grains in Rotation with Hay and/or Pasture	0.03	0.04
Vegetable Crops	2.90	3.16
Low Residue Annual Crops (e.g., Tobacco or Cotton)	0.87	1.03
Small Grains with Fallow	2.01	1.31
Row Crops and Small Grains with Fallow	1.72	1.80
Row Crops with Fallow	0.52	0.34
Miscellaneous Crop Rotations	0.54	0.43
Continuous Rice	0.34	0.31
Rice in Rotation with other crops	1.78	1.91
Continuous Perennial or Horticultural Crops	2.57	2.50
Continuous Hay	0.59	0.50
Continuous Hay with Legumes or Irrigation	1.31	1.12
CRP	1.03	0.96
Aquaculture	0.01	0.01
Grassland Systems	**12.02**	**8.68**
Rangeland	5.98	5.16
Continuous Pasture	3.76	2.49
Continuous Pasture with Legumes or Irrigation (i.e., improved)	2.25	1.03
CRP	0.02	0.00
Non-Agricultural Systems	**2.46**	**8.08**
Forest	1.53	3.95
Federal	0.01	0.05
Water	0.11	0.25
Settlements	0.04	2.46
Miscellaneous	0.77	1.36
Total	**46.01**	**46.01**

Organic soils are also categorized into land-use systems based on drainage (IPCC 2006). Undrained soils are treated as having no loss of organic C. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and greater losses of C, and those used for managed pasture, which are assumed to have less drainage and smaller losses of C. Overall, the area of organic soils drained for cropland and grassland has remained relatively stable since 1992 (see Table A-237).

Table A-237: Total Land Areas for Drained Organic Soils By Land Management Category and Climate Region (Million Hectares)

	Land Areas (10^6 ha)					
	Cold Temperate		**Warm Temperate**		**Tropical**	
IPCC Land-Use Category for Organic Soils	**1992**	**1997**	**1992**	**1997**	**1992**	**1997**
Undrained	0.07	0.06	0.0020	0.0017	0.12	0.09
Managed Pasture (Low Drainage)	0.42	0.42	0.0136	0.0119	0.07	0.08
Cultivated Cropland (High Drainage)	0.33	0.34	0.0971	0.0974	0.19	0.20
Other Land Uses[a]	0.02	0.01	0.0002	0.0017	0.00	0.02
Total	**0.84**	**0.84**	**0.11**	**0.11**	**0.39**	**0.39**

[a] Urban, water, and miscellaneous non-cropland, which are part of the agricultural land base because these areas were converted from or into agricultural land uses during the 1990s.

Step 1b: Obtain Additional Management Activity Data for the Tier 3 Century Model

Tillage Practices—Tillage practices were estimated for each cropping system based on data compiled by the Conservation Technology Information Center (CTIC 1998). CTIC compiles data on cropland area under five tillage classes by major crop species and year for each county. Because the surveys involve county-level aggregate area, they do not fully characterize tillage practices as they are applied within a management sequence (e.g., crop rotation). This is particularly true for area estimates of cropland under no-till, which include a relatively high proportion of "intermittent" no-till, where no-till in one year may be followed by tillage in a subsequent year. For example, a common practice in maize-soybean rotations is to use tillage in the maize crop while no-till is used for soybean, such that no-till practices are not continuous in time. Estimates of the area under continuous no-till were provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices were grouped into 3 categories: full, reduced, and no-tillage. Full tillage was defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. This definition corresponds to the intensive tillage and "reduced" tillage systems as defined by CTIC (1998).

No-till was defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. Reduced tillage made up the remainder of the cultivated area, including mulch tillage and ridge tillage as defined by CTIC and intermittent no-till. The specific tillage implements and applications used for different crops, rotations, and regions to represent the three tillage classes were derived from the 1995 Cropping Practices Survey by the Economic Research Service (ERS 1997).

Tillage data were further processed to construct probability distribution functions (PDFs) using CTIC tillage data. Transitions between tillage systems were based on observed county-level changes in the frequency distribution of the area under full, reduced, and no-till from the 1980s through 2004. Generally, the fraction of full tillage decreased during this time span, with concomitant increases in reduced till and no-till management. Transitions that were modeled and applied to NRI points occurring within a county were full tillage to reduced and no-till, and reduced tillage to no-till. The remaining amount of cropland was assumed to have no change in tillage (e.g., full tillage remained in full tillage). Transition matrices were constructed from CTIC data to represent tillage changes for three time periods, 1980-1989, 1990-1999, 2000-2010. Areas in each of the three tillage classes—full till (FT), reduced till (RT), no-till (NT)—in 1989 (the first year the CTIC data were available) were used for the first time period, data from 1997 were used for the second time period, and data from 2004 were used for the last time period. Percentage areas of cropland in each county were calculated for each possible transition (e.g., FT→FT, FT→RT, FT→NT, RT→RT, RT→NT) to obtain a probability for each tillage transition at an NRI point. Since continuous NT constituted < 1 percent of total cropland prior to 1990, there were no transitions for NT→FT or NT→NT. Uniform probability distributions were established for each tillage scenario in the county. For example, a particular crop rotation had 80 percent chance of remaining in full tillage over the two decades, a 15 percent chance of a transition from full to reduced tillage and a 5 percent chance of a transition from full to no-till. The uniform distribution was subdivided into three segments with random draws in the Monte Carlo simulation (discussed in Step 2b) leading to full tillage over the entire time period if the value was greater than or equal to 0 and less than 80, a transition from full to reduced till if the random draw was equal to or greater than 80 and less than 95, or a transition from full to no-till if the draw was greater than or equal to 95. See step 2b for additional discussion of the uncertainty analysis.

Mineral Fertilizer Application—Data on nitrogen fertilizer rates were obtained primarily from USDA's Economic Research Service's 1995 Cropping Practices Survey (ERS 1997). In this survey, data on inorganic nitrogen fertilization rates were collected for major crops (corn, cotton, soybeans, potatoes, winter wheat, durum wheat, and other spring wheat) in the key crop producing states. Note that all wheat data were combined into one category and assumed to represent small grains in general. Estimates for sorghum fertilizer rates were derived from corn rates using a ratio of national average corn fertilizer rates to national average sorghum fertilizer rates derived from additional publications (NASS 2004, 1999, 1992; ERS 1988; Grant and Krenz 1985; USDA 1954, 1957, 1966).

The ERS survey parameter "TOT N" (total amount of N applied per acre), with a small number of records deleted as outliers, was used in determining the fraction of crop acres receiving fertilizer and the average fertilizer rates for a region. Mean fertilizer rates and standard deviations for irrigated and rainfed crops were produced for each state at the finest resolution available. State-level data were produced for surveyed states if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). If a state was not surveyed for a particular crop or if fewer than 15 data points existed for one of the categories, then data at the Farm Production Region level were substituted. If Farm Production Region data were not available, then U.S.-level estimates (all major states surveyed) were used in the simulation for that particular crop in the state lacking sufficient data. Note that standard deviations for fertilizer rates on log scale were used to construct PDFs on a log-normal scale, in order to address uncertainties in application rates (see Step 2b for discussion of uncertainty methods).

Manure Application—County-level manure N addition estimates were obtained from the Natural Resources Conservation Service (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, NRCS has coupled estimates of manure nitrogen produced with estimates of manure nitrogen recoverability by animal waste management system to produce county-level estimates of manure nitrogen applied to cropland and pasture. Edmonds et al. (2003) defined a hierarchy of land use systems to which manure is applied, that included 24 crops, cropland used as pasture, and permanent pasture. They estimated the area amended with manure and manure nitrogen application rates in 1997 for both manure-producing farms and manure-receiving farms within a county, for two scenarios—before implementation of Comprehensive Nutrient Management Plans (baseline) and after implementation. The application rates for the baseline scenario were used in the inventory under the assumption that Comprehensive Nutrient Management Plans have not been fully implemented.

In order to derive estimates of manure application rates over time, the availability of managed manure N for application to soils (which are available annually) was used to adjust the amount of area amended with manure on a county scale (Note: Edmonds et al. (2003) only provide information on application rates for 1997). Specifically, the estimated available managed manure N in another year was divided by the managed manure N available in 1997. The amendment area in a county for 1997 was then multiplied by the ratio to reflect the probability of manure amendments based on the variation in available manure N across time. If more managed manure N was available in a given year for a county relative to the amount available in 1997 (ratio > 1), it was assumed that there was a higher probability of a manure amendment. In contrast, if less managed manure N was available (ratio < 1), the probability of an amendment declined in comparison to 1997. A detailed description of the derivation of the managed manure N availability data is provided in the Manure Management section (Section 6.2) and Annex (Annex 3.10). Managed manure N availability in the 1980s was based on USDA estimates (Kellogg et al. 2000) after adjusting for relative differences in manure N production between the USDA dataset and estimates derived from the method described in Annex 3.10. Unmanaged manure classified as pasture/range/paddock manure was assumed to have negligible impacts on soil C stocks because of the tradeoff between reduced litterfall C versus C ingested by livestock and deposited on soils in manure.

For Century simulations, the amended areas were averaged for three time periods (1980-1989, 1990-1999, and 2000-2010) similar to the tillage transitions. Rates for manure-producing farms and manure-receiving farms have been area-weighted and combined to produce a manure nitrogen application rate for each crop in a county. Several of the crops in Edmonds et al. (2003) have been area-weighted and combined into broader crop categories. For example, all small grain crops have been combined into one category. In order to address uncertainty, uniform probability distributions were constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if the 20 percent of land producing corn in a county was amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation (see Step 2b for further discussion of uncertainty methods).

To estimate the C inputs associated with the manure N application rates (from Edmonds et al. 2003), C:N ratios for various manure types (based on animal species and manure management system) were estimated from data in the *Agricultural Waste Management Field Handbook* (USDA 1996) and the *On-Farm Composting Handbook* (NRAES 1992). Weighted county-average C:N ratios for total manure applied were then calculated based on the C:N ratio and the manure N production rate for each manure type reported in the county. Manure C addition rates were then calculated by multiplying the county-average manure C:N ratio by the manure N application rates.

To account for the common practice of reducing inorganic nitrogen fertilizer inputs when manure is added to a cropland soil, a set of crop-specific reduction factors were derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (ERS 1997). In the simulations, mineral N fertilization rates were reduced for crops receiving manure nitrogen based on a fraction of the amount of manure nitrogen applied, depending on the crop and whether it was irrigated or a rainfed system. The reduction factors were selected from PDFs with normal densities in order to address uncertainties in this dependence between manure amendments and mineral fertilizer application.

Irrigation—NRI differentiates between irrigated and non-irrigated land but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation was modeled by assuming that applied water was sufficient to meet full crop demand (i.e., irrigation plus precipitation equaled potential evapotranspiration during the growing season).

Step 1c—Obtain Additional Management Activity Data for Tier 2 IPCC Method

Tillage Practices—PDFs were constructed for the CTIC tillage data, as bivariate normal on a log-ratio scale to reflect negative dependence among tillage classes. This structure ensured that simulated tillage percentages were non-negative and summed to 100 percent. CTIC data do not differentiate between continuous and intermittent use of no-tillage, which is important for estimating SOC storage. Thus, regionally based estimates for continuous no-tillage (defined as 5 or more years of continuous use) were modified based on consultation with CTIC experts, as discussed in Step 1a (downward adjustment of total no-tillage acres reported, Towery 2001).

Manure Amendments—Manure management is also a key practice in agricultural lands, with organic amendments leading to significant increases in SOC storage. USDA provides information on the amount of land amended with manure for 1997 based on manure production data and field-scale surveys detailing application rates that had been collected in the *Census of Agriculture* (Edmonds et al. 2003). Similar to the Century model discussion in Step1b, the amount of land receiving manure was based on the estimates provided by Edmonds et al. (2003), as a proportion of crop and grassland amended with manure within individual climate regions. The resulting proportions were used to re-classify a portion of crop and grassland into a new management category. Specifically, a portion of medium input cropping systems was re-classified as high input, and a portion of the high input systems was re-classified as high input with amendment. In grassland systems, the estimated proportions for land amended with manure were used to re-classify a portion of nominally-managed grassland as improved, and a portion of improved grassland as improved with high input.

These classification approaches are consistent with the IPCC inventory methodology (IPCC 2003, 2006). Uncertainties in the amount of land amended with manure were based on the sample variance at the climate region scale, assuming normal density PDFs (i.e., variance of the climate region estimates, which were derived from county-scale proportions).

Wetland Reserve—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 area 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 ±50 percent range was used to construct the PDFs for the uncertainty analysis.

Step 1d—Obtain Management Activity Data to Compute Additional Changes in Soil Organic C Stocks in Mineral Soils Due to Sewage Sludge Applications and CRP Enrollment after 2003

Two additional influences on soil organic C stocks in mineral soils were estimated using a Tier 2 method, including: sewage sludge additions to agricultural soils and changes in enrollment for the Conservation Reserve Program after 2003.

Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. Sewage sludge generation data are not available for 2005 onwards (Bastian 2007), so the 1990 through 2004 data were linearly extrapolated for the most recent years. The total sludge generation estimates were then converted to units of N by applying an average N content of 3.9 percent (McFarland 2001), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices were agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal. Sewage sludge N was assumed to be applied at the assimilative capacity provided in Kellogg et al. (2000), which is the amount of nutrients taken up by a crop and removed at harvest, representing the recommended application rate for manure amendments. This capacity varies from year to year, because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total sewage sludge N available for application was divided by the assimilative capacity to estimate the total land area over which sewage sludge had been applied. The resulting estimates were used for the estimation of soil C stock change.

The change in enrollment for the Conservation Reserve Program after 2003 was based on the amount of land under active contracts from 2004 through 2010 relative to 2003 (USDA-FSA 2010).

Step 1e: Obtain Climate and Soils Data

Tier 3 Century Model—Monthly weather data (temperature and precipitation) from the PRISM database (Parameter-elevation Regressions on Independent Slopes Model) (Daly et al. 1994) were used as an input to the Century model simulations for the period 1895 through 2003. PRISM is based on observed weather data from the National Weather Service network database and statistical models for interpolation and orographic corrections. The primary database consists of approximately 4×4 km grid cells. These data were averaged (weighted by area) for each county in the United States, so that counties are the finest spatial scale represented in the Century simulations.

Soil texture and natural drainage capacity (i.e., hydric vs. non-hydric soil characterization) were the main soil variables used as input to the Century model. Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, were estimated from soil texture data using pedo-transfer functions available in the model. Soil input data are derived from the NRI database, which contain descriptions for the soil type at each NRI point (used to specify land-use and management time series-see below). The data are based on field measurements collected as part of soil survey and mapping. Soils are classified according to “soil-series,” which is the most detailed taxonomic level used for soil mapping in the United States. Surface soil texture and hydric condition were obtained from the soil attribute table in the NRI database. Texture is one of the main controls on soil C turnover and stabilization in the Century model, which uses particle size fractions of sand (50-2,000 µm), silt (2-50 µm), and clay (< 2 µm) as inputs. NRI points were assigned to one of twelve texture classes for the simulations. Hydric condition specifies whether soils are poorly-drained, and hence prone to water-logging, or moderately to well-drained (non-hydric), in their native (pre-cultivation) condition.[80] Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from being fully aerobic to completely anaerobic, varying over the year. Decomposition rates are modified according to a linear

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[80] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in Century).[81]

IPCC Tier 2 Method—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 2006) (Table A-238). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table A-238: 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)[a]	> 20	1,000 – 2,000	< 5

[a] 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.

Mean climate (1961-1990) variables from the PRISM data set (Daly et al. 1994) were used to classify climate zones. Mean annual precipitation and annual temperature data were averaged (weighted by area) for each of the 4×4 km grid cells occurring within a MLRA region. These averages were used to assign a climate zone to each MLRA according to the IPCC climate classification (Figure A-15). MLRAs represent geographic units with relatively similar soils, climate, water resources, and land uses; and there are approximately 180 MLRAs in the United States (NRCS 1981).

Figure A-15: 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 2006). Six of the categories are mineral types and one is organic (i.e., Histosol). Reference C stocks, representing estimates from conventionally managed cropland, were computed for each of the mineral soil types across the various climate zones, based on pedon (i.e., soil) data from the National Soil Survey Characterization Database (NRCS 1997) (Table A-239). These stocks are used in conjunction with management factors to compute the change in SOC stocks that result from management and land-use activity. PDFs, 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 A-239: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

		Reference Carbon Stock in Climate Regions					
IPCC Inventory Soil Categories	USDA Taxonomic Soil Orders	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)

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[81] Hydric soils are primarily subject to anaerobic conditions outside the plant growing season (i.e., in the absence of active plant water uptake). Soils that are water-logged during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the Century model.

Organic Soils[a]	Histosols	NA	NA	NA	NA	NA	NA

[a] C stocks are not needed for organic soils.

Notes: C 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 (i.e., 'n' values refer to sample size).

Step 2: Estimate Organic C Stock Changes for Agricultural Lands on Mineral Soils Simulated with the Tier 3 Century Model

This methodology description is divided into two sub-steps. First, the model was used to establish the initial conditions and C stocks for 1979, which was the last year before the NRI survey was initiated. In the second sub-step, Century was used to estimate changes in soil organic C stocks based on the land-use and management histories recorded in the NRI (USDA-NRCS 2000), including the reporting period starting in 1990.

Step 2a: Simulate Initial Conditions (Pre-NRI Conditions)

Century model initialization involves two steps, with the goal of estimating the most accurate stock for the pre-NRI history, and the distribution of organic C among the pools represented in the model (e.g., Structural, Metabolic, Active, Slow, Passive). Each pool has a different turnover rate (representing the heterogeneous nature of soil organic matter), and the amount of C in each pool at any point in time influences the forward trajectory of the total soil organic C storage. There is currently no national set of soil C measurements that can be used for establishing initial conditions in the model. Sensitivity analysis of the Century model showed that the rate of change of soil organic matter is relatively insensitive to the *amount* of total soil organic C but is highly sensitive to the relative *distribution* of C among different pools (Parton et al. 1987). By simulating the historical land use prior to the inventory period, initial pool distributions are estimated in an unbiased way.

The first step involves running the model to a steady-state condition (e.g., equilibrium) under native vegetation, with long-term mean climate based on 30-yr averages of the PRISM data (1960-1990), and the soil physical attributes for the NRI points. Native vegetation is represented at the MLRA level for pre-settlement time periods in the United States. The model was run for 7,000 years to represent a pre-settlement era and achieve a steady-state condition.

The second step is to run the model for the period of time from settlement to the beginning of the NRI survey, representing the influence of historic land-use change and management, particularly the conversion of native vegetation to agricultural uses. This encompasses a varying time period from land conversion (depending on historical settlement patterns) to 1979. The information on historical cropping practices used for Century simulations was gathered from a variety of sources, ranging from the historical accounts of farming practices reported in the literature (e.g., Miner 1998) to national level databases (e.g., NASS 2004). A detailed description of the data sources and assumptions used in constructing the base history scenarios of agricultural practices can be found in Williams and Paustian (2005).

Step 2b—Estimate Soil Organic C Stock Changes and Uncertainties

After estimating model initialization, the model is used to simulate the NRI land use and management histories from 1979 through 2003.[82] The simulation system incorporates a dedicated MySQL database server and a 24-node parallel processing computer cluster. Input/output operations are managed by a set of run executive programs written in PERL. The assessment framework for this analysis is illustrated in Figure A-16.

Figure A-16: Uncertainty in Data Inputs

Evaluating uncertainty was an integral part of the analysis, and included three components: (1) uncertainty in the main activity data inputs affecting soil C balance (input uncertainty); (2) uncertainty in the model formulation and parameterization (structural uncertainty); and (3) uncertainty in the land-use and management system areas (scaling uncertainty) (Ogle et al. 2010). For component 1, input uncertainty was evaluated for fertilization management, manure applications, and tillage, which are the primary management activity data that were supplemental to the NRI observations and have significant influence on soil C dynamics. As described in Step 1b, PDFs were derived from surveys at the county scale in most cases. To represent uncertainty in these inputs, a Monte-Carlo Analysis was used with 100 iterations for each NRI cluster-point in which random draws were made from PDFs for fertilizer, manure application, and tillage. As described above, an adjustment factor was also selected from PDFs with normal densities to represent the dependence

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[82] The estimated soil C stock change in 2003 is currently assumed to represent the changes between 2004 and 2010. New estimates will be available in the future to extend the time series of land use and management data.

between manure amendments and N fertilizer application rates. The total number of Century simulations was over 12 million for the Monte Carlo Analysis with 100 iterations.

The second component dealt with uncertainty inherent in model formulation and parameterization. An empirically-based procedure was employed to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments (Ogle et al. 2007). The Century model was initialized for 45 long-term field experiments with over 800 treatments in which soil C was measured under a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, manure amendments). These studies were obtained from an extensive search of published studies. All studies located in North America that met minimum criteria of having sufficient site-level information and experimental designs were used, including C stock estimates, texture data, experimental designs with control plots, and land-use and management records for the experimental time period and pre-experiment condition. The inputs to the model were essentially known in the simulations for the long-term experiments, and, therefore, the analysis was designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization).

The relationship between modeled soil C stocks and field measurements was statistically analyzed using linear-mixed effect modeling techniques. Additional fixed effects were included in the mixed effect model if they explained significant variation in the relationship between modeled and measured stocks (i.e., if they met an alpha level of 0.05 for significance). Several variables were tested including: land-use class; type of tillage; cropping system; geographic location; climate; soil texture; time since the management change; original land cover (i.e., forest or grassland); grain harvest as predicted by the model compared to the experimental values; and variation in fertilizer and residue management. The final model included variables for organic matter amendments, fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, and inclusion of bare fallow in the rotation, which were significant at an alpha level of 0.05. These fixed effects were used to make an adjustment to modeled values due to biases that were creating significant mismatches between the modeled and measured stock values. Random effects captured the statistical dependence (i.e., the data are not fully independent) in time series and data collected from the same long-term experimental site. Accounting for this statistical dependency is needed to estimate appropriate standard deviations for parameter coefficients.

A Monte Carlo approach was used to apply the uncertainty estimator (Ogle et al. 2010). Parameter values for the statistical equation (i.e., fixed effects) were selected from their joint probability distribution, as well as random error associated with fine-scale estimates at NRI points, and the residual or unexplained error associated with the linear mixed-effect model. The stock estimate and associated management information was then used as input into the equation, and adjusted stock values were computed for each C stock estimate produced in the evaluation of input uncertainty for *Cropland Remaining Cropland* (Component 1 of the uncertainty analysis). Note that the uncertainty estimator needs further development for application to *Grassland Remaining Grassland* and the land-use change categories. This development is a planned improvement for the soil C inventory. The variance of the adjusted C stock estimates were computed from the 100 simulated values from the Monte Carlo analysis.

The third element was the uncertainty associated with scaling the Century results for each NRI point to the entire land base, using the expansion factors provided with the NRI database. The expansion factors represent the number of hectares associated with the land-use and management history for a particular point. This uncertainty was determined by computing the variances of the expanded estimates, accounting for the two-stage sampling design of the NRI.

For the land base that was simulated with the Century model, soil organic C stocks ranged from losses of 4.25 Tg CO_2 Eq. to gains of 68.05 Tg CO_2 Eq. annually, depending on the land-use/land-use change category and inventory time period. Estimates and uncertainties are provided in Table A-240.

Table A-240: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Simulated with the Tier 3 Century Model-Based Approach (Tg CO_2 Eq.)

	Cropland Remaining Cropland		Land Converted to Cropland		Grassland Remaining Grassland		Land Converted to Grassland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
1990	(55.19)	(111.72) to 1.33	(4.43)	(5.06) to (3.80)	(55.10)	(57.18) to (53.01)	(15.75)	(18.43) to (13.07)
1991	(57.50)	(90.49) to (24.51)	(4.30)	(4.93) to (3.68)	(28.04)	(29.87) to (26.21)	(15.06)	(17.58) to (12.54)
1992	(68.05)	(99.81) to (36.28)	(4.75)	(5.38) to (4.13)	(9.84)	(10.82) to (8.85)	(13.83)	(16.23) to (11.44)
1993	(64.25)	(95.93) to (32.56)	(8.66)	(9.34) to (7.98)	(1.48)	(3.29) to 0.33	(13.52)	(16.09) to (10.94)
1994	(62.38)	(94.48) to (30.29)	(12.61)	(13.42) to (11.80)	(66.74)	(68.28) to (65.20)	(17.87)	(20.62) to (15.12)
1995	(47.58)	(83.91) to (11.25)	(3.84)	(4.51) to (3.17)	(29.45)	(30.78) to (28.13)	(18.21)	(20.80) to (15.61)
1996	(54.99)	(83.65) to (26.32)	(4.55)	(5.24) to (3.85)	4.25	3.00 to 5.50	(15.19)	(17.78) to (12.60)
1997	(54.08)	(81.53) to (26.63)	(4.21)	(4.94) to (3.48)	(20.44)	(21.73) to (19.14)	(19.90)	(22.64) to (17.16)
1998	(44.34)	(77.06) to (11.61)	(10.77)	(11.60) to (9.94)	1.46	2.49 to 0.43	(17.33)	(20.33) to (14.33)
1999	(29.72)	(58.21) to (1.23)	(3.30)	(4.02) to (2.59)	(18.92)	(19.78) to (18.06)	(23.95)	(26.64) to (21.26)
2000	(54.83)	(85.86) to (23.80)	(4.41)	(5.15) to (3.67)	(55.15)	(56.04) to (54.26)	(23.11)	(26.26) to (19.97)

2001	(37.57)	(68.05) to (7.08)	(2.53)	(3.24) to (1.83)	(27.34)	(28.17) to (26.51)	(24.03)	(27.01) to (21.05)
2002	(36.14)	(67.43) to (4.85)	(1.97)	(2.68) to (1.25)	(46.81)	(47.62) to (46.00)	(22.72)	(25.70) to (19.73)
2003	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.65)	(12.50) to (10.79)	(20.69)	(23.50) to (17.89)
2004	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.49)	(12.34) to (10.64)	(20.51)	(23.31) to (17.70)
2005	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.32)	(12.17) to (10.47)	(20.31)	(23.11) to (17.50)
2006	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.14)	(11.99) to (10.29)	(20.10)	(22.90) to (17.30)
2007	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.97)	(11.82) to (10.12)	(19.90)	(22.70) to (17.09)
2008	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.79)	(11.65) to (9.94)	(19.69)	(22.49) to (16.89)
2009	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.62)	(11.47) to (9.77)	(19.48)	(22.29) to (16.68)
2010	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.62)	(11.47) to (9.77)	(19.48)	(22.29) to (16.68)

Note: Does not include the change in storage resulting from the annual application of sewage sludge, or the additional Conservation Reserve Program enrollment.

Step 3: Estimate C Stock Changes in Agricultural Lands on Mineral Soils Approximated with the Tier 2 Approach, in Addition to CO_2 Emissions from Agricultural Lands on Drained Organic Soils

Mineral and organic soil calculations were made for each climate by soil zone across the United States. Mineral stock values were derived for non-major crop rotations and land converted from non-agricultural uses to cropland in 1982, 1992, and 1997 based on the land-use and management activity data in conjunction with appropriate reference C stocks, land-use change, tillage, input, and wetland restoration factors. C losses from organic soils were computed based on 1992 and 1997 land use and management in conjunction with the appropriate C loss rate. Each input to the inventory calculations for the Tier 2 approach had some level of uncertainty that was quantified in PDFs, including the land-use and management activity data, reference C stocks, and management factors. A Monte Carlo Analysis was used to quantify uncertainty in SOC change for the inventory period based on uncertainty in the inputs. Input values were randomly selected from PDFs in an iterative process to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results.

Step 3a: Derive Mineral Soil Stock Change and Organic Soil Emission Factors

Stock change factors representative of U.S. conditions were estimated from published studies (Ogle et al. 2003, Ogle et al. 2006). The numerical factors quantify the impact of changing land use and management on SOC storage in mineral soils, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program), as well as the net loss of SOC from organic soils attributed to agricultural production on drained soils. Studies from the United States and Canada were used in this analysis under the assumption that they would best represent management impacts for the Inventory.

For mineral soils, studies had to report SOC stocks (or information to compute stocks), depth of sampling, and the number of years since a management change to be included in the analysis. The data were analyzed using linear mixed-effect modeling, 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 C 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 dependence in time series data and the dependence 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 (Table A-241). Variance was calculated for each of the U.S. factor values, and used to construct PDFs with a normal density. In the IPCC method, specific factor values are given for improved grassland, high input cropland with organic amendments, and for wetland rice, each of which influences the C balance of soils. Specifically, higher stocks are associated with increased productivity and C inputs (relative to native grassland) on improved grassland with both medium and high input.[83] Organic amendments in annual cropping systems also increase SOC stocks due to greater C inputs, while high SOC stocks in rice cultivation are associated with reduced decomposition due to periodic flooding. There were insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2003) were used under the assumption that they would best approximate the impacts, given the lack of sufficient data to derive U.S.-specific factors. A measure of uncertainty was provided for these factors in IPCC (2003), which was used to construct PDFs.

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[83] Improved grasslands are identified in the 1997 *National Resources Inventory* as grasslands that were irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-241: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

		U.S. Factor			
	IPCC default	Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Change Factors					
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 Grassland Factors[c]					
Medium Input	1.1	1.14±0.06	1.14±0.06	1.14±0.06	1.14±0.06
High Input	Na	1.11±0.04	1.11±0.04	1.11±0.04	1.11±0.04
Wetland Rice Production Factor[c]	1.1	1.1	1.1	1.1	1.1
Tillage Factors					
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
Cropland Input Factors					
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
High with amendment[c]	1.2	1.38±0.06	1.34±0.08	1.38±0.06	1.34±0.08

Note: The “n” values refer to sample size.

[a] Factors in the IPCC documentation (IPCC 2006) were converted to represent changes in SOC storage from a cultivated condition rather than a native condition.

[b] Default factor was higher for aquic soils at 1.7. The U.S. analysis showed no significant differences between aquic and non-aquic soils, so a single U.S. factor was estimated for all soil types.

[c] U.S.-specific factors were not estimated for land improvements, rice production, or high input with amendment because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for crop and grassland in the United States, or the impact of wetland rice production in the US. Factors provided in IPCC (2003) were used as the best estimates of these impacts.

Wetland restoration management also influences SOC storage in mineral soils, because restoration leads to higher water tables and inundation of the soil for at least part of the year. A stock change factor was estimated assessing the difference in SOC storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Euliss and Gleason 2002), which represents an initial increase of C in the restored soils over the first 10 years (Table A-242). A PDF with a normal density was constructed from these data based on results from a linear regression model. Following the initial increase of C, natural erosion and deposition leads to additional accretion of C in these wetlands. The mass accumulation rate of organic C was estimated using annual sedimentation rates (cm/yr) in combination with percent organic C, 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 PDF with a normal density (Table A-242).

Table A-242: Factor Estimate for the Initial and Subsequent Increase in Organic Soil C Following Wetland Restoration of Conservation Reserve Program

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 represents additional gains in C for mineral soils after the first 10 years (Euliss and Gleason 2002).

In addition, C loss rates were estimated for cultivated organic soils based on subsidence studies in the United States and Canada (Table A-243). PDFs were constructed as normal densities based on the mean C loss rates and associated variances.

Table A-243: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

	Cropland		Grassland	
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 grassland. Consequently, estimates are 25 percent of the values for cropland, which was an assumption used for the IPCC default organic soil C losses on grassland.

Step 3b: Estimate Annual Changes in Mineral Soil Organic C Stocks and CO_2 Emissions from Organic Soils

In accordance with IPCC methodology, annual changes in mineral soil C were calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[84] For this analysis, the base inventory estimate for 1990 through 1992 is the annual average of 1992 stock minus the 1982 stock. The annual average change between 1993 and 2010 is the difference between the 1997 and 1992 C stocks. Using the Monte Carlo approach, SOC 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 (Ogle et al. 2003).

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 in the United States. The results for 1992 were applied to the years 1990 through 1992, and the results for 1997 were applied to the years 1993 through 2010.

Mineral soils for the land base estimated with the Tier 2 approach accumulated about 1.7 to 3.0 Tg CO_2 Eq. annually in *Cropland Remaining Cropland*, while mineral soils in *Land Converted to Cropland* lost C at a rate of about 4.1 to 4.2 Tg CO_2 Eq. annually. Minerals soils in *Grassland Remaining Grassland* had small gains of about 0.2 to 0.3 Tg CO_2 Eq. annually and sequestered from 4.6 to 5.0 Tg CO_2 Eq. annually in *Land Converted to Grassland*. Organic soils lost about 27.4 to 27.7 Tg CO_2 Eq. annually in *Cropland Remaining Cropland* and 2.4 to 2.6 Tg CO_2 Eq. annually in *Land Converted to Cropland*, as well as an additional 3.7 to 3.9 Tg CO_2 Eq. annually in *Grassland Remaining Grassland* (Table A-244) and 0.5 to 0.9 Tg CO_2 Eq. annually in *Land Converted to Grassland*. Estimates and uncertainties are provided in Table A-244.

Table A-244: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values, Reference Carbon Stocks, and Carbon Loss Rates (Tg CO_2 Eq./yr)

	Cropland Remaining Cropland		**Land Converted to Cropland**		**Grassland Remaining Grassland***		**Land Converted to Grassland***	
Year	**Estimate**	**95% CI**	**Estimate**	**95% CI**	**Estimate**	**95% CI**	**Estimate**	**95% CI**
Mineral Soils								
1990-1992	(1.65)	(2.6) to 5.8	4.18	2.5 to 6.0	(0.33)	(0.6) to (0.1)	(4.55)	(6.5) to (2.7)
1993-2010	(3.01)	(6.9) to 0.8	4.14	2.5 to 6.0	(0.15)	(0.4) to 0.04	(4.99)	(7.2) to (2.9)
Organic Soils								
1990-1992	27.43	18.3 to 39.4	2.42	1.4 to 3.8	3.85	1.97 to 6.4	0.47	0.22 to 0.8
1993-2010	27.68	18.5 to 39.5	2.64	1.5 to 4.0	3.69	1.9 to 6.1	0.88	0.4 to 1.5

* Preliminary estimates that will be finalized after public review period following completion of quality control measures.

Step 4: Compute Additional Changes in Soil Organic C Stocks Due to Organic Amendments and CRP Enrollment after 2003

There are two additional land-use and management activities in U.S. agricultural lands that were not estimated in Steps 2 and 3. The first activity involved the application of sewage sludge to agricultural lands. Minimal data exist on where and how much sewage sludge is applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving sewage sludge can be approximated based on sewage sludge N production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). It was assumed that sewage sludge for agricultural land application was applied to grassland because of the high heavy metal content and other pollutants found in human waste, which limits its application to crops. The impact of organic amendments on SOC was calculated as 0.38 metric tonnes C/ha-yr. This rate is based on the IPCC default method and country-specific factors (see Table A- 245), by calculating the effect of converting nominal, medium-input grassland to high input improved grassland (assuming a reference C stock of 50 metric tonnes C/ha, which represents a mid-range value for the dominant cropland soils in the United States, the land use factor for grassland (1.4) and the country-specific factor of 1.11 for high input improved grassland, with the change in stocks occurring over a 20 year (default value) time period; i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). From 1990 through 2010, sewage sludge applications in agricultural lands increased SOC storage from 0.6 to 1.3 Tg CO_2 Eq./year (Table A- 245). A nominal ±50 percent uncertainty was attached to these estimates due to limited information on application and the rate of change in soil C stock change with sewage sludge amendments.

The second activity was the change in enrollment for the Conservation Reserve Program after 2003 for mineral soils. Relative to the enrollment in 2003, the total area in the Conservation Reserve Program decreased from 2004 to 2010, leading to a reduction in enrollment of 1.14 million ha over the six-year period (USDA-FSA 2010). An average

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[84] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

annual change in SOC of 0.5 metric tonnes C/ha-yr was used to estimate the effect of the enrollment changes. This rate is based on the IPCC default method and country-specific factors (see Table A-241) by calculating the impact of setting aside a medium input cropping system in the Conservation Reserve Program (assuming a reference C stock of 50 metric tonnes C/ha, which represents a mid-range value for the dominant cropland soils in the United States and the average country-specific factor of 1.2 for setting-aside cropland from production, with the change in stocks occurring over a 20 yr (default value) time period; i.e., [50 × 1.2 – 50] / 20 = 0.5). While increases in enrollment from 2004 to 2008 generated additional accumulation of CO_2 Eq. annually, reductions in enrollment in 2010 caused emissions of 2.09 Tg CO_2 Eq (Table A-246). A nominal ±50 percent uncertainty was also attached to these estimates due to limited information about the enrollment trends at subregional scales, which creates uncertainty in the rate of the soil C stock change (stock change factors for set-aside lands vary by climate region).

Step 5: Compute Net CO_2 Emissions and Removals from Agricultural Lands

The sum of total CO_2 emissions and removals from the Tier 3 Century Model Approach (Step 2), Tier 2 IPCC Methods (Step 3) and additional land-use and management considerations (Step 4) are presented in Table A-246. Overall, there was a net accumulation of 99.2 Tg CO_2 Eq. in 1990 for agricultural soils, and this rate had decreased by the end of the reporting period in 2010 to 41.6 Tg CO_2 Eq.

The total stock change (as seen in the Land Use, Land-Use Change, and Forestry chapter) as well as per hectare rate of change varies among the states (Figure A-17 and Figure A-18). On a per hectare basis, the highest rates of C accumulation occurred in the Northeast, Midwest, northern Great Plains, and Northwest. The states with highest total amounts of C sequestration were Iowa, Illinois, Missouri, Montana, Oklahoma, North Dakota, and South Dakota (Table A- 247). For organic soils, emission rates were highest in the regions that contain the majority of the drained organic soils, including California, Florida, Michigan, Minnesota, and New York. On a per hectare basis, the emission rate patterns were very similar to the total emissions in each state, with the highest rates in those regions with warmer climates and a larger proportion of the drained organic soil managed for crop production.

Figure A-17: Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2010

Figure A-18: Net C Stock Change, per Hectare, for Organic Soils Under Agricultural Management, 2010

Table A- 245: Assumptions and Calculations to Estimate the Contribution to Soil Organic Carbon Stocks from Application of Sewage Sludge to Mineral Soils

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Sewage Sludge N Applied to Agricultural Land (Mg N)[a]	52,198	55,658	59,250	62,977	65,966	69,001	72,081	75,195	78,353	80,932	83,523	86,124	88,736	91,358	93,991	98,081	100,887	103,682	106,468	109,245	109,245
Assimilative Capacity (Mg 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	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122
Area covered by Available Sewage Sludge N (ha)[c]	434,985	463,816	493,746	516,202	540,707	565,583	590,828	616,357	642,240	663,381	684,612	705,932	727,341	748,836	770,418	803,942	826,940	849,851	872,686	895,452	895,452
Average Annual Rate of C storage (Mg C/ha-yr)[d]	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Contribution to Soil C ($TgCO_2$/yr)[e,f]	**(0.61)**	**(0.65)**	**(0.69)**	**(0.72)**	**(0.75)**	**(0.79)**	**(0.82)**	**(0.86)**	**(0.89)**	**(0.92)**	**(0.95)**	**(0.98)**	**(1.01)**	**(1.04)**	**(1.07)**	**(1.12)**	**(1.15)**	**(1.18)**	**(1.22)**	**(1.25)**	**(1.25)**

Values in parentheses indicate net C storage.

[a] N applied to soils described in Step 1d.

[b] Assimilative Capacity is the national average amount of manure-derived N that can be applied on cropland without buildup of nutrients in the soil (Kellogg et al., 2000).

[c] Area covered by sewage sludge N available for application to soils is the available N applied at the assimilative capacity rate. The 1992 assimilative capacity rate was applied to 1990 – 1992 and the 1997 rate was applied to 1993-2010.

[d] Annual rate of C storage based on national average increase in C storage for grazing lands that is attributed to organic matter amendments (0.38 Mg/ha-yr)

[e] Contribution to Soil C is estimated as the product of the area covered by the available sewage sludge N and the average annual C storage attributed to an organic matter amendment.

[f] 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.

Table A-246: Annual Soil C Stock Change in *Cropland Remaining Cropland* (CRC), *Land Converted to Cropland* (LCC), *Grassland Remaining Grassland* (GRG), and *Land Converted to Grassland* (LCG), in U.S. Agricultural Soils (Tg CO_2 Eq.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Net emissions based on Tier 3 Century-based analysis (Step 2)																					
CRC	(55.2)	(57.5)	(68.0)	(64.2)	(62.4)	(47.6)	(55.0)	(54.1)	(44.3)	(29.7)	(54.8)	(37.6)	(36.1)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)
LCC	(4.4)	(4.3)	(4.8)	(8.7)	(12.6)	(3.8)	(4.5)	(4.2)	(10.8)	(3.3)	(4.4)	(2.5)	(2.0)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
GRG	(55.1)	(28.0)	(9.8)	(1.5)	(66.7)	(29.5)	4.2	(20.4)	1.5	(18.9)	(55.2)	(27.3)	(46.8)	(11.7)	(11.5)	(11.3)	(11.1)	(11.0)	(10.8)	(10.6)	(10.6)
LCG	(15.8)	(15.1)	(13.8)	(13.5)	(17.9)	(18.2)	(15.2)	(19.9)	(17.3)	(24.0)	(23.1)	(24.0)	(22.7)	(20.7)	(20.5)	(20.3)	(20.1)	(19.9)	(19.7)	(19.5)	(19.5)
Net emissions based on the IPCC Tier 2 analysis (Step 3)																					
Mineral Soils																					
CRC	(1.6)	(1.6)	(1.6)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)
LCC	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
GRG	(0.3)	(0.3)	(0.3)	(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)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
LCG	(4.5)	(4.5)	(4.5)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Organic Soils																					
CRC	27.4	27.4	27.4	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7
LCC	2.4	2.4	2.4	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
GRG	3.9	3.9	3.9	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
LCG	0.5	0.5	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Additional changes in net emissions from mineral soils based on application of sewage sludge to agricultural land (Step 4)																					
GRG	(0.6)	(0.6)	(0.7)	(0.7)	(0.8)	(0.8)	(0.8)	(0.9)	(0.9)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.1)	(1.1)	(1.2)	(1.2)	(1.2)	(1.3)	(1.3)
Additional changes in net emissions from mineral soils based on additional enrollment of CRP land (Step 4)																					
CRC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(0.4)	(0.6)	(1.4)	(2.0)	(0.4)	0.3	2.09
Total Stock Changes by Land Use/Land-Use Change Category (Step 5)																					
CRC	(29.4)	(31.7)	(42.3)	(39.6)	(37.7)	(22.9)	(30.3)	(29.4)	(19.7)	(5.1)	(30.2)	(12.9)	(11.5)	(17.7)	(18.1)	(18.3)	(19.1)	(19.7)	(18.1)	(17.4)	(15.6)
LCC	2.2	2.3	1.8	(1.9)	(5.8)	2.9	2.2	2.6	(4.0)	3.5	2.4	4.2	4.8	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
GRG	(52.2)	(25.2)	(7.0)	1.3	(64.0)	(26.7)	7.0	(17.8)	4.1	(16.3)	(52.6)	(24.8)	(44.3)	(9.2)	(9.0)	(8.9)	(8.8)	(8.6)	(8.5)	(8.3)	(8.3)

LCG	(19.8)	(19.1)	(17.9)	(17.6)	(22.0)	(22.3)	(19.3)	(24.0)	(21.4)	(28.0)	(27.2)	(28.1)	(26.8)	(24.8)	(24.6)	(24.4)	(24.2)	(24.0)	(23.8)	(23.6)	(23.6)
Total	**(99.2)**	**(73.7)**	**(65.3)**	**(57.8)**	**(129.5)**	**(69.0)**	**(40.4)**	**(68.6)**	**(41.0)**	**(46.0)**	**(107.6)**	**(61.6)**	**(77.8)**	**(45.7)**	**(45.8)**	**(45.6)**	**(46.1)**	**(46.3)**	**(44.4)**	**(43.4)**	**(41.6)**

Table A- 247: Soil C Stock Change for Mineral and Organic Soils during 2010 within individual states (Tg CO_2 Eq.))

State	Mineral Soil	Organic Soil	Total
AL	(0.45)	-	(0.45)
AR	(1.09)	-	(1.09)
AZ	(0.80)	-	(0. 80)
CA	(0.16)	2.29	2.14
CO	(0.54)	0.00	(0.54)
CT	(0.06)	-	(0.06)
DE	0.02	-	0.02
FL	0.26	10.84	11.10
GA	(0.21)	-	(0.21)
HI	(0.02)	0.25	0.24
IA	(4.67)	0.75	(3.92)
ID	(1.53)	0.11	(1.43)
IL	(5.16)	0.54	(4.61)
IN	(1.72)	2.93	1.21
KS	(2.34)	-	(2.34)
KY	(1.90)	-	(1.90)
LA	(0.93)	0.07	(0.86)
MA	(0.02)	0.03	0.01
MD	(0.19)	0.03	(0.16)
ME	(0.17)	-	(0.17)
MI	(2.28)	2.72	0.43
MN	(2.57)	7.30	4.73
MO	(9.54)	-	(9.54)
MS	(1.19)	0.00	(1.18)
MT	(6.10)	0.11	(5.99)
NC	(0.35)	2.25	1.90
ND	(6.03)	-	(6.03)
NE	(2.03)	-	(2.03)
NH	(0.04)	0.01	(0.03)
NJ	(0.09)	0.01	(0.08)
NM	(1.18)	-	(1.18)
NV	(0.23)	0.00	(0.23)
NY	(1.83)	0.61	(1.23)
OH	(2.91)	0.42	(2.49)
OK	(6.48)	-	(6.48)
OR	(2.13)	0.12	(2.00)
PA	(1.85)	0.01	(1.84)
RI	(0.01)	0.00	(0.00)
SC	0.05	0.04	0.09
SD	(5.86)	-	(5.86)
TN	(1.85)	-	(1.85)
TX	5.46	-	5.46
UT	(0.02)	-	(0.02)
VA	(0.50)	0.02	(0.48)
VT	(0.28)	0.00	(0.27)
WA	(2.19)	0.26	(1.93)
WI	(2.48)	2.88	0.41
WV	(0.41)	-	(0.41)
WY	0.17	0.01	0.18

Note: Parentheses indicate net C accumulation. Estimates do not include soil C stock change associated with CRP enrollment after 2003 or sewage sludge application to soils, which were only estimated at the national scale. The sum of state results will not match the national results because state results are generated in a separate programming package, the sewage sludge and CRP enrollment after 2003 are not included, and differences arise due to rounding of values in this table.

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 solid waste. By volume, landfill gas is about half CH_4 and half CO_2.[85] The amount and rate of CH_4 generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment.

Not all CH_4 generated within a landfill is emitted to the atmosphere. The CH_4 can be extracted and either flared or utilized for energy, thus oxidizing to CO_2 during combustion. Of the remaining CH_4, a portion oxidizes to CO_2 as it travels through the top layer of the landfill cover. 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.[86]To estimate the amount of CH_4 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). This information is not available for the majority landfills in the United States. Consequently, to estimate CH_4 generation, a methodology was developed based on the quantity of waste placed in landfills nationwide each year, the first order decay model, and model parameters from the analysis of measured CH_4 generation rates for U.S. landfills with gas recovery systems.

From various studies and surveys of the generation and disposal of solid waste, estimates of the amount of waste placed in MSW and industrial landfills were developed. A database of measured CH_4 generation rates at landfills with gas recovery systems was compiled and analyzed. The results of this analysis and other studies were used to develop an estimate of the CH_4 generation potential for use in the first order decay model. In addition, the analysis and other studies provided estimates of the CH_4 generation rate constant as a function of precipitation. The first order decay model was applied to annual waste disposal estimates for each year and for three ranges of precipitation to estimate CH_4 generation rates nationwide for the years of interest. Based on the organic content of industrial wastes and the estimates of the fraction of these wastes sent to industrial landfills, CH_4 emissions from industrial landfills were also estimated using the first order decay model. Total CH_4 emissions were estimated by adding the CH_4 from MSW and industrial landfills and subtracting the amounts recovered for energy or flaring and the amount oxidized in the soil. The steps taken to estimate CH_4 emissions from U.S. landfills for the years 1990 through 2009 are discussed in greater detail below.

Figure A-19 presents the CH_4 emissions process—from waste generation to emissions—in graphical format.

Step 1: Estimate Annual Quantities of Solid Waste Placed in Landfills

For 1989 to 2010, estimates of the annual quantity of waste placed in MSW landfills were developed from a survey of State agencies as reported in BioCycle's State of Garbage in America (BioCycle 2010), adjusted to include U.S. territories.[87] The BioCycle survey is the only continually updated nationwide survey of waste disposed in landfills in the United States. Table A-248 shows estimates of waste quantities contributing to CH_4 emissions. The table shows BioCycle estimates of total waste landfilled adjusted for U.S. territories for various years over the 1990 to 2010 timeframe. A linear interpolation was used for the amount of waste generated in 2001, 2003, 2005, 2007, 2009, and 2010 because there were no BioCycle surveys for those years. The most recent BioCycle survey was published in December 2010 representing 2008 data. The waste landfilled for 2007, 2008, and 2009 have been updated since the 1990 to 2009 inventory.

Figure A-19: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste

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[85] Typically, 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.

[86] See Box 8-1 "Biogenic Emissions and Sinks of Carbon" in the Waste chapter for additional background on how biogenic emissions of landfill CO_2 are addressed in the U.S. Inventory.

[87] Since the BioCycle survey does not include U.S. territories, waste landfilled in U.S. territories was estimated using population data for the U.S territories (U.S. Census Bureau 2010) and the per capita rate for waste landfilled from BioCycle (2010).

Table A-248: Solid Waste in MSW Landfills Contributing to CH_4 Emissions (Tg unless otherwise noted)

Description	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Waste Generated[a]	271	302	377	416	455	462	470	447	423	394	365	368	371
Percent of Wastes Landfilled[a]	77%	63%	61%	63%	66%	65%	64%	64%	65%	65%	69%	69%	69%
Total Wastes Landfilled[a]	206	187	227	260	294	295	297	283	269	251	250	252	254
Waste in Place (30 years)[b]	4,671	5,057	5,367	5,452	5,568	5,715	5,861	6,005	6,133	6,244	6,334	6,418	6,502
Waste Contributing to Emissions[c]	6,808	7,775	8,792	9,052	9,346	9,641	9,938	10,221	10,490	10,741	10,991	11,242	11,496

[a] Source: *BioCycle* (2006, 2008, 2010), adjusted for missing U.S. territories using U.S. Census Bureau (2011) population data and per capita disposal rate from *BioCycle*. The data, originally reported in short tons, are converted to metric tons. Estimates shown for 2001 and 2003 are based on an interpolation because there were no surveys in 2001 and 2003; estimates shown for 2005, 2007, 2009, and 2010 are based on the increase in population.

[b] This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the CH_4 generation. Values are based on EPA (1993).

[c] This estimate represents the cumulative amount of waste that has been placed in landfills from 1940 to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on EPA (1993).

Estimates of the annual quantity of waste placed in landfills from 1960 through 1988 were developed from EPA's 1993 Report to Congress (EPA 1993) and a 1986 survey of MSW landfills (EPA 1988). Based on the national survey and estimates of the growth of commercial, residential and other wastes, the annual quantity of waste placed in landfills averaged 127 million metric tons in the 1960s, 154 million metric tons in the 1970s, 190 million metric tons in the 1990s, and 285 million metric tons in the 2000's. Estimates of waste placed in landfills in the 1940s and 1950s were developed based on U.S. population for each year and the per capital disposal rates from the 1960s.

Step 2: Estimate CH_4 Generation at Municipal Solid Waste Landfills

The CH_4 generation was estimated from the integrated form of the first order decay (FOD) model using the procedures and spreadsheets from IPCC (2006) for estimating CH_4 emissions from solid waste disposal. The form of the FOD model that was applied incorporates a time delay of 6 months after waste disposal before the generation of CH_4 begins.

The input parameters needed for the FOD model equations are the mass of waste disposed each year, which was discussed in the previous section, degradable organic carbon (DOC), and the decay rate constant (k). The DOC is determined from the CH_4 generation potential (L_0 in m^3 CH_4/Mg waste), which is discussed in more detail in subsequent paragraphs, and the following equation:

$$DOC = [L_0 \times 6.74 \times 10^{-4}] \div [F \times 16/12 \times DOC_f \times MCF]$$

Where,

DOC = degradable organic carbon (fraction, Gg C/Gg waste),
L_0 = CH_4 generation potential (m^3 CH_4/Mg waste),
6.74×10^{-4} = CH_4 density (Mg/m^3),
F = fraction of CH_4 by volume in generated landfill gas (equal to 0.5)
16/12 = molecular weight ratio CH_4/C,
DOC_f = fraction of DOC that can decompose in the anaerobic conditions in the landfill (fraction equal to 0.5 for MSW), and
MCF = methane correction factor for year of disposal (fraction equal to 1 for anaerobic managed sites).

The DOC value used in the CH_4 generation estimates from MSW landfills is 0.203 based on the CH_4 generation potential of 100 m^3 CH_4/Mg waste as described below. Data from a set of 52 representative landfills across the U.S. in different precipitation ranges were chosen to evaluate L_o, and ultimately the country-specific DOC value. The 2004 Chartwell Municipal Solid Waste Facility Directory confirmed that each of the 52 landfills chosen accepted or accepts both MSW and construction and demolition (C&D) waste (Chartwell 2004; RTI 2009).

The methane generation potential (L_o) varies with the amount of organic content of the waste material. A higher L_o occurrs with a higher content of organic waste. Waste composition data is not collected for all landfills nationwide; thus a default value must be used. Values for L_o were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for L_o of 99 m^3/Mg of waste (RTI 2004). This value compares favorably with a range of 50 to 162 (midrange of 106) m^3/Mg presented by Peer, Thorneloe, and Epperson (1993); a range of 87 to 91 m^3/Mg from a detailed analysis of 18 landfills sponsored by the Solid Waste Association of North America (SWANA 1998); and a value of 100 m^3/Mg recommended in EPA's compilation of emission factors (EPA 1998; EPA 2008) based on data from 21 landfills. Based on the results from these studies, a value of 100 m^3/Mg appears to be a reasonable best estimate to use in the FOD model for the national inventory.

The FOD model was applied to the gas recovery data for the 52 landfills to calculate the rate constant (k) directly for L_0 = 100 m^3/Mg. The rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three ranges of precipitation, shown in Table A- 249 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A- 249. Average Values for Rate Constant (k) by Precipitation Range (yr^{-1})

Precipitation range (inches/year)	k (yr^{-1})
<20	0.020
20-40	0.038
>40	0.057

These values for k show reasonable agreement with the results of other studies. For example, EPA's compilation of emission factors (EPA 1998; EPA, 2008) recommends a value of 0.02 yr^{-1} for arid areas (less than 20 inches/year of precipitation) and 0.04 yr^{-1} for non-arid areas. The SWANA study of 18 landfills reported a range in values of k from 0.03 to 0.06 yr^{-1} based on CH_4 recovery data collected generally in the time frame of 1986 to 1995.

Using data collected primarily for the year 2000, the distribution of waste in place versus precipitation was developed from over 400 landfills (RTI 2004). A distribution was also developed for population vs. precipitation for comparison. The two distributions were very similar and indicated that population in areas or regions with a given precipitation range was a reasonable proxy for waste landfilled in regions with the same range of precipitation. Using U.S. Census data and rainfall data, the distributions of population versus rainfall were developed for each Census decade from 1950 through 2000. The distributions showed that the U.S. population has shifted to more arid areas over the past several decades. Consequently, the population distribution was used to apportion the waste landfilled in each decade according to the precipitation ranges developed for k, as shown in Table A-250.

Table A-250. Percent of U.S. Population within Precipitation Ranges (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000
<20	11	13	14	16	19	20
20-40	40	39	38	36	34	33
>40	49	48	48	48	47	47

Source: RTI (2004) using population data from the U.S. Bureau of Census and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration.

In developing the Inventory, the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 was re-evaluated. Based on the historical data presented by Mintz et al. (2003), a timeline was developed for the transition from the use of open dumps for solid waste disposed to the use of managed landfills. Based on this timeline, it was estimated that 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in open dumps. Between 1940 and 1980, the fraction of waste land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. For wastes disposed of in dumps, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006); this MCF is equivalent to assuming 50 percent of the open dumps are deep and 50 percent are shallow. The recommended IPCC default value for the MCF for managed landfills of 1 was used for the managed landfills (IPCC 2006).

Step 3: Estimate CH_4 Generation at Industrial Landfills

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. In national inventories prior to the 1990 through 2005 inventory, CH_4 generation at industrial landfills was estimated as seven percent of the total CH_4 generation from MSW landfills, based on a study conducted by EPA (1993). For the 1990 through 2007 and current inventories, the methodology was updated and improved by using activity factors (industrial production levels) to estimate the amount of industrial waste landfilled each year and by applying the FOD model to estimate CH_4 generation. A nationwide survey of industrial waste landfills found that over 99 percent of the organic waste placed in industrial landfills originated from two industries: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food processing and pulp and paper industries were taken from industry and government sources for recent years; estimates were developed for production for the earlier years for which data were not available. For the pulp and paper industry, production data published by the Lockwood-Post's Directory (ERG 2011) and U.S. Department of Agriculture (2011) were the primary sources for years 1965 through 2010. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964. For the food processing industry, production levels were obtained or developed from the U.S. Department of Agriculture (2011) for the years 1990 through 2010 (ERG 2011). An extrapolation based on U.S. population was used for the years 1940 through 1989.

In addition to production data for the pulp and paper and food processing industries, the following inputs were needed to use the FOD model for estimating CH_4 generation from industrial landfills: 1) quantity of waste that is disposed in industrial landfills (as a function of production), 2) CH_4 generation potential (L_0) or DOC, and 3) FOD decay constant (k). Research into waste generation and disposal in landfills for the pulp and paper industry indicated that the quantity of waste landfilled was about 0.050 Mg/Mg of product compared to 0.046 Mg/Mg product for the food processing industry (Weitz and Bahner 2006). These factors were applied to estimates of annual production to estimate annual waste disposal in landfills. Estimates for DOC were derived from available data (Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999). The DOC value for industrial pulp and paper waste is estimated at 0.20 (L_o of 99 m^3/Mg); the DOC value for industrial food waste is estimated as 0.26 (L_o of 128 m^3/Mg) (Coburn 2008). Estimates for k were taken from the default values in the 2006 IPCC Guidelines; the value of k given for food waste with disposal in a wet temperate climate is 0.19 yr^{-1}, and the value given for paper waste is 0.06 yr^{-1}.

A literature review was conducted for the current inventory year with the intent of updating values for Lo and k in the pulp and paper industry. Where pulp and paper mill wastewater treatment residuals or sludge are the primary constituents of pulp and paper waste landfilled, values for k range from 0.01/yr to 0.1/yr, while values for L_o range from 50 m^3/Mg to 200 m^3/Mg[88]. Values for these factors are highly variable and are dependent on the soil moisture content, which is generally related to rainfall amounts. At this time, insufficient data were obtained to warrant a change for the current inventory year. However, ongoing efforts and data reported through the Greenhouse Gas Reporting Program Subpart TT for industrial landfills may result in a U.S. industry-specific and/or region-specific k and/or L_o values rather than default IPCC values in future inventory years. As with MSW landfills, a similar trend in disposal practices from open dumps to managed landfills was expected for industrial landfills; therefore, the same time line that was developed for MSW landfills was applied to the industrial landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste land disposed transitioned from 6 percent managed landfills in 1940 and 94 percent open dumps to 100 percent managed landfills in 1980 and on. For wastes disposed of in dumps, an MCF of 0.6 was used and for wastes disposed of in managed landfills, an MCF of 1 was used, based on the recommended IPCC default values (IPCC 2006).

The parameters discussed above were used in the integrated form of the FOD model to estimate CH_4 generation from industrial landfills.

Step 4: Estimate CH_4 Emissions Avoided

The estimate of CH_4 emissions avoided (e.g., combusted) was based on landfill-specific data on landfill gas-to-energy (LFGTE) projects and flares. A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency was selected based on the range of efficiencies (86 to 99 percent) recommended for flares in EPA's "AP-42 Compilation of Air Pollutant Emission Factors, Draft Chapter 2.4" (EPA 2008), efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in the Landfill Methane Outreach Program (LMOP).

Step 4a: Estimate CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects

The quantity of CH_4 avoided due to LFGTE systems was estimated based on information from two sources: (1) a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007) and (2) a database compiled by LMOP (EPA 2011). The EIA database included location information for landfills with LFGTE projects, estimates of CH_4 reductions, descriptions of the projects, and information on the methodology used to determine the CH_4 reductions. Generally the CH_4 reductions for each reporting year were based on the measured amount of landfill gas collected and the percent CH_4 in the gas. For the LMOP database, data on landfill gas flow and energy generation (i.e., MW capacity) were used to estimate the total direct CH_4 emissions avoided due to the LFGTE project. Detailed information on the landfill name, owner or operator, city, and state were available for both the EIA and LMOP databases; consequently, it was straightforward to identify landfills that were in both databases. The EIA database was given priority because reductions were reported for each year and were based on direct measurements. Landfills in the LMOP database that were also in the EIA database were dropped to avoid double counting.

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[88] Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; and Skog 2000.

Step 4b: Estimate CH_4 Emissions Avoided Through Flaring

The quantity of CH_4 flared was based on data from the EIA database and on information provided by flaring equipment vendors. To avoid double-counting, flares associated with landfills in the EIA and LMOP databases were excluded from the flare vendor database. As with the LFGTE projects, reductions from flaring landfill gas in the EIA database were based on measuring the volume of gas collected and the percent of CH_4 in the gas. The information provided by the flare vendors included information on the number of flares, flare design flow rates or flare dimensions, year of installation, and generally the city and state location of the landfill. When a range of design flare flow rates was provided by the flare vendor, the median landfill gas flow rate was used to estimate CH_4 recovered from each remaining flare (i.e., for each flare not associated with a landfill in the EIA or LMOP databases). Several vendors provided information on the size of the flare rather than the flare design gas flow rate. To estimate a median flare gas flow 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. Some flare vendors reported the maximum capacity of the flare. An analysis of flare capacity versus measured CH_4 flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the actual flow was estimated as 50 percent of capacity. Total CH_4 avoided through flaring from the flare vendor database was estimated by summing the estimates of CH_4 recovered by each flare for each year.

Step 4c: Reduce CH_4 Emissions Avoided Through Flaring

As mentioned in Step 4b, flares in the flare vendor database associated with landfills in the EIA and LMOP databases were excluded from the flare reduction estimates in the flare vendor database. If comprehensive data on flares were available, each LFGTE project in the EIA and LMOP databases would have an identified flare because it is assumed that most LFGTE projects have flares. However, given that the flare vendor 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, yet flares were unable to be identified for one of two reasons: 1) inadequate identifier information in the flare vendor data; or 2) a lack of the flare in the flare vendor database. For those projects for which a flare was not identified due to inadequate information, CH_4 avoided would be overestimated, as both the CH_4 avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, the CH_4 avoided from LFGTE projects with no identified flares was determined and the flaring estimate from the flare vendor database was reduced by this quantity (referred to as a flare correction factor) on a state-by-state basis. This step likely underestimates CH_4 avoided due to flaring but was applied to be conservative in the estimates of CH_4 emissions avoided.

Additional effort was undertaken to improve the methodology behind the flare correction factor for the 1990-2009 Inventory to reduce the total number of flares in the flare vendor database that were not matched (512) to landfills and/or LFGTE projects in the EIA and LMOP databases. Each flare in the flare vendor database not associated with a LFGTE project in the EIA or LMOP databases was investigated to determine if it could be matched to either a landfill in the EIA database or a LFGTE project in the LMOP database. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database. In other instances, the landfill names were slightly different between what the flare vendor provided and the actual landfill name as listed in the EIA and LMOP databases.

It was found that a large majority of the unmatched flares are associated with landfills in LMOP that are currently flaring, but are also considering LFGTE. These landfills projects considering a LFGTE project are labeled as candidate, potential, or construction in the LMOP database. The flare vendor database was improved to match flares with operational, shutdown as well as candidate, potential, and construction LFGTE projects, thereby reducing the total number of unidentified flares in the flare vendor database, all of which are used in the flare correction factor. The results of this effort significantly decreased the number of flares used in the flare correction factor, and consequently, increased recovered flare emissions, and decreased net emissions from landfills for the 1990-2009 Inventory. The revised state-by-state flare correction factors were applied to the entire Inventory time series.

Step 5: Estimate CH_4 Oxidation

A portion of the CH_4 escaping from a landfill oxidizes to CO_2 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 of the CH_4 generated, minus the amount of gas recovered for flaring or LFGTE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The factor of 10 percent is consistent with the value recommended in the 2006 IPCC revised guidelines for managed and covered landfills, and was therefore applied to the estimates of CH_4 generation minus recovery for both MSW and industrial landfills

A recent literature review was conducted in 2011 (RTI 2011) to provide recommendations for the most appropriate oxidation rate assumptions. It was found that oxidation values are highly variable and range from zero to over 100 percent (i.e., the landfill is considered to be an atmospheric sink by virtue of the landfill gas extraction system pulling atmospheric methane down through the cover). There is considerable uncertainty and variability surrounding estimates of oxidation because it is difficult to measure and varies considerably with the thickness and type of the cover material, size and area of the landfill, climate, and the presence of cracks and/or fissures in the cover material through which methane can escape. IPCC (2006) notes that test results from field and laboratory studies may lead to over-estimations of oxidation in landfill cover soils because they largely determine oxidation using uniform and homogeneous soil layers. In addition, a number of studies note that gas escapes more readily through the side slopes of a landfill as compared to moving through the cover thus complicating the correlation between oxidation and cover type or gas recovery.

Spokas et al. (2006), in particular, helps to illustrate expected patterns (e.g., seasonality of generation, effectiveness of gas recovery) associated with landfill methane production and flux through the cover system. This study also highlights the large variability in oxidation between and within sites and ultimately reports oxidation ranging between 4-50 percent. All but one of the test sites had an active gas recovery system in place. For landfills with gas collection systems, there have been studies to show that gas recovery increases oxidation because it slows the flux of methane through the cover system. Although this may be true, there does not appear to be enough data to support the premise that landfills with gas recovery systems increase oxidation. This is demonstrated by the Spokas et al. (2006) data where the oxidation rates were about the same for a landfill site with and without gas recovery. However, the site also had a thin temporary cover so the oxidation would be less than a site with a final cover system. Based on this and other studies, there does not appear to be adequate justification for increasing the default oxidation value for landfills with gas recovery. It is difficult to make general conclusions from the Spokas et al. (2006) study except that seasonality clearly affects oxidation in landfills with final covers.

Sites with landfill gas collection systems are generally designed and managed better to improve gas recovery. More recent research (2006-2011) on landfill cover methane oxidation has relied on stable isotope techniques that may provide a more reliable measure of oxidation. Results from this recent research consistently point to higher cover soil methane oxidation rates than the IPCC (2006) default of 10 percent. Changing the oxidation rate from 10 percent to 20 percent for municipal landfills with gas collection and control has a minimal impact on the net emissions over the past decade, but does result in an approximately 10 percent decrease in emissions over the 1990 to 2000 timeframe as less landfill gas was recovered. The current default oxidation factor of 10 percent is recommended for all landfills in the Inventory until more reliable, peer-reviewed data is available about the influence of climate, cover type, and gas recovery is better understood.

Step 6: Estimate Total CH_4 Emissions

Total CH_4 emissions were calculated by adding emissions from MSW and industrial landfills, and subtracting CH_4 recovered and oxidized, as shown in Table A- 251.

Table A- 251: CH_4 Emissions from Landfills (Gg)

Activity	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
MSW Generation	8,219	9,132	9,854	10,068	10,367	10,754	11,126	11,486	11,790	12,041	12,227	12,401	12,574
Industrial Generation	554	618	692	705	712	720	725	733	736	740	746	752	758
Potential Emissions	**8,773**	**9,750**	**10,546**	**10,773**	**11,079**	**11,474**	**11,852**	**12,219**	**12,526**	**12,781**	**12,973**	**13,153**	**13,332**
Landfill Gas-to-Energy	(640)	(1,081)	(2,390)	(2,592)	(2,596)	(2,533)	(2,626)	(2,662)	(2,773)	(2,946)	(3,152)	(3,543)	(3,802)
Flare	(321)	(1,298)	(2,278)	(2,492)	(2,760)	(2,908)	(3,386)	(3,593)	(3,842)	(3,923)	(3,837)	(3,726)	(3,825)
Emissions Avoided	**(960)**	**(2,378)**	**(4,668)**	**(5,084)**	**(5,356)**	**(5,441)**	**(6,013)**	**(6,255)**	**(6,615)**	**(6,869)**	**(6,988)**	**(7,270)**	**(7,627)**
Oxidation at MSW Landfills	**(726)**	**(675)**	**(519)**	**(498)**	**(501)**	**(531)**	**(511)**	**(523)**	**(518)**	**(517)**	**(524)**	**(513)**	**(495)**
Oxidation at Industrial Landfills	**(55)**	**(62)**	**(69)**	**(71)**	**(71)**	**(72)**	**(73)**	**(73)**	**(74)**	**(74)**	**(75)**	**(75)**	**(76)**
Net Emissions	**7,032**	**6,634**	**5,290**	**5,120**	**5,151**	**5,430**	**5,255**	**5,367**	**5,320**	**5,320**	**5,386**	**5,295**	**5,135**

Note: Totals may not sum exactly to the last significant figure due to rounding.

Note: MSW generation in Table A-247 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation. represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.

Note: Parentheses denote negative values.

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Figure A- 4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2010 (Tg CO2 Eq.)

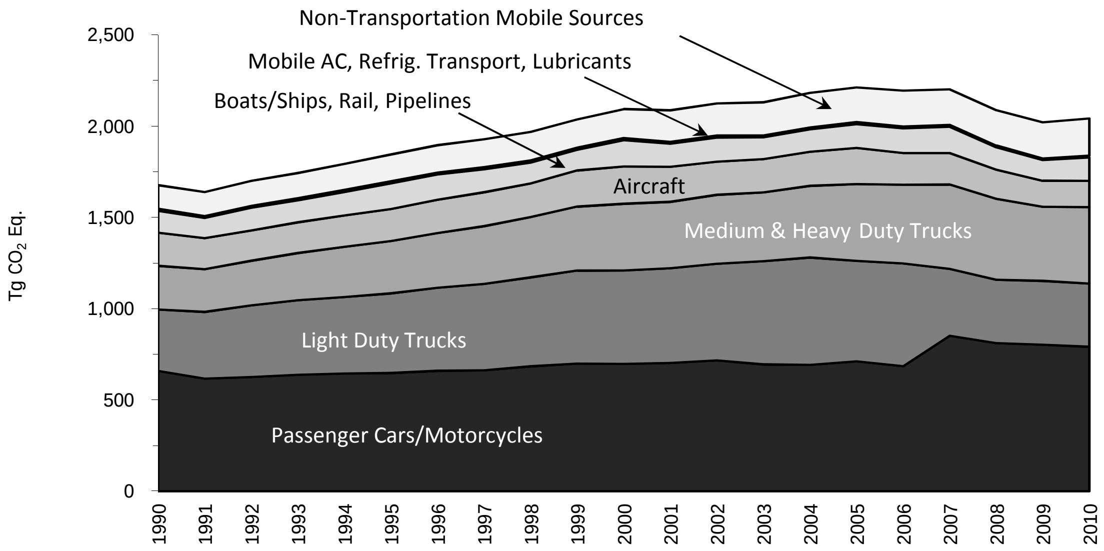


Figure A-5

Effect of Soil Temperature, Water-Filled Pore Space, and pH on Nitrification Rates

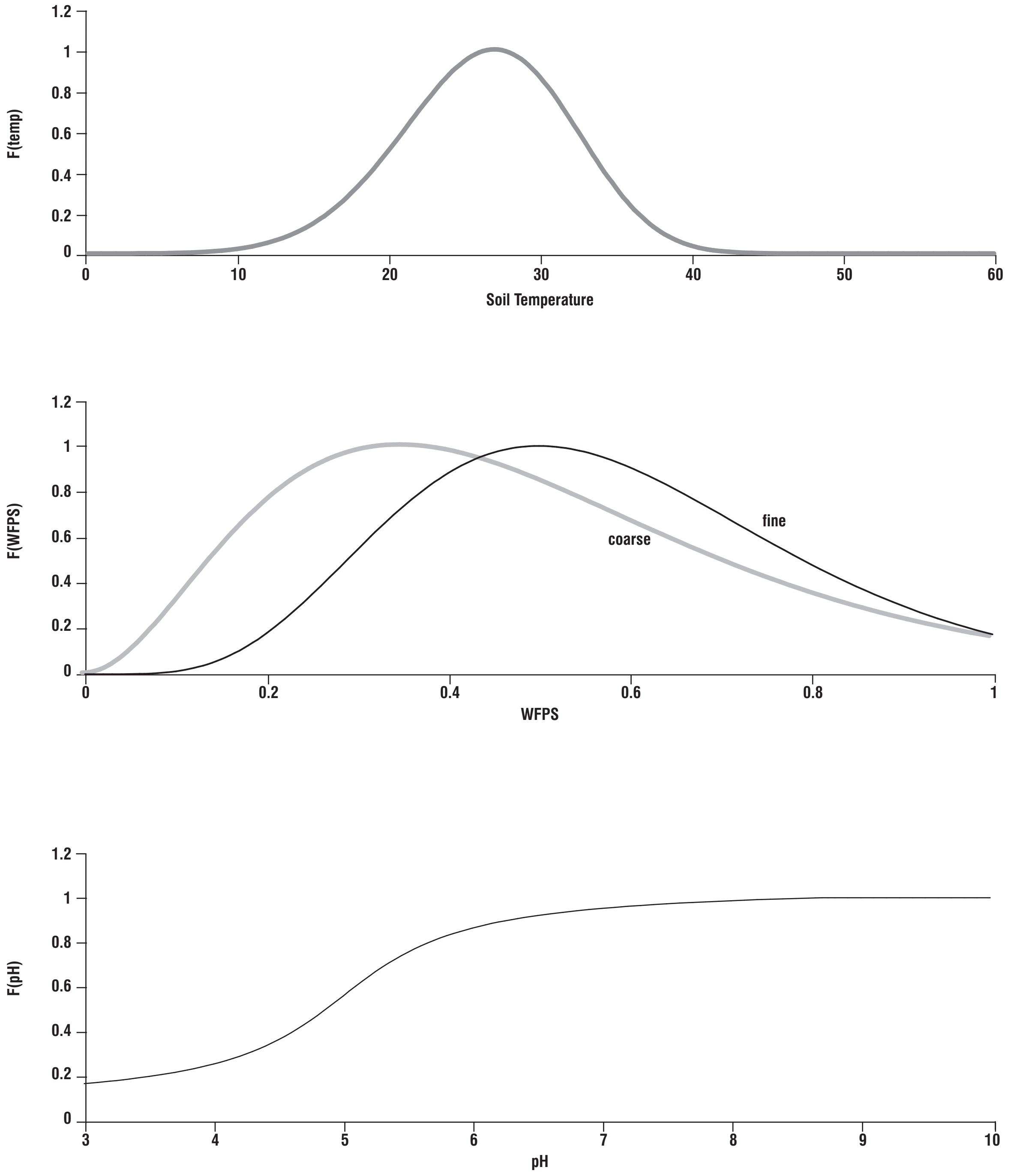
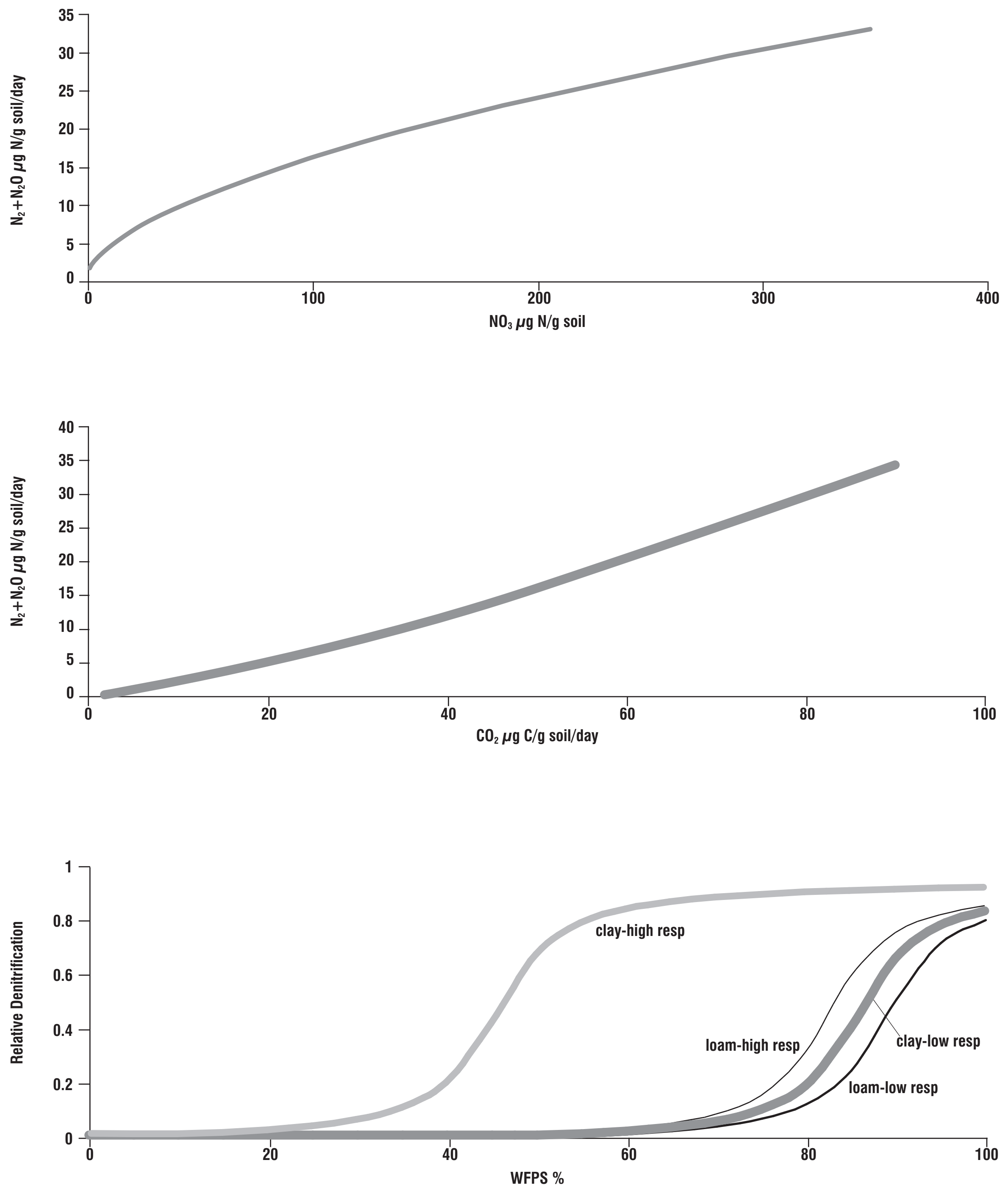


Figure A-6

Effect of Soil Nitrite Concentration, Heterotrophic Respiration Rates, and Water-Filled Pore Space on Denitrification Rates



DAYCENT MODEL

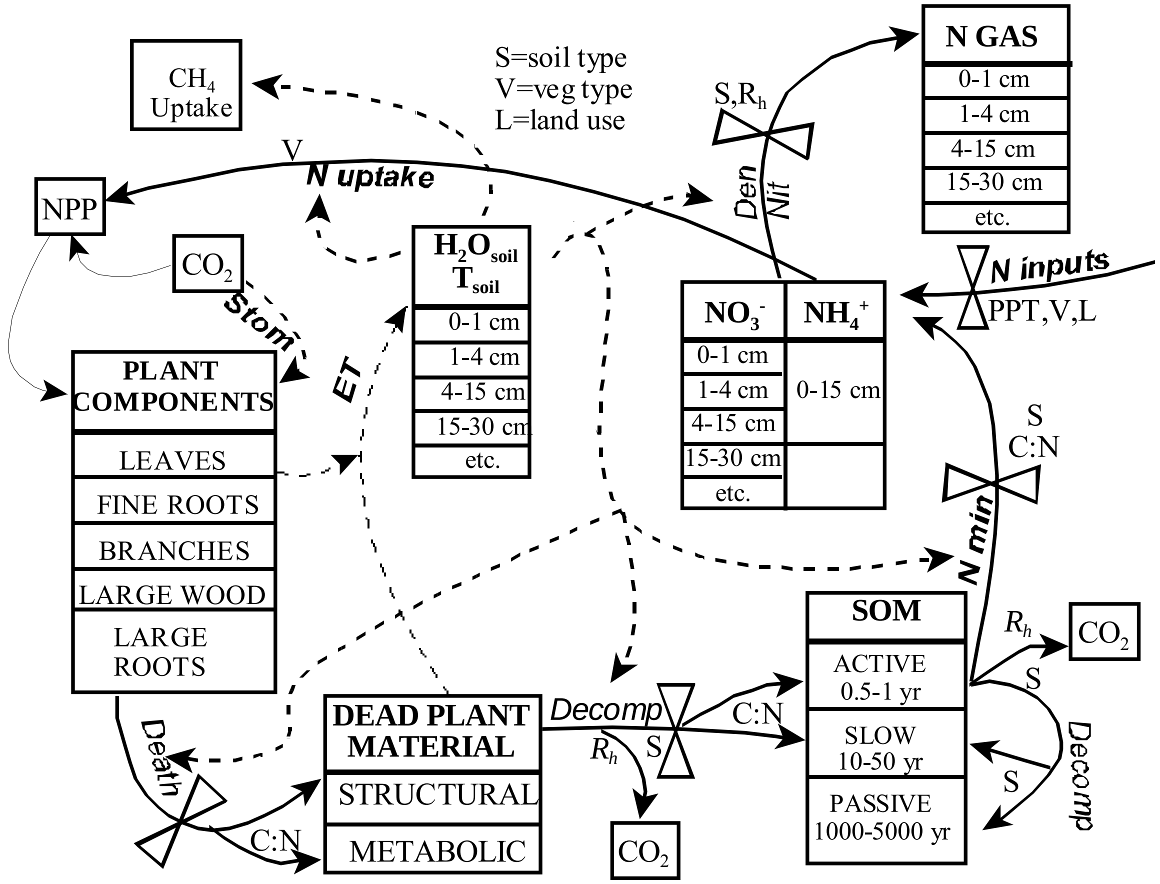


Figure A-7: DAYCENT model flow diagram

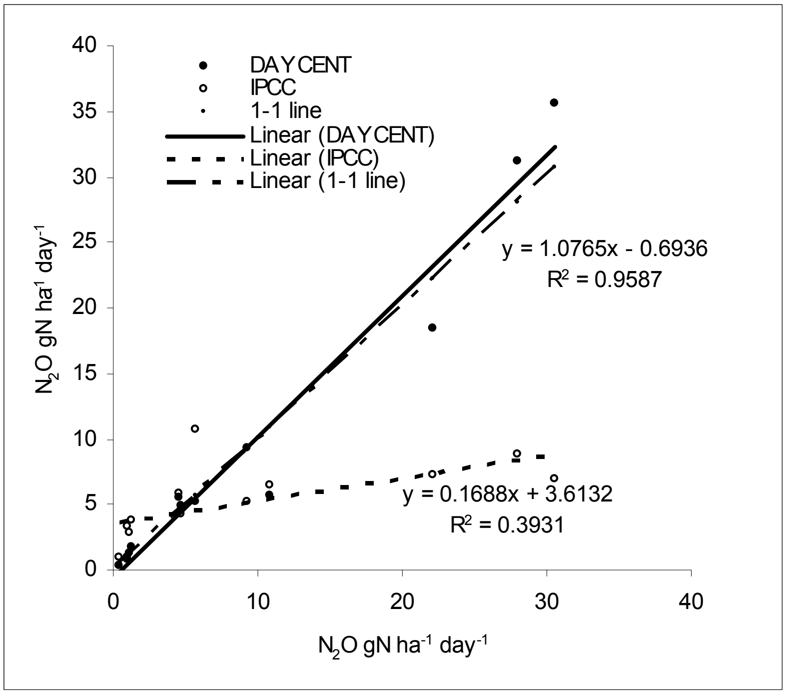


Figure A-8: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N2O Emissions

Figure A-9

Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990–2010 (Metric Tons CO_2 Eq./ha/year)

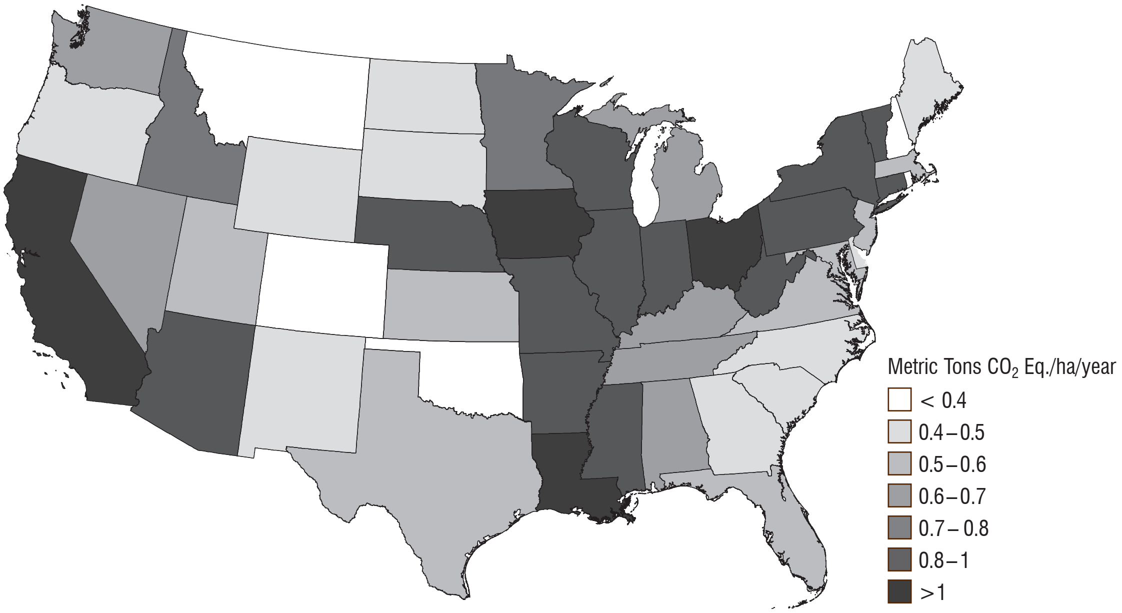


Figure A-10

Major Crops, Average Annual N losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (kg N/ha/year)

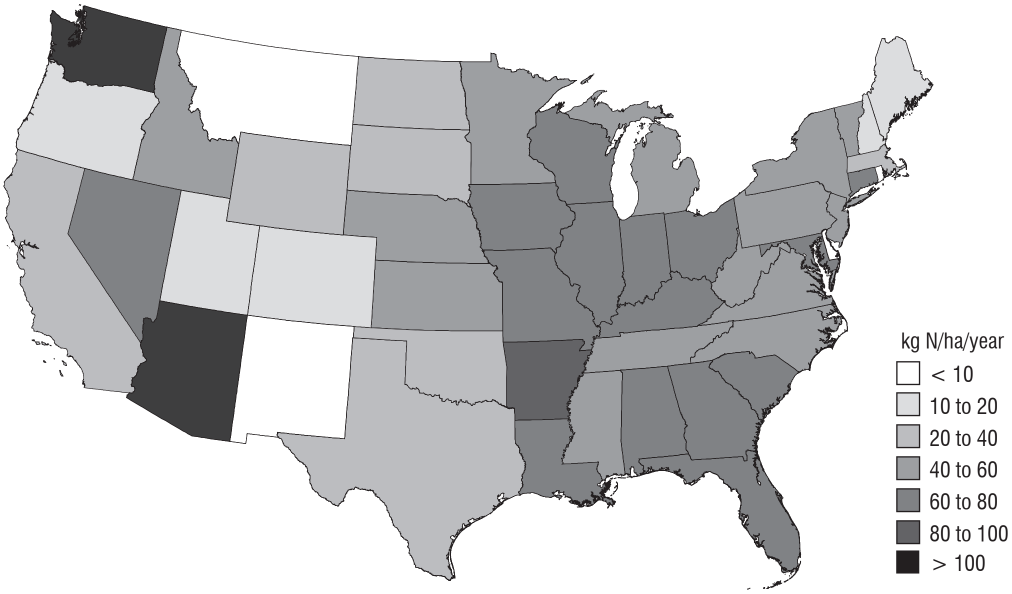


Figure A-11

Grasslands, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990–2010 (Metric Tons CO_2 Eq./ha/year)

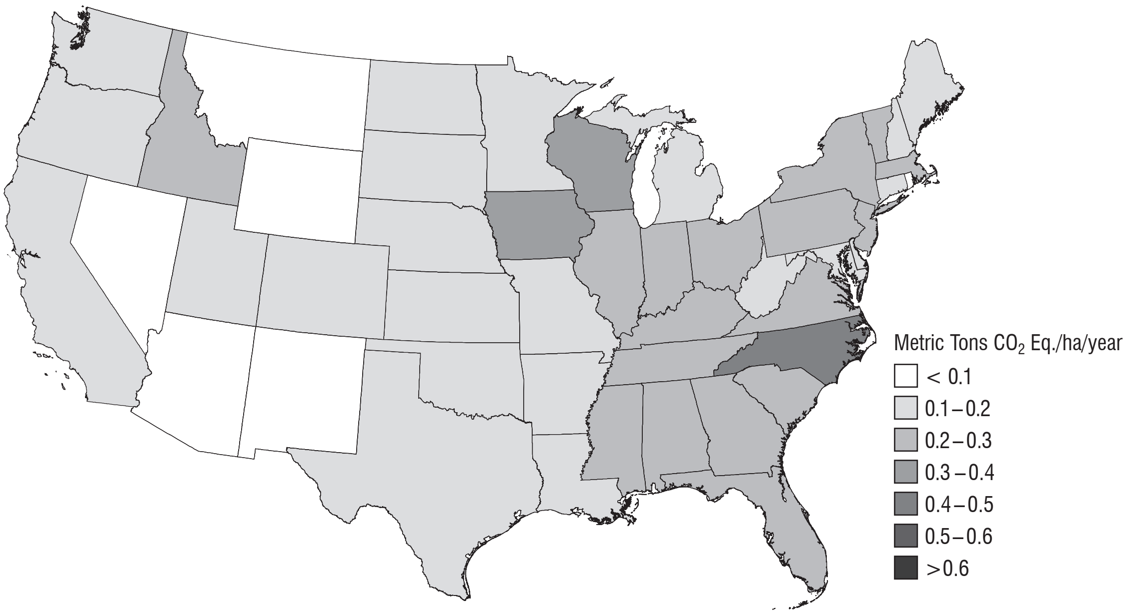


Figure A-12

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (kg N/ha/year)

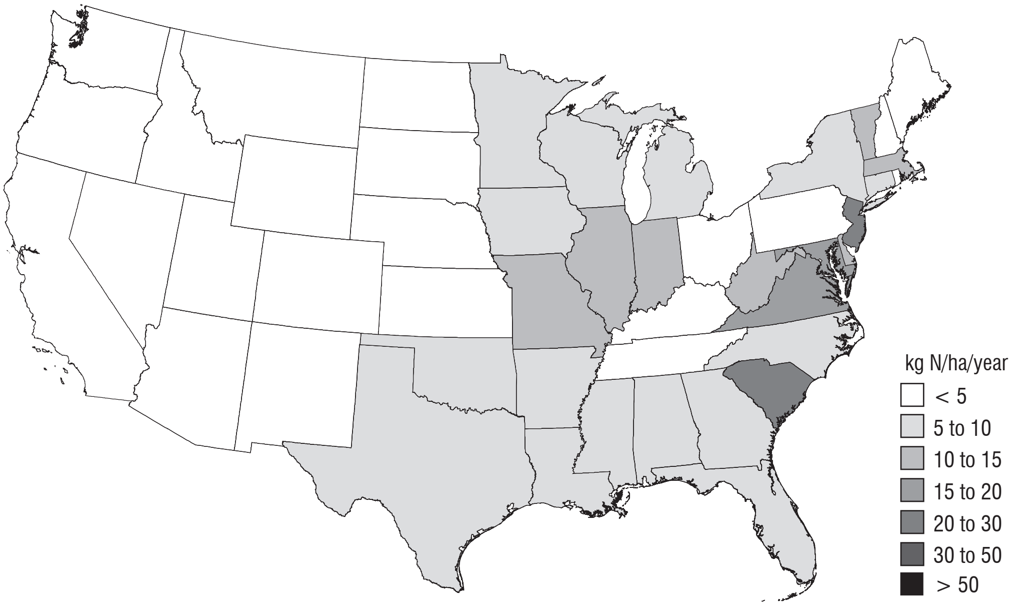


Figure A-13

Flow diagram of Carbon submodel (A) and Nitrogen submodel (B)

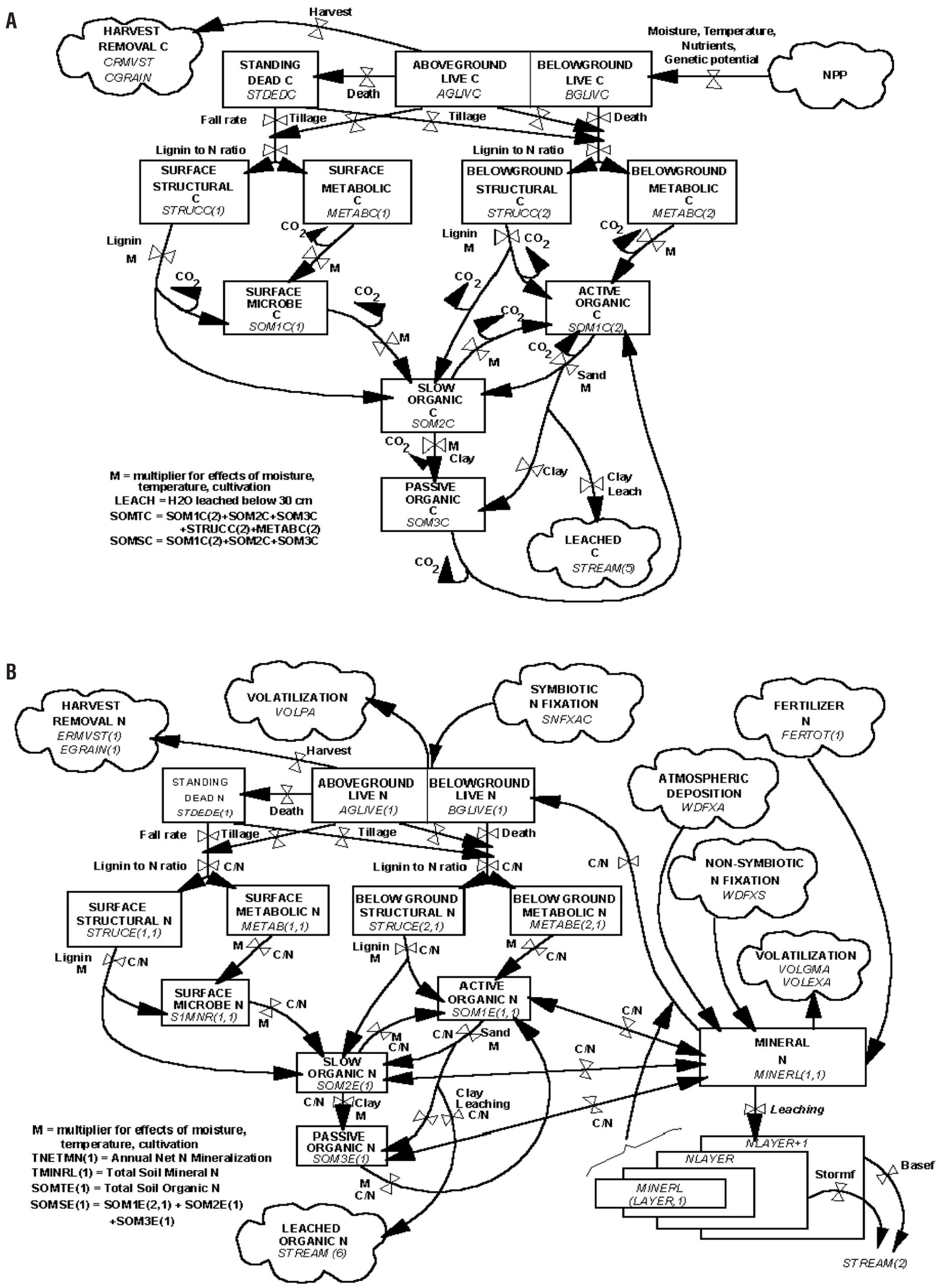


Figure A-14

Comparison of Measured Soil Organic C from Experimental Sites to Modeled Soil Organic C Using the Century Model

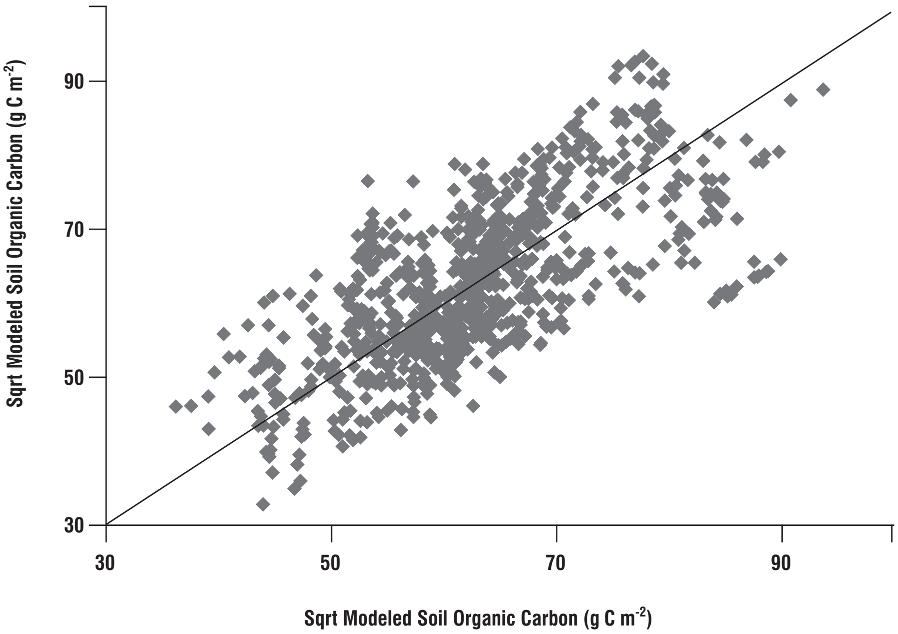
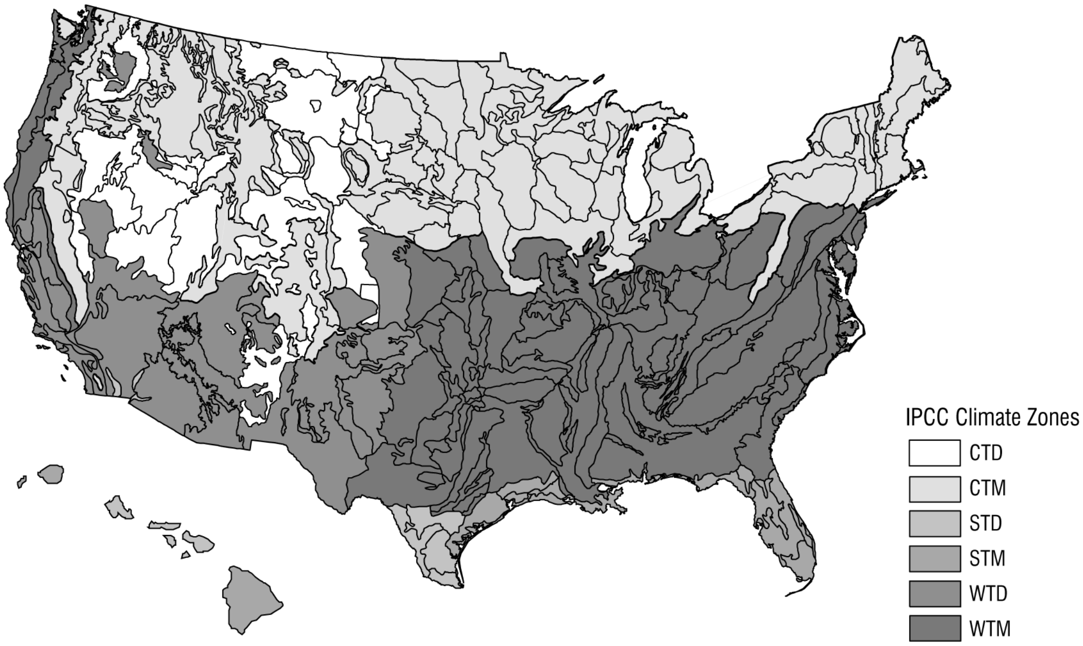


Figure A-15

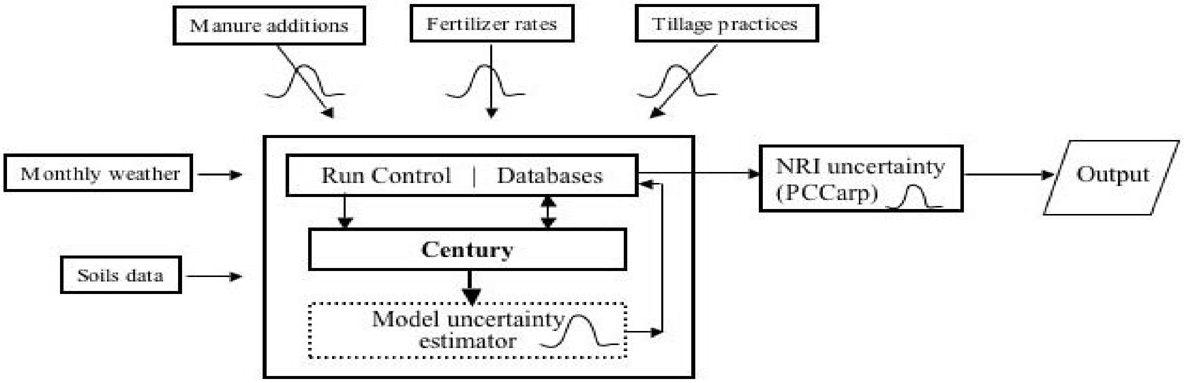
Major Land Resource Areas by IPCC Climate Zone



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 A-16

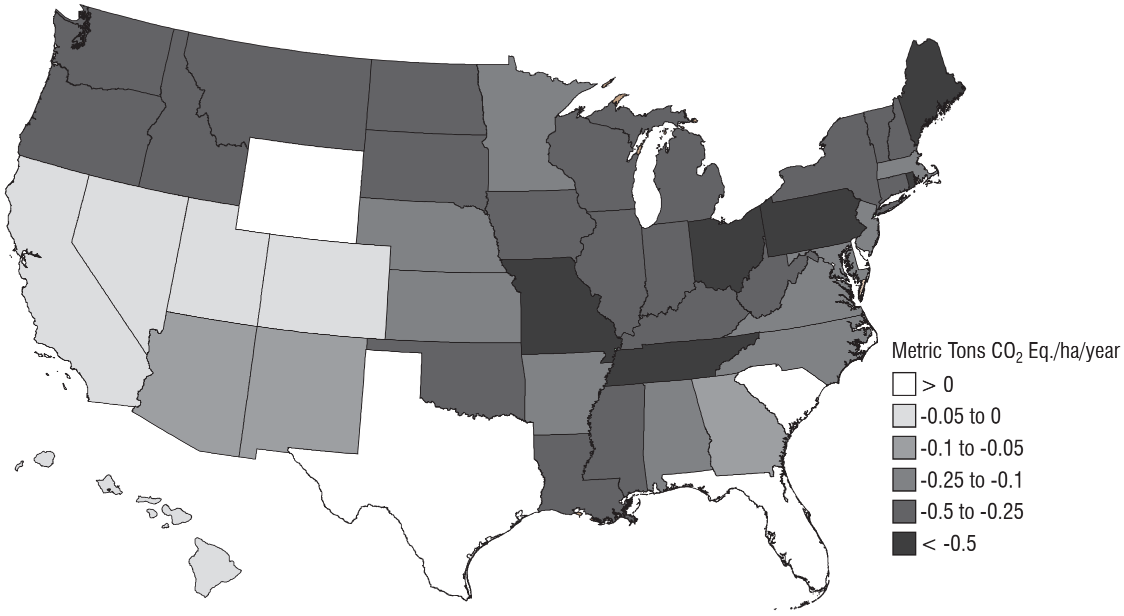
Uncertainty in Data Inputs



Uncertainty in data inputs (i.e. fertilizer, manure and tillage practices) are estimated using a Monte-Carlo procedure with 100 random draws from input data probability distributions, for each NRI point simulated. Model uncertainty is estimated through an empirical-based approach. Uncertainty in the land representation of NRI is estimated from the statistics compiled from the NRI surveys to determine the land area expansion factors, which are used to upscale data to the national level.

Figure A-17

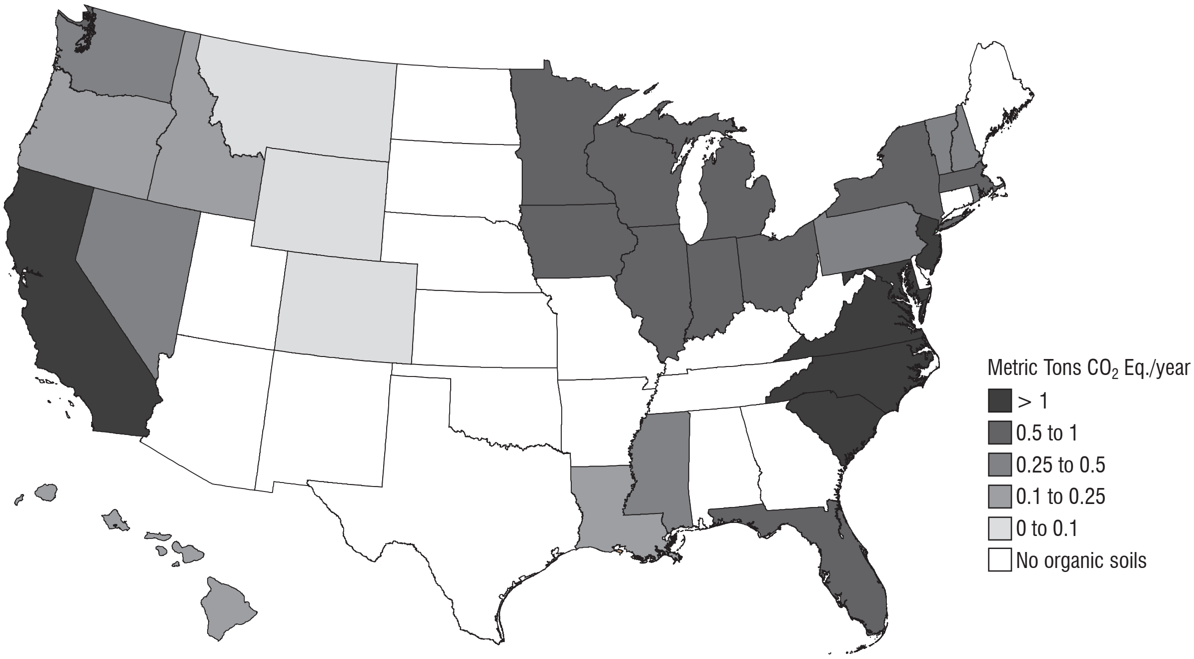
Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2010



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

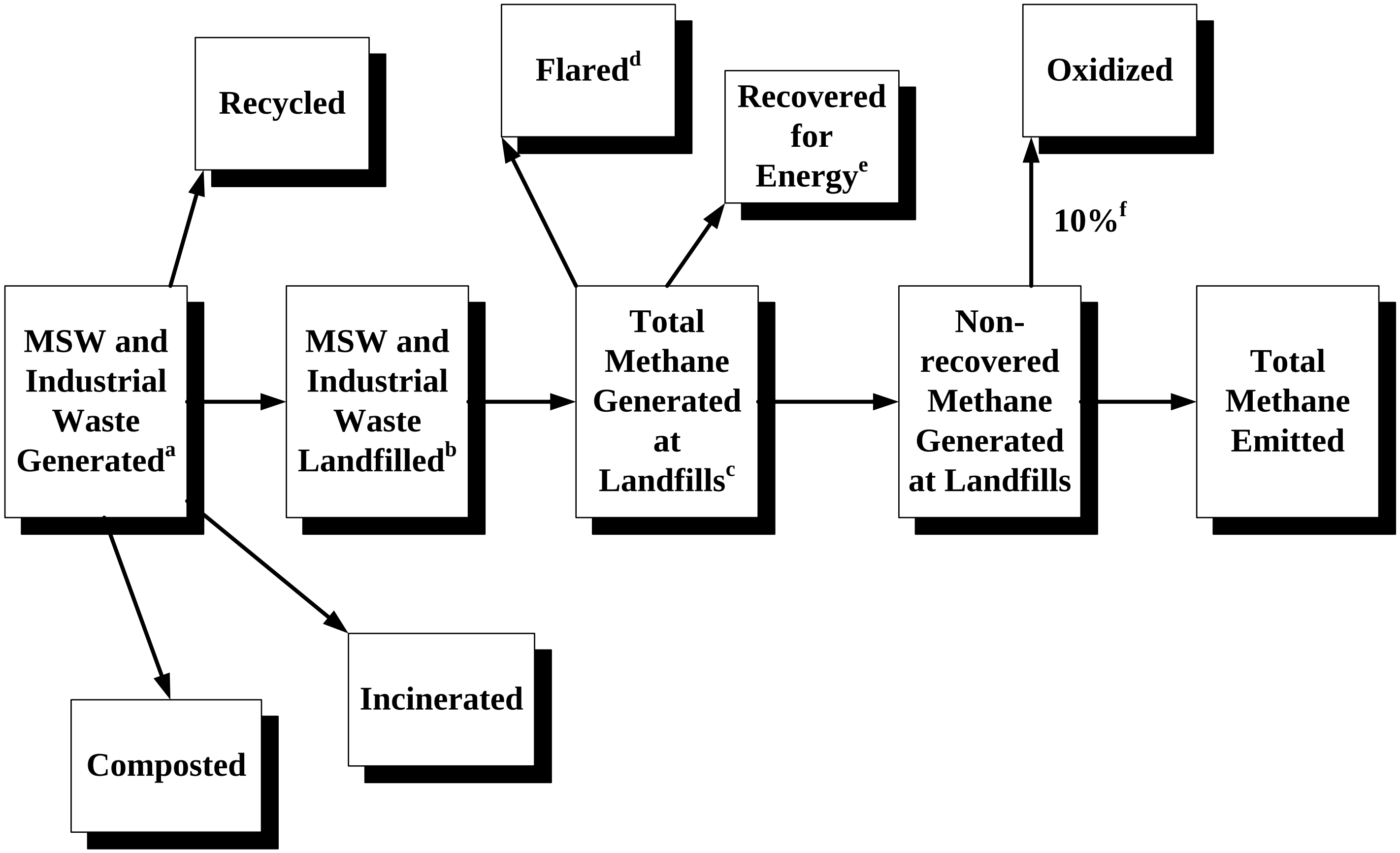
Figure A-18

Net C Stock Changes, per Hectare, for Organic Soils Under Agricultural Management, 2010



Note: Values greater than zero represent emissions.

Figure A-19: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



[a] BioCycle 2006 for MSW and activity factors for industrial waste.
[b] 1960 through 1988 based on EPA 1988 and EPA 1993; 1989 through 2006 based on BioCycle 2006.
[c] 2006 IPCC Guidelines – First Order Decay Model.
[d] EIA 2007 and flare vendor database.
[e] EIA 2007 and EPA (LMOP) 2007.
[f] 2006 IPCC Guidelines; Mancinelli and McKay 1985; Czepiel et al 1996