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 emissions from stationary combustion were estimated using IPCC emission factors and methods. Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This "top-down" methodology is characterized by two basic steps, described below. Data are presented in Table A-85 through Table A-90.

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 and wood consumption data for the United States were obtained from EIA's *Monthly Energy Review, February 2015* and Published Supplemental Tables on Petroleum Product detail (EIA 2015). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were collected separately from the EIA's International Energy Statistics (Jacobs 2010).[16] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[17] Construction and agricultural fuel use was obtained from EPA (2013). 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-85 provides annual energy consumption data for the years 1990 through 2013.

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 2014a). This combustion technology-and fuel-use data was available by facility from 1996 to 2013. Since there was a difference between the EPA (2014a) and EIA (2015) total energy consumption estimates, the remainder between total energy consumption using EPA (2014a) and EIA (2015) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2013.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2014a) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2015) and the ratio of combustion technology and fuel types from EPA 2014a. 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 (2014a) and EIA (2015) 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 (2015).

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, 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

[16] 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.

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

in which each fuel was combusted. Table A-86 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-87. Emission factors were used from the *2006 IPCC Guidelines* as the factors presented in these IPCC guidelines were taken directly from U.S. EPA publications on emissions rates for combustion sources.

Estimates of NOx, CO, and NMVOC Emissions

Emissions estimates for NO_x, CO, and NMVOCs were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2014b), and disaggregated based on EPA (2003).

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 2006).

Table A-85: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Coal	**19,610**	**20,888**	**23,080**	**22,391**	**22,343**	**22,576**	**22,636**	**22,949**	**22,458**	**22,710**	**22,225**	**19,670**	**20,697**	**18,989**	**16,715**	**17,400**
Residential	31	17	11	12	12	12	11	8	6	8	0	0	0	0	0	0
Commercial	124	117	92	97	90	82	103	97	65	70	81	73	70	62	44	41
Industrial	1,640	1,527	1,349	1,358	1,244	1,249	1,262	1,219	1,189	1,131	1,081	877	952	866	782	801
Electric Power	17,807	19,217	21,618	20,920	20,987	21,199	21,228	21,591	21,161	21,465	21,026	18,682	19,639	18,024	15,852	16,521
U.S. Territories	7	10	10	4	11	34	32	33	37	37	37	37	37	37	37	37
Petroleum	**6,168**	**5,655**	**6,161**	**6,642**	**6,021**	**6,405**	**6,577**	**6,503**	**6,214**	**6,072**	**5,246**	**4,682**	**4,807**	**4,420**	**4,034**	**4,133**
Residential	1,375	1,261	1,427	1,463	1,359	1,466	1,468	1,368	1,202	1,220	1,201	1,140	1,118	1,065	854	917
Commercial	869	694	694	719	646	763	764	715	677	679	634	669	644	629	511	547
Industrial	2,751	2,378	2,298	2,548	2,385	2,511	2,686	2,793	3,125	3,005	2,433	1,960	2,065	1,980	1,948	2,133
Electric Power	797	860	1,269	1,279	1,074	1,043	1,007	1,004	590	618	488	383	412	266	273	180
U.S. Territories	375	462	472	632	557	622	653	623	620	550	490	531	567	480	448	357
Natural Gas	**17,266**	**19,337**	**20,919**	**20,224**	**20,908**	**20,894**	**21,152**	**20,938**	**20,626**	**22,019**	**22,286**	**21,952**	**22,912**	**23,115**	**24,137**	**24,922**
Residential	4,491	4,954	5,105	4,889	4,995	5,209	4,981	4,946	4,476	4,835	5,010	4,883	4,878	4,805	4,242	5,040
Commercial	2,682	3,096	3,252	3,097	3,212	3,261	3,201	3,073	2,902	3,085	3,228	3,187	3,165	3,216	2,960	3,363
Industrial	7,716	8,723	8,656	7,949	8,086	7,845	7,914	7,330	7,323	7,521	7,571	7,125	7,683	7,873	8,203	8,505
Electric Power	2,376	2,564	3,894	4,266	4,591	4,551	5,032	5,565	5,899	6,550	6,447	6,730	7,159	7,194	8,683	7,964
U.S. Territories	0	0	13	23	23	27	25	24	26	27	29	27	28	27	49	49
Wood	**2,216**	**2,370**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,137**	**2,099**	**2,089**	**2,059**	**1,931**	**1,981**	**2,010**	**2,010**	**2,138**
Residential	580	520	420	370	380	400	410	430	380	420	470	500	440	450	420	580
Commercial	66	72	71	67	69	71	70	70	65	70	73	73	72	69	61	70
Industrial	1,442	1,652	1,636	1,443	1,396	1,363	1,476	1,452	1,472	1,413	1,339	1,178	1,273	1,309	1,339	1,281
Electric Power	129	125	134	126	150	167	165	185	182	186	177	180	196	182	190	207
U.S. Territories	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-86: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[1]

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-87: CH_4 and N_2O Emission Factors by Technology Type and Fuel Type for the Electric Power Sector (g/GJ)[2]

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 Dual-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

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

Table A-88: NO_x Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Electric Power	**6,045**	**5,792**	**4,829**	**4,454**	**4,265**	**3,930**	**3,595**	**3,434**	**3,249**	**3,064**	**2,847**	**2,552**	**2,226**	**1,893**	**1,654**	**1,665**
Coal	5,119	5,061	4,130	3,802	3,634	3,349	3,063	2,926	2,768	2,611	2,426	2,175	1,896	1,613	1,409	1,419
Fuel Oil	200	87	147	149	142	131	120	114	108	102	95	85	74	63	55	55
Natural gas	513	510	376	325	310	286	262	250	236	223	207	186	162	138	120	121
Wood	NA	NA	36	37	36	33	30	29	27	26	24	21	19	16	14	14
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	140	140	143	132	121	115	109	103	95	86	75	63	55	56
Industrial	**2,559**	**2,650**	**2,278**	**2,296**	**1,699**	**1,641**	**1,580**	**1,515**	**1,400**	**1,285**	**1,165**	**1,126**	**1,087**	**1,048**	**1,048**	**1,048**
Coal	530	541	484	518	384	371	357	342	316	290	263	254	245	237	237	237
Fuel Oil	240	224	166	153	114	110	106	101	94	86	78	75	73	70	70	70
Natural gas	877	999	710	711	526	508	489	469	433	398	361	348	336	324	324	324
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	116	86	83	80	76	70	65	59	57	55	53	53	53
Internal Combustion	792	774	809	798	591	570	549	527	486	446	405	391	378	364	364	364
Commercial	**671**	**607**	**507**	**428**	**438**	**408**	**378**	**490**	**471**	**452**	**433**	**445**	**456**	**548**	**548**	**548**
Coal	36	35	21	21	19	19	19	19	18	17	15	15	15	15	15	15
Fuel Oil	88	94	52	52	50	49	49	49	46	43	39	39	38	37	37	37
Natural gas	181	210	161	165	157	156	156	155	145	135	124	122	120	118	118	118
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	189	212	183	154	267	263	258	254	269	284	378	378	378
Residential	**749**	**813**	**439**	**446**	**422**	**422**	**420**	**418**	**390**	**363**	**335**	**329**	**324**	**318**	**318**	**318**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	22	21	21	21	20	19	18	16	16	16	16	16	16
Other Fuels[a]	707	769	417	424	402	401	400	398	371	345	318	313	308	302	302	302
Total	**10,023**	**9,862**	**8,053**	**7,623**	**6,825**	**6,401**	**5,973**	**5,858**	**5,511**	**5,163**	**4,780**	**4,452**	**4,092**	**3,807**	**3,567**	**3,579**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2014b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2014b).

Note: Totals may not sum due to independent rounding.

Table A-89: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Electric Power	**329**	**337**	**439**	**439**	**594**	**591**	**586**	**582**	**609**	**637**	**660**	**676**	**693**	**710**	**710**	**710**
Coal	213	227	221	220	298	296	294	292	305	319	330	339	347	356	356	356
Fuel Oil	18	9	27	28	38	37	37	37	38	40	42	43	44	45	45	45
Natural gas	46	49	96	92	125	124	123	122	128	134	138	142	145	149	149	149
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	32	44	43	43	43	45	47	48	50	51	52	52	52
Internal Combustion	52	52	63	67	91	90	90	89	93	97	101	103	106	108	108	108
Industrial	**797**	**958**	**1,106**	**1,137**	**1,150**	**1,116**	**1,081**	**1,045**	**968**	**892**	**815**	**834**	**853**	**872**	**872**	**872**
Coal	95	88	118	125	127	123	119	115	107	98	90	92	94	96	96	96

Fuel Oil	67	64	48	45	46	44	43	42	39	35	32	33	34	35	35	35
Natural gas	205	313	355	366	370	359	348	336	312	287	262	268	274	281	281	281
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	321	325	316	306	295	274	252	230	236	241	247	247	247
Internal Combustion	177	222	285	279	282	274	266	257	238	219	200	205	209	214	214	214
Commercial	**205**	**211**	**151**	**154**	**177**	**173**	**169**	**166**	**156**	**146**	**137**	**138**	**140**	**142**	**142**	**142**
Coal	13	14	14	13	15	15	15	14	14	13	12	12	12	12	12	12
Fuel Oil	16	17	17	17	20	19	19	19	18	16	15	16	16	16	16	16
Natural gas	40	49	83	84	97	95	93	91	86	80	75	76	77	78	78	78
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	38	44	43	42	41	39	37	34	35	35	35	35	35
Residential	**3,668**	**3,877**	**2,644**	**2,648**	**3,044**	**2,982**	**2,919**	**2,856**	**2,690**	**2,524**	**2,357**	**2,387**	**2,416**	**2,446**	**2,446**	**2,446**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,424	2,787	2,730	2,673	2,615	2,463	2,310	2,158	2,185	2,212	2,239	2,239	2,239
Other Fuels[a]	238	248	228	224	257	252	247	241	227	213	199	202	204	207	207	207
Total	**5,000**	**5,383**	**4,340**	**4,377**	**4,965**	**4,862**	**4,756**	**4,648**	**4,423**	**4,198**	**3,969**	**4,036**	**4,103**	**4,170**	**4,170**	**4,170**

NA (Not Applicable)
[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2014b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2014b).
Note: Totals may not sum due to independent rounding.

Table A-90: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Electric Power	**43**	**40**	**56**	**55**	**45**	**45**	**44**	**44**	**42**	**41**	**40**	**39**	**38**	**37**	**37**	**37**
Coal	24	26	27	26	21	21	21	21	20	20	19	18	18	18	18	18
Fuel Oil	5	2	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Natural Gas	2	2	12	12	10	10	10	10	9	9	9	9	8	8	8	8
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	10	9	9	8	8	8	8	8	7	7	7	7	7
Industrial	**165**	**187**	**157**	**159**	**138**	**132**	**126**	**120**	**113**	**105**	**97**	**99**	**100**	**101**	**101**	**101**
Coal	7	5	9	10	9	9	8	8	7	7	6	6	7	7	7	7
Fuel Oil	11	11	9	9	7	7	7	6	6	6	5	5	5	5	5	5
Natural Gas	52	66	53	54	47	45	43	41	38	36	33	33	34	34	34	34
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	29	25	24	23	22	21	19	18	18	18	19	19	19
Internal Combustion	49	60	58	57	49	47	45	43	40	37	35	35	36	36	36	36
Commercial	**18**	**21**	**28**	**29**	**61**	**54**	**48**	**33**	**34**	**35**	**36**	**38**	**40**	**42**	**42**	**42**
Coal	1	1	1	1	1	1	1	1	1	+	+	+	+	+	+	+
Fuel Oil	3	3	4	4	6	5	3	2	2	2	2	2	2	2	2	2
Natural Gas	7	10	14	14	23	18	14	9	8	7	6	7	7	7	7	7
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	8	9	10	31	30	30	22	24	26	28	29	31	32	32	32

Residential	**686**	**725**	**837**	**836**	**1,341**	**1,067**	**793**	**518**	**465**	**411**	**358**	**378**	**399**	**419**	**419**	**419**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	809	1,297	1,032	767	502	450	398	346	366	386	406	406	406
Other Fuels[a]	35	37	27	27	43	35	26	17	15	13	12	12	13	14	14	14
Total	**912**	**973**	**1,077**	**1,080**	**1,585**	**1,298**	**1,011**	**716**	**654**	**593**	**531**	**553**	**576**	**599**	**599**	**599**

NA (Not Applicable)

+ Does not exceed 0.5 kt.

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2014b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2014b).

Note: Totals may not sum due to independent rounding.

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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 CO_2 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 (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 2014 and EIA 2013a) and apportioned to individual modes (considered a "top down" approach). CO_2 emissions from commercial jet fuel use are obtained directly from the Federal Aviation Administration (FAA 2014), while CO_2 emissions from other aircraft jet fuel consumption is determined using 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 consumption in the transportation sector, based on the availability of reliable data sources. A "bottom up" diesel calculation was first 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. Estimated motor gasoline and diesel consumption data for on-road vehicles by vehicle type come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2014),[1] 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 Annex Tables A.1 through A.6 (DOE 1993 through 2014) 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 on-road vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Table MF-27 (FHWA 1996 through 2014). This resulted in a final "bottom up" 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.

A primary challenge to switching from a top-down approach to a bottom-up approach for the transportation sector relates to potential incompatibilities with national energy statistics. From a multi-sector national standpoint, EIA develops the most accurate estimate of total motor gasoline and diesel fuel supplied and consumed in the United States. EIA then allocates this total fuel consumption to each major end-use sector (residential, commercial, industrial and transportation) using data from the *Fuel Oil and Kerosene Sales* (FOKS) report for distillate fuel oil and FHWA for motor gasoline. However, the "bottom-up" approach used for the on-road and non-road fuel consumption estimate, as described above, is considered to be the most representative of the transportation sector's share of the EIA total consumption. Therefore, for years in which there was a disparity between EIA's fuel allocation estimate for the transportation sector and the "bottom-up" estimate, adjustments were made to other end-use sector fuel allocations (residential, commercial and industrial) in order for the consumption of all sectors combined to equal the "top-down" EIA value.

In the case of motor gasoline, estimates of fuel use by recreational boats come from EPA's NONROAD Model (EPA 2013b), and these estimates, along with those from other sectors (e.g., commercial sector, industrial sector), were adjusted for years in which the bottom-up on-road motor gasoline consumption estimate exceeded the EIA estimate for total gasoline consumption of all sectors. 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 proportionately.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2013) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2013 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004)

[1] In 2011 FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007-12 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "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.

and Whorton (2006 through 2013) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2014) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2014).

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 (2014) for domestic and international commercial aircraft, and DESC (2014) for domestic and international military aircraft. General aviation jet fuel consumption is calculated as the difference between total jet fuel consumption as reported by EIA and the total consumption from commercial and military jet fuel consumption. Commercial jet fuel CO_2 estimates are obtained directly from the Federal Aviation Administration (FAA 2014), while CO_2 emissions from domestic military and general aviation jet fuel consumption is determined using a top down approach. Domestic commercial jet fuels CO_2 from FAA is subtracted from total domestic jet fuel CO_2 emissions, and this remaining value is apportioned among domestic military and domestic general aviation based on their relative proportion of energy consumption. Estimates for biofuels, including ethanol and biodiesel were discussed separately in Chapter 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating CO_2 from Fossil Combustion, and in Chapter 3.10 Wood Biomass and Ethanol Consumption and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2015).

Table A-91 displays estimated fuel consumption by fuel and vehicle type. Table A-92 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. The motor gasoline and diesel fuel consumption volumes published by EIA and FHWA include ethanol blended with gasoline and biodiesel blended with diesel. Biofuels blended with conventional fuels were subtracted from these consumption totals in order to be consistent with IPCC methodological guidance and UNFCCC reporting obligations, for which 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 fuel volumes were removed from motor gasoline consumption estimates for years 1990-2013 and biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001-2013, as there was negligible use of biodiesel as a diesel blending competent prior to 2001. The subtraction or removal of biofuels blended into motor gasoline and diesel were conducted following the methodology outlined in Step 2 ("Remove Biofuels from Petroleum") of the EIA's Monthly Energy Review (MER) Section 12 notes.

In order to remove the volume of biodiesel blended into diesel fuel, the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA Petroleum Supply Annual (EIA 2015) *Table 18 - Refinery Net Input of Crude Oil and Petroleum Products* and *Table 20 - Blender Net Inputs of Petroleum Products* were subtracted from the transportation sector's total diesel fuel consumption volume (for both the "top-down" EIA and "bottom-up" FHWA estimates). To remove the fuel ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2014) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates.

Total ethanol and biodiesel consumption estimates are shown separately in Table A-93.[2]

[2] Note that the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA's Petroleum Supply Annual (PSA) differs from the biodiesel volume presented in Table A-93. The PSA data is representative of the amount of biodiesel that refineries and blenders added to diesel fuel to make low level biodiesel blends. This is the appropriate value to subtract from total diesel fuel volume, as it represents the amount of biofuel blended into diesel to create low-level biodiesel blends. The biodiesel consumption value presented in Table A-93 is representative of the total biodiesel consumed and includes biodiesel components in all types of fuel formulations, from low level (<5%) to high level (6-20%, 100%) blends of biodiesel. This value is sourced from MER Table 10.4 and is calculated as biodiesel production plus biodiesel net imports minus biodiesel stock exchange.

Table A-91. Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013
Motor Gasoline[b]	**110,417**	**117,429**	**128,174**	**129,613**	**132,192**	**132,624**	**134,359**	**133,317**	**131,359**	**130,791**	**125,072**	**124,211**	**123,197**	**120,519**	**120,056**	**120,160**
Passenger Cars	69,763	67,496	72,320	72,921	74,313	71,931	71,505	73,856	70,792	88,607	84,715	83,919	83,231	82,622	82,465	82,465
Light-Duty Trucks	34,698	44,074	50,398	50,871	52,023	55,418	57,540	53,733	54,798	34,933	33,075	33,474	33,263	31,612	31,270	31,306
Motorcycles	194	199	208	192	189	184	193	182	210	472	487	468	411	401	459	437
Buses	39	41	43	40	38	36	49	41	41	79	81	84	82	80	92	94
Medium- and Heavy-Duty Trucks	4,350	4,044	4,065	3,961	4,006	3,446	3,475	3,922	3,961	5,164	5,220	4,798	4,773	4,383	4,358	4,455
Recreational Boats[c]	1,374	1,575	1,140	1,629	1,624	1,610	1,596	1,583	1,559	1,536	1,495	1,469	1,437	1,422	1,411	1,402
Distillate Fuel Oil (Diesel Fuel)	**25,631**	**31,605**	**39,241**	**39,058**	**40,348**	**41,177**	**42,668**	**44,659**	**45,848**	**46,432**	**44,032**	**39,879**	**41,485**	**42,286**	**42,050**	**42,668**
Passenger Cars	771	765	356	357	364	412	419	414	403	403	363	354	367	399	401	398
Light-Duty Trucks	1,119	1,452	1,961	2,029	2,133	2,652	2,822	2,518	2,611	1,327	1,184	1,181	1,227	1,277	1,271	1,264
Buses	781	851	997	906	860	930	1,316	1,030	1,034	1,520	1,437	1,335	1,326	1,419	1,515	1,544
Medium- and Heavy-Duty Trucks	18,574	23,241	30,180	30,125	31,418	31,540	32,599	35,160	36,092	37,522	35,732	32,369	33,689	33,864	33,881	34,411
Recreational Boats	190	228	266	274	282	289	297	305	313	321	329	337	345	351	358	362
Ships and Other Boats	735	1,204	1,377	1,248	1,202	1,178	807	785	729	800	773	774	731	1,000	739	748
Rail	3,461	3,864	4,106	4,119	4,089	4,176	4,407	4,446	4,665	4,539	4,216	3,529	3,799	3,976	3,885	3,940
Jet Fuel[d]	**19,186**	**17,991**	**20,002**	**19,454**	**19,004**	**18,389**	**19,147**	**19,420**	**18,695**	**18,407**	**17,749**	**15,809**	**15,537**	**15,036**	**14,705**	**15,088**
Commercial Aircraft	11,569	12,136	14,672	13,121	12,774	12,943	13,147	13,976	14,426	14,708	13,400	12,588	11,931	12,067	11,932	12,031
General Aviation Aircraft	4,034	3,361	3,163	3,975	4,119	3,323	3,815	3,583	2,590	2,043	2,682	1,787	2,322	1,895	1,659	2,033
Military Aircraft	3,583	2,495	2,167	2,359	2,110	2,123	2,185	1,860	1,679	1,656	1,667	1,434	1,283	1,074	1,114	1,024
Aviation Gasoline[d]	**374**	**329**	**302**	**291**	**281**	**251**	**260**	**294**	**278**	**263**	**235**	**221**	**225**	**225**	**209**	**186**
General Aviation Aircraft	374	329	302	291	281	251	260	294	278	263	235	221	225	225	209	186
Residual Fuel Oil[d, e]	**2,006**	**2,587**	**2,963**	**1,066**	**1,522**	**662**	**1,245**	**1,713**	**2,046**	**2,579**	**1,812**	**1,241**	**1,818**	**1,723**	**1,410**	**1,338**
Ships and Other Boats	2,006	2,587	2,963	1,066	1,522	662	1,245	1,713	2,046	2,579	1,812	1,241	1,818	1,723	1,410	1,338
Natural Gas[d] (trillion cubic feet)	**0.7**	**0.7**	**0.7**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.8**	**0.9**
Passenger Cars	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Light-Duty Trucks	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Buses	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipelines	0.7	0.7	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.9
LPG[d]	**265**	**206**	**138**	**159**	**166**	**207**	**222**	**327**	**320**	**257**	**468**	**331**	**348**	**403**	**443**	**475**
Buses	-	1.6	1.5	0.3	0.6	0.7	0.7	1.0	1.0	-	-	-	-	-	-	-
Light-Duty Trucks	106	98	88	108	117	144	167	247	229	185	340	228	243	282	317	340
Medium- and Heavy-Duty Trucks	159	106	49	51	49	62	55	79	89	72	128	103	106	121	126	135
Electricity[d,f]	**4,751**	**4,975**	**5,382**	**5,724**	**5,517**	**6,810**	**7,224**	**7,506**	**7,358**	**8,173**	**7,700**	**7,781**	**7,712**	**7,672**	**7,320**	**7,525**
Rail	4,751	4,975	5,382	5,724	5,517	6,810	7,224	7,506	7,358	8,173	7,700	7,781	7,712	7,672	7,320	7,525

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007-2013 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

[b] Figures do not include ethanol blended in motor gasoline or biodiesel blended into distillate fuel oil. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter. This table is calculated with the heat content for gasoline without ethanol (from Table A.2 in the EIA Annual Energy Review) rather than the annually variable quantity-weighted heat content for gasoline with ethanol, which varies by year. This change was made in the current inventory to reflect the fact that the source fuel volumes for the table do not contain ethanol. In addition, updates to heat content data in this year's Inventory from EIA for years 1993 through present resulted in changes to the time series for overall energy consumption and emissions compared to previous years' Inventory. Similarly, new data from Oak Ridge National Laboratory's Transportation Energy Book (Edition 33) for transit buses impacted the distribution of energy consumption and emissions between vehicle classes for the time series starting in 2006.

[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.

[f] Million Kilowatt-hours

+ Less than 0.05 million gallons or 0.05 trillion cubic feet

- Unreported or zero

Table A-92: Energy Consumption by Fuel and Vehicle Type (Tbtu)

Fuel/Vehicle Type[f]	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013
Motor Gasoline[b]	**13,810**	**14,687**	**16,031**	**16,211**	**16,533**	**16,587**	**16,804**	**16,674**	**16,429**	**16,262**	**15,551**	**15,444**	**15,318**	**14,985**	**14,927**	**14,940**
Passenger Cars	8,725	8,442	9,045	9,120	9,294	8,997	8,943	9,237	8,854	11,017	10,533	10,434	10,348	10,273	10,253	10,253
Light-Duty Trucks	4,340	5,512	6,303	6,363	6,507	6,931	7,197	6,721	6,854	4,343	4,112	4,162	4,136	3,930	3,888	3,892
Motorcycles	24	25	26	24	24	23	24	23	26	59	61	58	51	50	57	54
Buses	5	5	5	5	5	4	6	5	5	10	10	10	10	10	11	12
Medium- and Heavy-Duty Trucks	544	506	508	495	501	431	435	491	495	642	649	597	593	545	542	554
Recreational Boats[c]	172	197	142	204	203	201	200	198	195	191	186	183	179	177	175	174
Distillate Fuel Oil (Diesel Fuel)	**3,555**	**4,383**	**5,442**	**5,417**	**5,596**	**5,711**	**5,918**	**6,194**	**6,359**	**6,440**	**6,107**	**5,531**	**5,754**	**5,865**	**5,832**	**5,918**
Passenger Cars	107	106	49	50	51	57	58	57	56	56	50	49	51	55	56	55
Light-Duty Trucks	155	201	272	281	296	368	391	349	362	184	164	164	170	177	176	175
Buses	108	118	138	126	119	129	183	143	143	211	199	185	184	197	210	214
Medium- and Heavy-Duty Trucks	2,576	3,223	4,186	4,178	4,357	4,374	4,521	4,876	5,006	5,204	4,956	4,489	4,672	4,697	4,699	4,772
Recreational Boats	26	32	37	38	39	40	41	42	43	45	46	47	48	49	50	50
Ships and Other Boats	102	167	191	173	167	163	112	109	101	111	107	107	101	139	103	104
Rail	480	536	569	571	567	579	611	617	647	630	585	489	527	551	539	546
Jet Fuel[d]	**2,590**	**2,429**	**2,700**	**2,626**	**2,565**	**2,482**	**2,585**	**2,622**	**2,524**	**2,485**	**2,396**	**2,134**	**2,097**	**2,030**	**1,985**	**2,037**
Commercial Aircraft	1,562	1,638	1,981	1,771	1,725	1,747	1,775	1,887	1,948	1,986	1,809	1,699	1,611	1,629	1,611	1,624
General Aviation Aircraft	545	454	427	537	556	449	515	484	350	276	362	241	314	256	224	274
Military Aircraft[f]	484	337	293	318	285	287	295	251	227	224	225	194	173	145	150	138
Aviation Gasoline[d]	**45**	**40**	**36**	**35**	**34**	**30**	**31**	**35**	**33**	**32**	**28**	**27**	**27**	**27**	25	22
General Aviation Aircraft	45	40	36	35	34	30	31	35	33	32	28	27	27	27	25	22
Residual Fuel Oil[d, e]	**300**	**387**	**443**	**159**	**228**	**99**	**186**	**256**	**306**	**386**	**271**	**186**	**272**	**258**	**211**	**200**
Ships and Other Boats	300	387	443	159	228	99	186	256	306	386	271	186	272	258	211	200
Natural Gas[d]	**680**	**724**	**672**	**658**	**699**	**627**	**602**	**624**	**625**	**663**	**692**	**715**	**719**	**734**	**780**	**920**
Passenger Cars	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Light-Duty Trucks	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Buses	-	1	8	9	12	14	16	16	16	19	21	22	20	20	20	20
Pipelines	680	721	664	649	687	614	586	608	609	645	672	693	699	713	760	901
LPG[d]	**23**	**18**	**12**	**14**	**14**	**18**	**19**	**28**	**27**	**22**	**40**	**28**	**29**	**34**	**37**	**40**
Buses	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Light-Duty Trucks	9	8	8	9	10	12	14	21	20	16	29	19	21	24	27	29
Medium- and Heavy-Duty Trucks	14	9	4	4	4	5	5	7	8	6	11	9	9	10	11	11
Electricity[d]	**16**	**17**	**18**	**20**	**19**	**23**	**25**	**26**	**25**	**28**	**26**	**27**	**26**	**26**	**25**	**25**
Rail	16	17	18	20	19	23	25	26	25	28	26	27	26	26	25	25
Total	**21,019**	**22,685**	**25,356**	**25,140**	**25,688**	**25,579**	**26,170**	**26,459**	**26,329**	**26,317**	**25,112**	**24,090**	**24,243**	**23,958**	**23,822**	**24,103**

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007-2013 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

[b] Figures do not include ethanol blended in motor gasoline or biodiesel blended into distillate fuel oil. 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. Residual fuel oil for ships and other boats data is based on EIA's February 2015 Monthly Energy Review data.
[f] Note that updates in the current Inventory to heat content data from EIA for years 1993 through present resulted in changes to the time series for energy consumption and emissions compared to previous Inventory. Similarly, new data from Oak Ridge National Laboratory's Transportation Energy Book (Edition 33) for transit buses impacted the distribution of energy consumption and emissions between vehicle classes for the time series starting in 2006.
-Unreported or zero

Table A-93. Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Ethanol	712	1,326	1,590	1,660	1,975	2,689	3,375	3,860	5,207	6,563	9,263	10,537	12,282	12,329	12,324	12,645
Biodiesel	NA	NA	NA	10	16	14	27	91	261	354	304	322	260	886	895	1,404

NA (Not Available)
Note: According to the MER, there was no biodiesel consumption prior to 2001. The time series has changed due to applying the annual ethanol heat factor to each year accordingly. For the current inventory, the same heat factor (2013 value) was applied across the board.

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 *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

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,[1] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2014).[2] 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 2014) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book*, *Tables A.5 and A.6* (DOE 1993 through 2014). 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. Fuel shares were first adjusted proportionately such that gasoline and diesel shares for each vehicle/fuel type category equaled 100 percent of national VMT. 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 total VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[3] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A- 94 and Table A- 95, 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 30 model years shown for 2013 in Table A- 98. 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 2009 forward (EPA 2014c).[4] Age-specific vehicle mileage accumulation was obtained from EPA's MOVES2014 model (EPA 2014).[5]

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- 102 through Table A- 105. 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

[1] Medium- and heavy-duty trucks correspond to FHWA's reporting categories of single-unit trucks and combination trucks. Single-unit trucks are defined as single frame trucks that have 2-axles and at least 6 tires or a gross vehicle weight rating (GVWR) exceeding 10,000 lbs.

[2] In 2011 FHWA changed its methods for estimated vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007-12 time period. This resulted in large changes in VMT data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "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.

[3] 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.

[4] 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.

[5] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES 2014 model resulted in an increase in emissions due to more miles driven by older light-duty gasoline vehicles.

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).[6] 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 2013 were determined using confidential engine family sales data submitted to EPA (EPA 2014b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2014a). 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 utilizing Tier 2 and Low Emission Vehicle (LEV) technologies were developed by ICF (2006b); all other gasoline and diesel on-road vehicle emissions factors were developed by ICF (2004).These factors were based on EPA, CARB and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada 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) and "Methodology for Highway Vehicle Alternative Fuel GHG Projections Estimates" (Browning, 2014). 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.[7] Most alternative fuel vehicle VMT were calculated using the Energy Information Administration (EIA) Alternative Fuel Vehicle Data. This provided vehicle counts and fuel consumption in gasoline equivalent gallons for all vehicle classes for calendar years 2003 through 2011. For 1992 to 2002, EIA Data Tables were used to estimate fuel consumption and vehicle counts by vehicle type. These tables give total vehicle fuel use and vehicle counts by fuel and calendar year for the United States over the period 1992 through 2010. Breakdowns by vehicle type for 1992 through 2002 (both fuel consumed and vehicle counts) were assumed to be at the same ratio as for 2003 where data existed. For 1990, 1991, 2012 and 2013, fuel consumed by alternative fuel and vehicle type were extrapolated based on a regression analysis using the best curve fit based upon R^2 using the nearest 5 years of data.

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

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

[7] Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol and diesel is blended with biodiesel; dual-fuel vehicles can run on gasoline or an alternative fuel – either natural gas or LPG – but not at the same time, while flex-fuel vehicles are designed to run on E85 (85 percent ethanol) or gasoline, or any mixture of the two in between. Heavy-duty vehicles are more likely to run on diesel fuel, natural gas, or LPG.

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 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- 96, while more detailed estimates of VMT by control technology are shown in Table A- 97.

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- 107.[8]

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- 101. Consumption data for ships and other boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2014) for distillate fuel, and DHS (2008) and EIA (2014a) for residual fuel; marine transport fuel consumption data for U.S. territories (EIA 2014b) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[9] Gasoline consumption by recreational boats was obtained from EPA's NONROAD model (EPA 2014b). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2013), diesel consumption from commuter rail was obtained from APTA (2007 through 2013) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2013).[10] Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2013). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2014) and FAA (2014), 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 (DESC 2014 and FAA 2014). Pipeline fuel consumption was obtained from EIA (2007 through 2014) (note: pipelines are a transportation source but are stationary, not mobile, sources). Data on fuel consumption by all non-transportation mobile sources were obtained from EPA's NONROAD model (EPA 2014b) and from FHWA (1996 through 2014) for gasoline consumption for trucks used off-road.[11]

Emissions of CH_4 and N_2O from non-road mobile sources were calculated by multiplying U.S. default emission factors in the *2006 IPCC Guidelines* by activity data for each source type (see Table A- 108).

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[8] New data from EIA on the population and activity of alternative fuel vehicles significantly changed the mix of alternative fuel vehicles in the population from last year's inventory, resulting in changes in the average emissions per mile associated with different classes of alternative fuel vehicles (light-duty, heavy-duty, buses, etc.).

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

[10] Diesel consumption from Class II and Class III railroad were unavailable for 2012. Values are proxied from 2010, which is the last year the data was available.

[11] "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.

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 2014), 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. Table A- 109 through Table A- 111 provides complete emission estimates for 1990 through 2013.

Table A- 94: Vehicle Miles Traveled for Gasoline On-Road Vehicles (million miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles	Motorcycles
1990	1,391.3	554.2	25.6	9.6
1991	1,341.8	627.1	25.1	9.2
1992	1,355.0	682.7	24.9	9.6
1993	1,356.7	720.2	24.6	9.9
1994	1,387.6	738.5	25.0	10.2
1995	1,420.8	762.2	24.8	9.8
1996	1,454.9	787.7	24.1	9.9
1997	1,488.8	820.7	23.7	10.1
1998	1,536.9	836.7	23.7	10.3
1999	1,559.4	867.4	23.9	10.6
2000	1,591.9	886.6	23.8	10.5
2001	1,619.8	904.8	23.5	9.6
2002	1,649.7	925.6	23.4	9.6
2003	1,663.2	942.7	23.8	9.6
2004	1,690.9	984.1	24.2	10.1
2005	1,699.3	997.4	24.4	10.5
2006	1,681.4	1,037.1	24.5	12.0
2007[a]	2,093.1	561.3	33.9	21.4
2008	2,013.8	579.3	34.7	20.8
2009	2,004.8	590.9	32.3	20.8
2010	2,014.6	595.6	32.1	18.5
2011	2,034.4	577.1	30.0	18.5
2012	2,049.5	573.8	30.3	21.4
2013	2,057.5	575.0	31.0	21.4

Source: Derived from FHWA (1996 through 2014).

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007-2013 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.

Table A- 95: Vehicle Miles Traveled for Diesel On-Road Vehicles (million miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[b]
1990	16.9	19.6	125.5
1991	16.3	21.6	129.2
1992	16.5	23.4	133.3
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	164.2
1997	13.5	29.0	173.3
1998	12.4	30.5	178.3
1999	9.4	32.6	185.1
2000	8.0	35.2	187.8
2001	8.1	37.0	190.8
2002	8.3	38.9	196.0
2003	8.4	39.6	198.9
2004	8.5	41.4	201.3
2005	8.5	41.8	202.6
2006	8.4	43.3	201.2
2007	10.4	23.4	280.4
2008	10.1	24.2	286.6
2009	10.0	24.7	266.1

2010	10.1	24.9	264.3
2011	10.0	23.7	242.6
2012	10.1	23.6	244.7
2013[c]	9.9	23.2	246.1

Source: Derived from FHWA (1996 through 2014).

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007-2012 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.

[b] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses

Table A- 96: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (million miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	0.1	0.7	0.9
1991	0.1	0.8	0.9
1992	0.1	0.8	1.0
1993	0.2	0.8	1.0
1994	0.2	0.9	1.1
1995	0.2	0.9	1.1
1996	0.2	1.0	1.2
1997	0.2	1.1	1.4
1998	0.3	1.1	1.4
1999	0.3	1.0	1.3
2000	0.3	1.3	1.5
2001	0.4	1.4	1.8
2002	0.5	1.6	2.0
2003	0.5	1.8	2.0
2004	0.5	1.7	2.1
2005	0.6	1.8	2.5
2006	0.7	2.1	3.6
2007	0.8	1.9	4.4
2008	0.9	2.0	4.2
2009	0.9	2.0	4.4
2010	1.1	2.2	4.0
2011	1.9	3.4	8.9
2012	3.3	3.8	9.0
2013	7.0	5.1	13.1

Source: Derived from Browning (2014).

[a] Heavy Duty-Vehicles includes medium-duty trucks, heavy-duty trucks, and buses.

Table A- 97: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Light-Duty Cars	**89.4**	**190.2**	**345.8**	**402.4**	**462.9**	**480.3**	**526.4**	**595.1**	**733.0**	**840.3**	**892.8**	**921.3**	**1,080.8**	**1,913.4**	**3,294.0**	**7,011.9**
Methanol-Flex Fuel ICE	+	42.9	13.9	10.6	8.2	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	+	2.2	46.3	52.4	64.5	94.5	118.3	158.0	203.1	292.6	355.5	437.6	601.6	1,006.3	1,152.4	1,578.3
CNG ICE	4.2	17.0	44.7	53.9	63.0	69.0	72.4	77.2	84.9	89.5	98.9	97.2	102.7	109.8	112.0	118.0
CNG Bi-fuel	5.6	22.7	59.8	72.9	85.3	93.5	95.5	95.5	83.1	77.9	74.5	40.8	38.7	38.4	37.3	37.8
LPG ICE	34.3	40.1	39.1	40.2	42.1	42.8	44.9	44.5	90.3	91.7	91.8	88.9	93.8	99.8	92.4	87.3
LPG Bi-fuel	42.4	49.5	48.3	49.7	52.0	53.0	57.0	55.3	52.8	41.7	39.7	15.3	14.5	14.7	14.1	14.3
Biodiesel (BD100)	+	+	1.3	2.6	4.0	3.7	7.3	23.5	65.1	87.0	71.1	81.3	65.9	252.0	255.6	417.7
NEVs	+	6.2	30.9	41.5	47.6	53.9	58.2	65.0	77.7	84.1	86.6	87.7	87.7	96.4	94.0	95.7
Electric Vehicle	3.0	9.6	61.5	78.6	96.0	69.9	72.7	75.7	75.5	74.7	73.5	71.0	74.3	294.0	935.7	2,786.4
SI PHEV - Electricity	+	+	+	+	+	+	+	+	+	+	+	+	+	+	598.3	1,874.0
Fuel Cell Hydrogen	+	+	+	+	+	0.1	0.1	0.4	0.6	1.2	1.2	1.6	1.5	1.9	2.1	2.3
Light-Duty Trucks	**729.7**	**918.4**	**1,267.7**	**1,408.2**	**1,563.0**	**1,755.8**	**1,689.5**	**1,848.7**	**2,083.5**	**1,906.4**	**1,962.9**	**1,950.7**	**2,161.3**	**3,407.6**	**3,825.1**	**5,111.6**
Ethanol-Flex Fuel ICE	+	1.4	187.7	233.6	287.5	420.4	509.1	608.0	700.8	827.2	947.6	1,061.8	1,318.6	2,064.6	2,567.1	3,435.6
CNG ICE	7.3	29.4	77.2	94.2	110.0	120.5	125.1	119.1	118.6	113.2	105.7	136.0	132.3	134.7	130.5	136.6
CNG Bi-fuel	13.6	55.3	145.1	176.9	206.7	226.3	186.0	184.2	198.6	185.7	169.9	139.2	141.5	146.2	130.8	127.1
LPG ICE	126.0	146.5	142.4	146.4	153.1	155.6	131.7	131.2	128.1	120.5	111.6	108.5	105.1	106.6	105.4	107.9
LPG Bi-fuel	581.9	676.8	657.8	676.0	707.1	718.9	582.0	564.6	488.7	324.0	341.4	190.2	183.8	184.8	128.5	112.9
LNG	+	0.2	0.5	0.7	0.7	1.0	0.9	1.0	1.0	0.9	1.2	1.1	0.9	1.0	1.0	0.9
Biodiesel (BD100)	+	+	5.8	11.6	19.0	19.3	39.7	114.7	338.5	229.5	186.0	217.3	176.6	653.9	657.2	1,084.0
Electric Vehicle	1.0	8.8	51.2	68.9	79.0	93.9	115.0	125.8	109.1	105.0	99.2	96.1	101.7	114.8	103.4	104.6
Fuel Cell Hydrogen	+	+	+	+	+	+	+	0.2	0.2	0.3	0.3	0.5	0.8	1.1	1.4	1.9
Medium Duty Trucks	**455.8**	**543.9**	**666.2**	**794.3**	**851.0**	**835.4**	**751.1**	**794.0**	**791.0**	**863.3**	**864.1**	**869.7**	**773.1**	**1,550.5**	**1,473.8**	**2,018.4**
CNG ICE	3.4	13.6	39.5	54.0	62.7	55.0	71.3	70.8	59.0	86.1	113.9	122.1	132.3	149.8	166.4	185.2
CNG Bi-fuel	6.9	27.2	79.5	108.4	126.0	110.5	76.3	75.9	65.9	68.3	74.5	56.6	55.0	53.8	49.4	45.9
LPG ICE	217.2	245.1	264.8	304.6	317.0	320.7	273.0	261.7	188.3	162.0	155.4	150.3	146.3	141.7	120.2	111.4
LPG Bi-fuel	228.2	257.6	278.3	320.1	333.1	337.0	307.2	296.0	211.8	167.6	144.2	95.9	93.5	89.6	63.1	55.4
LNG	+	0.5	1.5	2.0	2.1	2.4	1.5	1.5	1.5	1.5	1.7	1.6	1.6	1.5	1.4	1.4
Biodiesel (BD20)	+	+	2.6	5.2	9.9	9.8	21.8	88.1	264.5	377.8	374.5	443.1	344.4	1,114.2	1,073.4	1,619.1
Heavy-Duty Trucks	**408.8**	**479.2**	**574.0**	**694.3**	**762.6**	**753.7**	**879.7**	**1,135.3**	**2,189.5**	**2,803.9**	**2,497.1**	**2,589.4**	**2,259.8**	**6,228.2**	**6,400.7**	**9,815.8**
CNG ICE	1.3	5.1	15.3	21.0	24.5	21.5	22.6	23.5	25.6	28.1	41.8	51.8	69.4	87.6	106.5	130.2
LPG ICE	397.7	461.1	510.8	590.3	617.1	627.1	674.2	536.7	567.7	556.3	545.1	536.3	525.6	521.2	525.4	523.7
LPG Bi-fuel	9.9	11.5	12.7	14.7	15.3	15.6	15.1	15.0	13.0	12.9	12.8	11.3	11.5	13.9	13.4	14.3
LNG	+	1.4	4.6	6.5	6.9	9.8	11.1	19.8	21.6	23.9	34.9	38.2	44.3	47.9	55.1	61.4
Biodiesel (BD20)	+	+	30.6	61.9	98.8	79.8	156.7	540.2	1,561.5	2,182.7	1,862.4	1,951.8	1,608.9	5,557.7	5,700.3	9,086.1
Buses	**41.0**	**108.2**	**242.5**	**327.6**	**373.9**	**363.5**	**490.6**	**532.0**	**620.0**	**701.0**	**829.5**	**894.4**	**925.8**	**1,084.9**	**1,128.0**	**1,267.3**
Neat Methanol ICE	2.9	8.6	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	0.1	3.5	+	+	+	+	+	+	+	+	+	+	+	0.9	1.0	1.4
CNG ICE	15.5	62.0	184.1	252.1	294.0	260.7	350.7	382.8	438.6	485.7	618.3	676.9	719.3	757.5	780.5	813.0
LPG ICE	22.2	25.6	28.1	32.4	33.9	34.4	38.2	39.9	46.9	47.2	50.1	51.8	53.4	57.2	62.2	66.1
LNG	+	7.4	23.4	32.7	34.7	49.4	80.9	83.2	87.8	92.3	91.2	90.8	90.4	90.2	90.4	90.9
Biodiesel (BD20)	+	+	0.6	1.1	1.7	1.5	4.0	10.3	29.6	58.8	51.2	55.9	43.8	160.2	174.6	276.2
Electric	0.4	1.2	6.3	9.2	9.6	17.6	16.8	15.8	17.0	16.8	18.1	18.3	18.2	18.1	18.5	18.7
Fuel Cell Hydrogen	+	+	+	+	+	+	+	0.1	0.1	0.2	0.6	0.6	0.7	0.8	0.9	1.1
Total VMT	**1,724.8**	**2,239.9**	**3,096.2**	**3,626.8**	**4,013.3**	**4,188.8**	**4,337.3**	**4,905.0**	**6,417.1**	**7,115.0**	**7,046.5**	**7,225.5**	**7,200.7**	**14,184.6**	**16,121.7**	**25,225.0**

Source: Derived from Browning (2003) and Browning (2014).
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 data. 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

Table A- 98: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2013

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	6.9%	7.6%	6.5%	15.4%	8.4%	6.4%	7.4%
1	6.6%	7.2%	0.0%	14.9%	8.0%	0.0%	0.0%
2	4.1%	4.9%	0.0%	9.2%	5.5%	0.0%	6.0%
3	4.6%	4.3%	0.0%	8.9%	3.2%	0.0%	5.5%
4	4.2%	3.3%	0.0%	5.9%	2.9%	0.0%	5.7%
5	5.3%	5.6%	4.0%	0.5%	7.3%	4.6%	10.0%
6	5.8%	5.9%	3.7%	0.4%	6.6%	9.0%	8.9%
7	5.4%	6.0%	5.2%	7.1%	8.4%	7.8%	8.4%
8	5.4%	6.2%	4.1%	4.9%	7.2%	7.1%	7.4%
9	5.0%	6.2%	5.1%	2.9%	6.4%	5.0%	6.3%
10	5.2%	5.7%	4.4%	3.9%	5.9%	4.4%	5.4%
11	5.1%	5.5%	4.4%	4.2%	5.1%	3.6%	4.7%
12	4.9%	4.8%	3.7%	2.8%	5.8%	4.7%	4.0%
13	5.1%	4.5%	7.2%	2.5%	3.1%	7.3%	3.2%
14	4.1%	4.0%	6.9%	1.5%	4.6%	5.8%	2.4%
15	3.4%	3.1%	2.9%	1.4%	1.7%	3.9%	2.1%
16	3.1%	2.7%	5.4%	0.5%	2.2%	3.8%	2.0%
17	2.6%	2.0%	3.2%	0.6%	1.7%	3.4%	1.7%
18	2.6%	2.0%	4.5%	0.5%	1.2%	4.1%	1.3%
19	2.0%	1.7%	3.6%	0.1%	0.7%	3.1%	1.5%
20	1.7%	1.2%	2.8%	0.2%	0.8%	2.3%	1.2%
21	1.4%	0.9%	2.2%	0.3%	0.7%	1.6%	1.0%
22	1.2%	0.8%	1.8%	0.6%	0.4%	1.6%	0.8%
23	1.0%	0.7%	2.5%	0.2%	0.3%	1.9%	0.7%
24	0.8%	0.7%	2.9%	0.1%	0.3%	1.9%	0.5%
25	0.6%	0.6%	2.4%	0.0%	0.3%	1.6%	0.4%
26	0.5%	0.5%	2.3%	1.3%	0.1%	1.4%	0.4%
27	0.4%	0.5%	2.3%	0.7%	0.4%	1.0%	0.3%
28	0.3%	0.3%	1.7%	2.2%	0.3%	1.0%	0.3%
29	0.3%	0.3%	1.5%	2.3%	0.3%	0.8%	0.3%
30	0.2%	0.2%	2.7%	3.9%	0.2%	1.0%	0.2%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Source: EPA (2014).
Note: This year's Inventory includes updated vehicle population data based on the MOVES 2014 Model.

[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).

Table A- 99: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	13,897	15,707	19,241	13,897	15,707	40,529	7,569
1	13,633	15,412	19,245	13,633	15,412	41,218	4,042
2	13,348	15,079	17,897	13,348	15,079	48,103	3,058
3	13,043	14,715	16,346	13,043	14,715	49,197	2,528
4	12,722	14,322	15,881	12,722	14,322	50,954	2,188
5	12,385	13,904	16,765	12,385	13,904	36,623	1,945
6	12,036	13,466	14,100	12,036	13,466	48,397	1,764
7	11,675	13,011	14,463	11,675	13,011	41,013	1,620
8	11,306	12,542	12,357	11,306	12,542	39,083	1,499
9	10,930	12,067	12,270	10,930	12,067	32,506	1,400
10	10,550	11,584	11,036	10,550	11,584	31,586	1,317
11	10,169	11,102	10,250	10,169	11,102	27,270	1,241
12	9,787	10,623	8,905	9,787	10,623	25,419	1,181
13	9,407	10,152	9,688	9,407	10,152	23,924	1,120
14	9,032	9,692	8,465	9,032	9,692	20,806	1,067
15	8,663	9,245	7,096	8,663	9,245	19,018	1,022
16	8,302	8,820	5,795	8,302	8,820	13,063	984
17	7,953	8,416	5,491	7,953	8,416	13,950	946
18	7,616	8,041	5,464	7,616	8,041	11,762	908
19	7,294	7,697	4,957	7,294	7,697	10,471	878
20	6,989	7,387	4,951	6,989	7,387	9,847	848
21	6,705	7,117	4,266	6,705	7,117	9,081	825
22	6,441	6,889	4,222	6,441	6,889	8,357	635
23	6,201	6,710	3,998	6,201	6,710	7,256	757
24	5,987	6,581	3,776	5,987	6,581	6,399	712
25	5,801	6,506	3,442	5,801	6,506	5,829	666
26	5,645	6,492	3,198	5,645	6,492	5,646	613
27	5,521	6,492	3,038	5,521	6,492	4,791	568
28	5,432	6,492	2,991	5,432	6,492	3,990	537
29	5,379	6,492	2,796	5,379	6,492	3,212	500
30	5,379	6,492	2,233	5,379	6,492	2,573	462

Source: EPA (2014).

[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- 100: VMT Distribution by Vehicle Age and Vehicle/Fuel Type, [a] 2013

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	8.88%	9.83%	14.09%	18.58%	10.54%	9.89%	27.20%
1	8.42%	9.22%	0.00%	17.62%	9.88%	0.00%	0.00%
2	5.10%	6.05%	0.00%	10.67%	6.64%	0.00%	8.98%
3	5.61%	5.27%	0.00%	10.09%	3.82%	0.00%	6.71%
4	4.98%	3.88%	0.00%	6.51%	3.37%	0.00%	6.01%
5	6.16%	6.48%	7.46%	0.58%	8.09%	6.40%	9.47%
6	6.53%	6.61%	5.79%	0.39%	7.06%	16.52%	7.64%
7	5.88%	6.47%	8.43%	7.18%	8.71%	12.12%	6.65%
8	5.67%	6.46%	5.68%	4.80%	7.26%	10.57%	5.39%
9	5.10%	6.20%	7.01%	2.79%	6.23%	6.14%	4.27%
10	5.10%	5.44%	5.52%	3.53%	5.47%	5.31%	3.44%
11	4.86%	5.01%	5.12%	3.70%	4.53%	3.69%	2.85%
12	4.51%	4.23%	3.68%	2.37%	4.94%	4.56%	2.30%
13	4.50%	3.80%	7.85%	2.04%	2.53%	6.61%	1.74%
14	3.47%	3.17%	6.59%	1.15%	3.54%	4.58%	1.25%
15	2.74%	2.40%	2.34%	1.07%	1.27%	2.81%	1.03%
16	2.41%	2.00%	3.54%	0.39%	1.53%	1.86%	0.94%
17	1.89%	1.40%	2.01%	0.41%	1.13%	1.78%	0.80%
18	1.84%	1.30%	2.78%	0.30%	0.80%	1.85%	0.58%
19	1.37%	1.07%	1.99%	0.04%	0.45%	1.24%	0.64%
20	1.11%	0.74%	1.58%	0.14%	0.46%	0.86%	0.50%
21	0.88%	0.54%	1.07%	0.18%	0.41%	0.55%	0.41%
22	0.71%	0.45%	0.85%	0.35%	0.23%	0.49%	0.25%
23	0.58%	0.39%	1.11%	0.11%	0.18%	0.53%	0.24%
24	0.46%	0.39%	1.24%	0.07%	0.16%	0.45%	0.17%
25	0.35%	0.33%	0.94%	0.02%	0.13%	0.36%	0.13%
26	0.27%	0.25%	0.81%	0.62%	0.05%	0.29%	0.12%
27	0.22%	0.25%	0.78%	0.34%	0.18%	0.18%	0.09%
28	0.17%	0.17%	0.59%	1.04%	0.13%	0.15%	0.07%
29	0.13%	0.14%	0.48%	1.08%	0.14%	0.10%	0.06%
30	0.12%	0.09%	0.67%	1.84%	0.13%	0.10%	0.05%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Note: Estimated by weighting data in Table A- 98 by data in Table A- 99. This year's Inventory includes updated vehicle population data based on the MOVES 2014 Model that affects this distribution.
[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).

Table A- 101: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

Vehicle Type/Year	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Aircraft[a]	**19,560**	**18,320**	**20,304**	**19,745**	**19,284**	**18,640**	**19,407**	**19,714**	**18,973**	**18,670**	**17,984**	**16,030**	**15,762**	**15,262**	**14,914**	**15,274**
Aviation Gasoline	374	329	302	291	281	251	260	294	278	263	235	221	225	225	209	186
Jet Fuel	19,186	17,991	20,002	19,454	19,004	18,389	19,147	19,420	18,695	18,407	17,749	15,809	15,537	15,036	14,705	15,088
Commercial Aviation	*11,569*	*12,136*	*14,672*	*13,121*	*12,774*	*12,943*	*13,147*	*13,976*	*14,426*	*14,708*	*13,400*	*12,588*	*11,931*	*12,067*	*11,932*	*12,031*
Ships and Other Boats	**4,507**	**5,789**	**6,431**	**4,416**	**4,834**	**4,089**	**4,300**	**4,881**	**5,143**	**5,746**	**4,882**	**4,312**	**5,763**	**5,937**	**5,362**	**5,308**
Diesel	1,043	1,546	1,750	1,630	1,592	1,711	1,347	1,470	1,409	1,489	1,470	1,480	1,446	1,727	1,475	1,499
Gasoline	1,403	1,597	1,653	1,655	1,654	1,648	1,640	1,630	1,620	1,610	1,600	1,591	1,578	1,567	1,557	1,550
Residual	2,061	2,646	3,028	1,131	1,588	730	1,313	1,781	2,115	2,647	1,812	1,241	2738	2,643	2,330	2,258
Construction/ Mining Equipment[b]	**4,160**	**4,835**	**5,439**	**5,897**	**6,067**	**6,248**	**6,428**	**6,520**	**6,656**	**6,684**	**6,835**	**6,960**	**7,204**	**7,307**	**7,473**	**8,071**
Diesel	3,674	4,387	5,095	5,241	5,386	5,532	5,678	5,823	5,968	6,113	6,258	6,403	6,547	6,693	6,839	6,984
Gasoline	486	448	344	657	681	716	751	697	688	571	577	558	656	614	634	1,086
Agricultural Equipment[c]	**3,134**	**3,698**	**3,875**	**4,107**	**4,220**	**4,324**	**4,648**	**4,715**	**4,948**	**4,862**	**4,517**	**4,641**	**4,739**	**4,928**	**5,086**	**4,948**
Diesel	2,321	2,772	3,222	3,305	3,388	3,471	3,554	3,637	3,719	3,801	3,883	3,965	4,046	4,129	4,211	4,294
Gasoline	813	927	652	802	832	853	1,094	1,078	1,229	1,061	634	676	692	799	875	655
Rail	**3,461**	**3,864**	**4,106**	**4,119**	**4,089**	**4,176**	**4,407**	**4,446**	**4,665**	**4,539**	**4,216**	**3,535**	**3,807**	**3,999**	**3,921**	**4,016**
Diesel	3,461	3,864	4,106	4,119	4,089	4,176	4,407	4,446	4,665	4,539	4,216	3,535	3,807	3,999	3,921	4,016
Other[d]	**5,916**	**6,525**	**6,826**	**7,657**	**7,840**	**8,049**	**8,263**	**8,281**	**8,396**	**8,256**	**8,387**	**8,482**	**8,830**	**8,795**	**8,730**	**8,827**
Diesel	1,423	1,720	2,016	2,079	2,144	2,210	2,275	2,340	2,405	2,471	2,536	2,601	2,666	2,731	2,797	2,862
Gasoline	4,493	4,805	4,810	5,578	5,696	5,840	5,988	5,941	5,991	5,785	5,851	5,881	6,164	6,063	5,933	5,965
Total	**40,738**	**43,031**	**46,980**	**45,941**	**46,334**	**45,528**	**47,453**	**48,558**	**48,781**	**48,755**	**46,821**	**43,959**	**46,105**	**46,227**	**45,487**	**46,445**

Sources: AAR (2008 through 2013), APTA (2007 through 2013), BEA (1991 through 2013), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2013), DESC (2013), DOE (1993 through 2013), DOT (1991 through 2013), EIA (2002), EIA (2007b), EIA (2008), EIA (2007 through 2014), EIA (1991 through 2014), EPA (2013b), FAA (2014), 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-102: 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%
2009-13	-	-	-	-	-	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-103: 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%
2008-2013	-	-	-	-	-	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- 104: 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%
2008-2013	-	-	-	-	-	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- 105: 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	1996-2013
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960-1990
Moderate control	1991-2003
Advanced control	2004-2006
Aftertreatment	2007-2013
Motorcycles	
Uncontrolled	1960-1995
Non-catalyst controls	1996-2013

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

Table A- 106: 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 *2006 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this annex.

Table A- 107: 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- 108: 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[b]		
Gasoline	0.08	0.18

Diesel	0.08	0.18
Other Non-Road		
All "Other" Categories[c]	0.08	0.18
Aircraft		
Jet Fuel[d]	0.10	0.00
Aviation Gasoline	0.04	2.64

Source: IPCC (2006) 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.

[d] Emissions of CH_4 from jet fuels have been zeroed out across the time series. Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al, 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consumer methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, methane emissions factors for jet aircraft were changed to zero in this year's Inventory to reflect the latest emissions testing data.

Table A- 109: NO_x Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gasoline On-Road	**5,746**	**4,560**	**3,812**	**3,715**	**4,940**	**4,621**	**4,303**	**3,984**	**3,819**	**3,654**	**3,317**	**2,966**	**2,724**	**2,805**	**2,585**	**2,365**
Passenger Cars	3,847	2,752	2,084	2,027	2,695	2,521	2,347	2,174	2,083	1,993	1,810	1,618	1,486	1,530	1,410	1,290
Light-Duty Trucks	1,364	1,325	1,303	1,285	1,708	1,598	1,488	1,378	1,321	1,264	1,147	1,026	942	970	894	818
Medium- and Heavy-Duty Trucks and Buses	515	469	411	390	518	485	452	418	401	383	348	311	286	294	271	248
Motorcycles	20	14	13	14	18	17	16	15	14	13	12	11	10	10	10	9
Diesel On-Road	**2,956**	**3,493**	**3,803**	**3,338**	**4,438**	**4,152**	**3,866**	**3,580**	**3,431**	**3,283**	**2,980**	**2,665**	**2,448**	**2,520**	**2,323**	**2,125**
Passenger Cars	39	19	7	6	8	7	7	6	6	6	5	5	4	4	4	4
Light-Duty Trucks	20	12	6	5	7	7	6	6	6	5	5	4	4	4	4	3
Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,791	3,326	4,423	4,138	3,853	3,568	3,420	3,272	2,970	2,656	2,439	2,512	2,315	2,118
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,483**	**2,584**	**2,643**	**3,107**	**2,981**	**2,856**	**2,731**	**2,490**	**2,249**	**2,226**	**2,166**	**2,118**	**1,968**	**1,881**	**1,793**
Ships and Boats	402	488	506	544	643	617	591	565	515	465	460	448	438	407	389	371
Rail	338	433	451	485	574	550	527	504	460	415	411	400	391	363	347	331
Aircraft[b]	25	31	40	39	46	45	43	41	37	34	33	32	32	29	28	27
Agricultural Equipment[c]	437	478	484	480	562	539	516	494	450	407	402	392	383	356	340	324
Construction/Mining Equipment[d]	641	697	697	690	807	774	742	709	647	584	578	563	550	511	488	466
Other[e]	318	357	407	406	476	456	437	418	381	344	341	332	324	301	288	274
Total	**10,862**	**10,536**	**10,199**	**9,696**	**12,485**	**11,755**	**11,025**	**10,295**	**9,740**	**9,186**	**8,523**	**7,797**	**7,290**	**7,294**	**6,788**	**6,283**

[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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES is a change that affects the emissions time series.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Table A- 110: CO Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gasoline On-Road	**98,328**	**74,673**	**60,657**	**56,716**	**46,115**	**43,498**	**40,882**	**38,265**	**35,781**	**33,298**	**29,626**	**24,515**	**25,235**	**24,442**	**22,925**	**21,408**
Passenger Cars	60,757	42,065	32,867	31,600	25,693	24,235	22,777	21,319	19,936	18,552	16,506	13,659	14,060	13,618	12,773	11,927
Light-Duty Trucks	29,237	27,048	24,532	22,574	18,355	17,313	16,272	15,230	14,242	13,253	11,792	9,758	10,044	9,729	9,125	8,521
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	3,104	2,411	1,960	1,849	1,738	1,627	1,521	1,416	1,259	1,042	1,073	1,039	975	910
Motorcycles	240	155	154	131	107	101	95	89	83	77	69	57	58	57	53	50
Diesel On-Road	**1,696**	**1,424**	**1,088**	**869**	**707**	**667**	**626**	**586**	**548**	**510**	**454**	**376**	**387**	**375**	**351**	**328**
Passenger Cars	35	18	7	6	5	4	4	4	4	3	3	3	3	3	2	2
Light-Duty Trucks	22	16	6	5	4	4	4	4	3	3	3	2	2	2	2	2
Medium- and Heavy-Duty Trucks and Buses	1,639	1,391	1,075	858	698	658	618	579	541	504	448	371	382	370	347	324
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,533**	**21,814**	**22,266**	**20,414**	**20,197**	**19,980**	**19,763**	**18,382**	**17,001**	**16,137**	**14,365**	**13,853**	**13,488**	**13,214**	**12,940**
Ships and Boats	1,559	1,781	1,825	1,831	1,679	1,661	1,643	1,626	1,512	1,398	1,327	1,182	1,140	1,109	1,087	1,064

Rail	85	93	90	90	82	81	81	80	74	69	65	58	56	54	53	52
Aircraft[b]	217	224	245	233	214	212	210	207	193	178	169	151	145	141	139	136
Agricultural Equipment[c]	581	628	626	621	569	563	557	551	513	474	450	401	386	376	369	361
Construction/Mining Equipment[d]	1,090	1,132	1,047	1,041	955	944	934	924	860	795	755	672	648	631	618	605
Other[e]	15,805	17,676	17,981	18,449	16,914	16,735	16,555	16,375	15,231	14,087	13,371	11,903	11,479	11,176	10,949	10,722
Total	**119,360**	**97,630**	**83,559**	**79,851**	**67,235**	**64,362**	**61,488**	**58,615**	**54,712**	**50,809**	**46,217**	**39,256**	**39,475**	**38,305**	**36,491**	**34,676**

[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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES is a change that affects the emissions time series.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Table A- 111: NMVOCs Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gasoline On-Road	**8,110**	**5,819**	**4,615**	**4,285**	**3,473**	**3,308**	**3,144**	**2,979**	**2,997**	**3,015**	**2,641**	**2,384**	**2,393**	**2,485**	**2,279**	**2,074**
Passenger Cars	5,120	3,394	2,610	2,393	1,939	1,847	1,756	1,664	1,674	1,684	1,475	1,332	1,336	1,388	1,273	1,158
Light-Duty Trucks	2,374	2,019	1,750	1,664	1,348	1,285	1,221	1,157	1,164	1,171	1,025	926	929	965	885	805
Medium- and Heavy-Duty Trucks and Buses	575	382	232	206	167	159	151	143	144	145	127	115	115	120	110	100
Motorcycles	42	24	23	22	18	17	16	15	15	15	14	12	12	13	12	11
Diesel On-Road	**406**	**304**	**216**	**207**	**168**	**160**	**152**	**144**	**145**	**146**	**128**	**115**	**116**	**120**	**110**	**100**
Passenger Cars	16	8	3	3	2	2	2	2	2	2	2	2	2	2	2	1
Light-Duty Trucks	14	9	4	4	3	3	3	3	3	3	2	2	2	2	2	2
Medium- and Heavy-Duty Trucks and Buses	377	286	209	201	163	155	147	140	140	141	124	112	112	116	107	97
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,622**	**2,398**	**2,379**	**2,800**	**2,733**	**2,667**	**2,600**	**2,491**	**2,383**	**2,310**	**2,150**	**2,082**	**1,957**	**1,863**	**1,768**
Ships and Boats	608	739	744	730	859	839	818	798	764	731	709	660	639	600	572	543
Rail	33	36	35	35	42	41	40	39	37	35	34	32	31	29	28	26
Aircraft[b]	28	28	24	19	23	22	22	21	20	19	19	17	17	16	15	14
Agricultural Equipment[c]	85	86	76	72	85	83	81	79	76	73	70	65	63	60	57	54
Construction/Mining Equipment[d]	149	152	130	125	147	144	140	137	131	125	121	113	109	103	98	93
Other[e]	1,512	1,580	1,390	1,397	1,644	1,605	1,566	1,527	1,463	1,399	1,356	1,263	1,223	1,149	1,094	1,038
Total	**10,932**	**8,745**	**7,230**	**6,872**	**6,440**	**6,201**	**5,962**	**5,724**	**5,634**	**5,544**	**5,078**	**4,650**	**4,591**	**4,562**	**4,252**	**3,942**

[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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES is a change that affects the emissions time series.
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- 102 through Table A- 105 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 and were compiled from EPA (1993, 1994a, 1994b, 1998, 1999a) and IPCC/UNEP/OECD/IEA (1997).

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 percent 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 three 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 NO_x 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 report 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- 112 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- 112: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Agricultural Equipment[a]	31.0	36.6	38.8	41.0	42.1	43.1	46.1	46.8	49.0	48.3	45.3	46.5	47.5	49.2	50.7	49.7
Construction/Mining Equipment[b]	42.0	48.9	55.3	59.5	61.2	63.0	64.8	65.9	67.3	67.7	69.2	70.5	72.8	73.9	75.6	81.0
Other Sources[c]	54.5	59.9	62.8	70.3	72.0	73.8	75.9	76.1	77.3	76.1	76.8	77.5	80.3	80.0	79.5	80.5
Total	**127.6**	**145.4**	**156.9**	**170.8**	**175.4**	**180.0**	**186.8**	**188.7**	**193.6**	**192.1**	**191.3**	**194.5**	**200.6**	**203.2**	**205.9**	**211.1**

[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- 113 below presents these HFC emissions. Table A- 114 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A- 113: HFC Emissions from Transportation Sources

Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Mobile AC	**-**	**18.9**	**53.5**	**59.1**	**61.3**	**62.7**	**64.3**	**65.0**	**65.6**	**66.0**	**66.3**	**65.2**	**61.7**	**55.7**	**49.9**	**44.0**
Passenger Cars	-	11.2	28.1	30.7	31.5	31.6	31.8	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3
Light-Duty Trucks	-	7.8	25.4	28.4	29.8	31.1	32.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7
Comfort Cooling for Trains and Buses	**-**	**+**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
School and Tour Buses	-	+	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Transit Buses	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Rail	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	**-**	**2.7**	**11.2**	**12.2**	**13.0**	**13.8**	**14.7**	**15.1**	**15.5**	**15.7**	**15.7**	**15.8**	**15.8**	**15.9**	**15.9**	**15.9**
Medium- and Heavy-Duty Trucks	-	2.0	8.6	9.4	10.0	11.6	12.3	12.7	12.9	13.1	13.1	13.2	13.2	13.3	13.3	13.3
Rail	-	0.6	2.4	2.6	2.8	2.2	2.4	2.5	2.5	2.5	2.5	2.6	2.6	2.6	2.6	2.6
Ships and Other Boats	-	+	0.2	0.2	0.2	+	+	+	+	+	+	+	+	+	+	+
Total	**-**	**21.6**	**64.8**	**71.4**	**74.4**	**76.7**	**79.2**	**80.4**	**81.4**	**82.0**	**82.5**	**81.4**	**77.9**	**72.0**	**66.3**	**60.5**

Note: Totals may not sum due to independent rounding.

+ Less than 0.05 MMT CO_2 Eq.

- Unreported or zero

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

Table A- 114 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 2,023.4 MMT CO_2 Eq. in 2013, an increase of 20 percent from 1990. Transportation sources account for 1,810.3 MMT CO_2 Eq. while non-transportation mobile sources account for 213.1 MMT 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 the Substitutes for Ozone Depleting Substances section of the IPPU chapter; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A- 110 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 emission 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 estimates for jet fuel and aviation gasoline and CH_4 estimates for aviation gasoline 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 2014). Emissions of CH_4 from jet fuels are no longer considered to be emitted across the time series from aircraft gas turbine engines burning jet fuel A at higher power settings.[1] Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al, 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consumer methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, CH_4 emission factors for jet aircraft were reported as zero to reflect the latest emissions testing data.

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 2014). 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 transport, and the release of CO_2 from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,810.3 MMT CO_2 Eq. in 2013.

On-road vehicles were responsible for about 75 percent of all transportation and non-transportation mobile GHG emissions in 2013. 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 2013, greenhouse gas emissions from passenger cars increased by 16 percent, while emissions from light-duty trucks decreased by four percent.[2] Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks increased 76 percent between 1990 and 2013, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

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[1] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines," EPA-420-R-09-901, May 27, 2009 (see http://www.epa.gov/otaq/regs/nonroad/aviation/420r09901.pdf>

[2] 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 Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

Greenhouse gas emissions from aircraft decreased 21 percent between 1990 and 2013. Emissions from military aircraft decreased 69 percent between 1990 and 2013. Commercial aircraft emissions rose 27 percent between 1990 and 2007 then dropped 18 percent from 2007 to 2013, a change of approximately 4 percent between 1990 and 2013.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 213.1 MMT CO_2 Eq. in 2013. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 66 percent between 1990 and 2013. 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.

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

Table A- 115 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 2013). Emissions of CO_2 from transportation and mobile sources increased by 306.1 MMT CO_2 Eq. between 1990 and 2013. In contrast, the combined emissions of CH_4 and N_2O decreased by 26.3 MMT CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[3] Meanwhile, HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 60.5 MMT CO_2 Eq. in 2013 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 per UNFCCC reporting requirements.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A- 116 and Table A- 117 present 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- 116. 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- 117. Commercial aircraft do carry some freight, in addition to passengers, and emissions have been split between passenger and freight 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 emission 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- 114. In addition, estimates of fuel consumption from DOE (1993 through 2014) were used to allocate rail emissions between passenger and freight categories.

In 2013, passenger transportation modes emitted 1,250.2 MMT CO_2 Eq., while freight transportation modes emitted 528.8 MMT CO_2 Eq. Between 1990 and 2013, the percentage growth of greenhouse gas emissions from freight sources was 49 percent, while emissions from passenger sources grew by 8 percent. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

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

Table A- 114: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Percent Change 1990-2013
Transportation Total[a]	**1,554.4**	**1,701.2**	**1,940.9**	**1,928.4**	**1,968.6**	**1,959.1**	**2,004.5**	**2,022.5**	**2,016.8**	**2,018.0**	**1,919.4**	**1,839.9**	**1,848.1**	**1,819.7**	**1,799.8**	**1,810.3**	**16%**
On-Road Vehicles	**1,233.5**	**1,372.7**	**1,584.6**	**1,597.3**	**1,635.7**	**1,646.3**	**1,679.9**	**1,688.1**	**1,684.5**	**1,680.5**	**1,601.0**	**1,554.6**	**1,555.2**	**1,528.3**	**1517.6**	**1,516.6**	**23%**
Passenger Cars	**656.6**	**646.7**	**699.6**	**706.6**	**719.8**	**697.0**	**692.9**	**711.2**	**684.7**	**844.9**	**802.8**	**792.9**	**783.6**	**774.3**	**768.0**	**763.3**	**16%**
Gasoline[h]	648.7	627.6	667.8	672.2	684.6	661.2	656.7	675.2	648.9	809.3	767.8	759.3	752.3	746.3	743.2	741.80	14%
Diesel	7.9	7.9	3.7	3.7	3.7	4.2	4.3	4.2	4.1	4.1	3.7	3.6	3.8	4.1	4.1	4.1	-48%
AFVs	+	0.1	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	2,036%
HFCs from Mobile AC	+	11.2	28.1	30.7	31.5	31.6	31.8	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3	NA
Light-Duty Trucks	**335.6**	**436.8**	**516.0**	**523.5**	**534.7**	**569.4**	**591.0**	**553.3**	**565.6**	**367.7**	**348.8**	**351.6**	**349.0**	**332.1**	**326.2**	**323.4**	**-4%**
Gasoline[h]	323.5	413.6	470.0	473.7	482.3	510.3	528.7	492.9	503.6	318.5	299.7	303.1	300.9	285.8	282.1	281.9	-13%
Diesel	11.5	14.9	20.1	20.8	21.9	27.2	29.0	25.9	26.8	13.6	12.2	12.1	12.6	13.1	13.0	13.0	13%
AFVs	0.6	0.5	0.5	0.6	0.7	0.8	0.9	1.4	1.3	1.0	1.8	1.2	1.3	1.5	1.7	1.9	221%
HFCs from Mobile AC	+	7.8	25.4	28.4	29.8	31.1	32.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7	NA
Medium- and Heavy-Duty Trucks	**231.1**	**278.1**	**355.8**	**355.1**	**369.5**	**367.3**	**379.1**	**409.8**	**420.1**	**445.9**	**428.0**	**389.6**	**403.0**	**401.3**	**401.4**	**407.7**	**76%**
Gasoline[h]	39.5	36.8	37.0	36.1	36.6	31.6	31.8	35.7	36.1	47.0	47.2	43.4	43.2	39.6	39.4	40.2	2%
Diesel	190.7	238.6	309.8	309.3	322.6	323.8	334.7	360.9	370.5	385.3	366.9	332.4	345.9	347.7	347.9	353.3	85%
AFVs	0.9	0.6	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.8	0.6	0.6	0.7	0.7	0.8	-10%
HFCs from Refrigerated Transport	+	2.0	8.6	9.4	10.0	11.6	12.3	12.7	12.9	13.1	13.1	13.2	13.2	13.3	13.3	13.3	NA
Buses	**8.4**	**9.2**	**11.2**	**10.3**	**10.0**	**10.9**	**15.1**	**12.1**	**12.2**	**17.7**	**17.1**	**16.2**	**15.9**	**16.9**	**18.0**	**18.3**	**118%**
Gasoline[h]	0.4	0.4	0.4	0.4	0.3	0.3	0.5	0.4	0.4	0.7	0.7	0.8	0.7	0.7	0.8	0.9	142%
Diesel	8.0	8.7	10.2	9.3	8.8	9.5	13.5	10.6	10.6	15.6	14.8	13.7	13.6	14.6	15.6	15.9	98%
AFVs	+	0.1	0.5	0.5	0.7	0.8	0.9	0.9	0.9	1.0	1.2	1.3	1.1	1.2	1.1	1.1	39,009%
HFCs from Comfort Cooling	+	0.0	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	NA
Motorcycles	**1.8**	**1.8**	**1.9**	**1.7**	**1.7**	**1.7**	**1.8**	**1.7**	**1.9**	**4.3**	**4.4**	**4.2**	**3.7**	**3.6**	**4.2**	**4.0**	**123%**
Gasoline[h]	1.8	1.8	1.9	1.7	1.7	1.7	1.8	1.7	1.9	4.3	4.4	4.2	3.7	3.6	4.2	4.0	123%
Aircraft	**189.1**	**176.7**	**199.4**	**193.9**	**189.4**	**183.1**	**190.6**	**193.6**	**186.3**	**183.4**	**176.6**	**157.4**	**154.8**	**149.9**	**146.5**	**150.0**	**-21%**
General Aviation Aircraft	**42.9**	**35.8**	**35.9**	**43.7**	**45.1**	**36.9**	**41.9**	**40.1**	**30.1**	**24.4**	**30.5**	**21.2**	**26.7**	**22.5**	**19.9**	**23.6**	**-45%**
Jet Fuel	39.8	33.0	33.4	41.2	42.7	34.7	39.7	37.6	27.7	22.2	28.5	19.4	24.8	20.6	18.2	22.0	-45%
Aviation Gasoline	3.2	2.8	2.6	2.5	2.4	2.1	2.2	2.5	2.4	2.2	2.0	1.9	1.9	1.9	1.8	1.6	-50%
Commercial Aircraft	**110.9**	**116.3**	**140.6**	**125.7**	**122.4**	**124.0**	**126.0**	**133.9**	**138.3**	**141.0**	**128.4**	**120.6**	**114.3**	**115.6**	**114.3**	**115.4**	**4%**
Jet Fuel	110.9	116.3	140.6	125.7	122.4	124.0	126.0	133.9	138.3	141.0	128.4	120.6	114.3	115.6	114.3	115.4	4%
Military Aircraft	**35.3**	**24.5**	**22.8**	**24.5**	**21.9**	**22.2**	**22.7**	**19.5**	**18.0**	**18.0**	**17.7**	**15.5**	**13.7**	**11.7**	**12.2**	**11.1**	**-69%**
Jet Fuel	35.3	24.5	22.8	24.5	21.9	22.2	22.7	19.5	18.0	18.0	17.7	15.5	13.7	11.7	12.2	11.1	-69%
Ships and Boats[b]	**44.9**	**58.6**	**61.3**	**42.8**	**47.6**	**37.3**	**40.1**	**45.2**	**48.3**	**55.0**	**45.6**	**38.9**	**45.0**	**46.7**	**40.4**	**39.6**	**-12%**
Gasoline[h]	12.4	14.1	10.2	14.6	14.6	14.4	14.3	14.2	14.0	13.8	13.4	13.2	12.9	12.7	12.6	12.6	2%
Distillate Fuel	9.6	14.9	17.1	15.8	15.4	15.3	11.5	11.4	10.9	11.7	11.5	11.6	11.2	14.1	11.5	11.6	20%
Residual Fuel[g]	22.9	29.5	33.8	12.2	17.4	7.6	14.2	19.6	23.4	29.4	20.7	14.2	20.9	19.8	16.2	15.4	-33%
HFCs from Refrigerated Transport	+	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Rail	**39.0**	**43.8**	**48.4**	**48.9**	**48.6**	**49.8**	**52.6**	**53.3**	**55.4**	**54.7**	**51.0**	**43.7**	**46.5**	**48.1**	**46.8**	**47.5**	**22%**

Distillate Fuel	35.8	40.0	42.5	42.6	42.3	43.2	45.6	46.0	48.3	47.0	43.6	36.5	39.3	41.2	40.2	40.8	14%
Electricity	3.1	3.1	3.5	3.7	3.5	4.3	4.6	4.8	4.6	5.1	4.7	4.5	4.5	4.3	3.9	4.0	32%
Other Emissions from Rail Electricity Use	0.1	0.1	+	+	+	+	0.1	0.1	+	0.1	+	+	+	+	+	+	-38%
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	NA
HFCs from Refrigerated Transport	+	0.6	2.4	2.6	2.8	2.2	2.4	2.5	2.5	2.5	2.5	2.6	2.6	2.6	2.6	2.6	NA
Pipelines[c]	**36.0**	**38.2**	**35.2**	**34.4**	**36.4**	**32.5**	**31.1**	**32.2**	**32.3**	**34.2**	**35.6**	**36.7**	**37.1**	**37.8**	**40.3**	**47.7**	**32%**
Natural Gas	36.0	38.2	35.2	34.4	36.4	32.5	31.1	32.2	32.3	34.2	35.6	36.7	37.1	37.8	40.3	47.7	32%
Other Transportation	**11.8**	**11.3**	**12.1**	**11.1**	**10.9**	**10.1**	**10.2**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**9.5**	**9.0**	**8.3**	**8.8**	**-26%**
Lubricants	11.8	11.3	12.1	11.1	10.9	10.1	10.2	10.2	9.9	10.2	9.5	8.5	9.5	9.0	8.3	8.8	-26%
Non-Transportation Mobile Total	**128.8**	**146.8**	**158.4**	**172.4**	**177.0**	**181.7**	**188.5**	**190.5**	**195.4**	**194.0**	**193.1**	**196.3**	**202.5**	**205.1**	**207.8**	**213.1**	**66%**
Agricultural Equipment[d]	**31.4**	**37.0**	**39.2**	**41.4**	**42.5**	**43.6**	**46.6**	**47.3**	**49.5**	**48.9**	**45.8**	**47.0**	**48.0**	**49.8**	**51.3**	**50.2**	**60%**
Gasoline	7.3	8.3	5.8	7.1	7.4	7.6	9.7	9.6	11.0	9.4	5.6	5.9	6.0	7.0	7.6	5.7	-22%
Diesel	24.1	28.7	33.4	34.3	35.1	36.0	36.9	37.7	38.6	39.4	40.3	41.1	42.0	42.8	43.7	44.5	85%
Construction/ Mining Equipment[e]	**42.4**	**49.4**	**55.8**	**60.1**	**61.8**	**63.6**	**65.4**	**66.4**	**67.9**	**68.3**	**69.8**	**71.1**	**73.5**	**74.6**	**76.3**	**81.7**	**93%**
Gasoline	4.4	4.0	3.1	5.8	6.1	6.4	6.7	6.2	6.1	5.1	5.1	4.9	5.7	5.3	5.5	9.4	116%
Diesel	38.0	45.4	52.7	54.2	55.7	57.2	58.8	60.3	61.8	63.3	64.8	66.3	67.7	69.3	70.8	72.3	90%
Other Equipment[f]	**55.0**	**60.4**	**63.4**	**70.9**	**72.7**	**74.5**	**76.5**	**76.7**	**78.0**	**76.8**	**77.5**	**78.2**	**81.1**	**80.8**	**80.3**	**81.2**	**48%**
Gasoline	40.3	42.6	42.5	49.4	50.5	51.6	53.0	52.5	53.1	51.2	51.2	51.2	53.5	52.5	51.3	51.6	28%
Diesel	14.7	17.8	20.9	21.5	22.2	22.9	23.5	24.2	24.9	25.6	26.2	26.9	27.6	28.3	28.9	29.6	101%
Transportation and Non-Transportation Mobile Total	**1,683.1**	**1,848.0**	**2,099.3**	**2,100.7**	**2,145.6**	**2,140.8**	**2,193.0**	**2,213.0**	**2,212.2**	**2,211.9**	**2,112.5**	**2,036.2**	**2,050.6**	**2,024.9**	**2,007.6**	**2,023.4**	**20%**

[a] Not including emissions from international bunker fuels.

[b] Fluctuations in emission estimates reflect data collection problems. Note that CH_4 and N_20 from U.S. Territories are included in this value, but not CO_2 emissions from U.S. Territories, which are estimated separately in the section on territories.

[c] Includes only CO_2 from natural gas used to power natural gas 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.

[g] Domestic residual fuel for ships and boats is estimated by taking the total amount of residual fuel and subtracting out an estimate of international bunker fuel use. The international bunker fuel portion of this was proxied from 2012, while the total volume of fuel estimated decreased, resulting in a large decrease in domestic marine residual fuel use in 2013.

[h] Updates to motor gasoline heat content data in this Inventory from EIA for years 1993 through 2013 resulted in changes to the time series for energy consumption and emissions compared to previous years' Inventory.

Note: New data from Oak Ridge National Laboratory's Transportation Energy Book (Edition 33) for transit buses impacted the distribution of energy consumption and emissions between vehicle classes for the time series starting in 2006. Increases to CH_4 and N_2O emissions from mobile combustion relative to previous Inventories are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series. There have also been updates to emission estimates from alternative fuel vehicles. See Section 3.1 "CH_4 and N_2O from Mobile Combustion" for more detail.

+ Less than 0.05 MMT CO_2 Eq.

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

Table A- 115: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Percent Change 1990-2013
CO_2	1,636.2	1,769.9	1,978.3	1,975.5	2,021.0	2,017.3	2,069.4	2,091.4	2,092.7	2,097.1	2,001.1	1,927.8	1,946.6	1,928.0	1,918.8	1,942.3	19%
N_2O	41.2	51.2	52.0	49.7	46.5	43.4	41.1	38.1	35.2	30.0	26.5	24.6	23.7	22.5	20.2	18.4	-55%
CH_4	5.6	5.2	4.1	4.1	3.6	3.4	3.2	3.0	2.9	2.6	2.4	2.3	2.3	2.3	2.2	2.1	-62%
HFC	-	21.6	64.8	71.4	74.4	76.7	79.2	80.4	81.4	82.0	82.5	81.4	77.9	72.0	66.3	60.5	N/A
Total	**1,683.1**	**1,847.9**	**2,099.2**	**2,100.7**	**2,145.6**	**2,140.7**	**2,193.0**	**2,212.9**	**2,211.8**	**2,211.8**	**2,112.5**	**2,036.1**	**2,050.6**	**2,024.8**	**2,007.5**	**2,023.3**	**20%**

Note: The current Inventory includes updated vehicle population data based on the MOVES 2014 Model.

Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1. Data for year 2013 has not yet been published by FHWA, therefore 2013 VMT data was proxied using data from Table VM-1 for 2012 and estimates of overall 2013 VMT growth from FHWA's Traffic Volume Trends. .

- 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 2013 (MMT CO_2 Eq.)

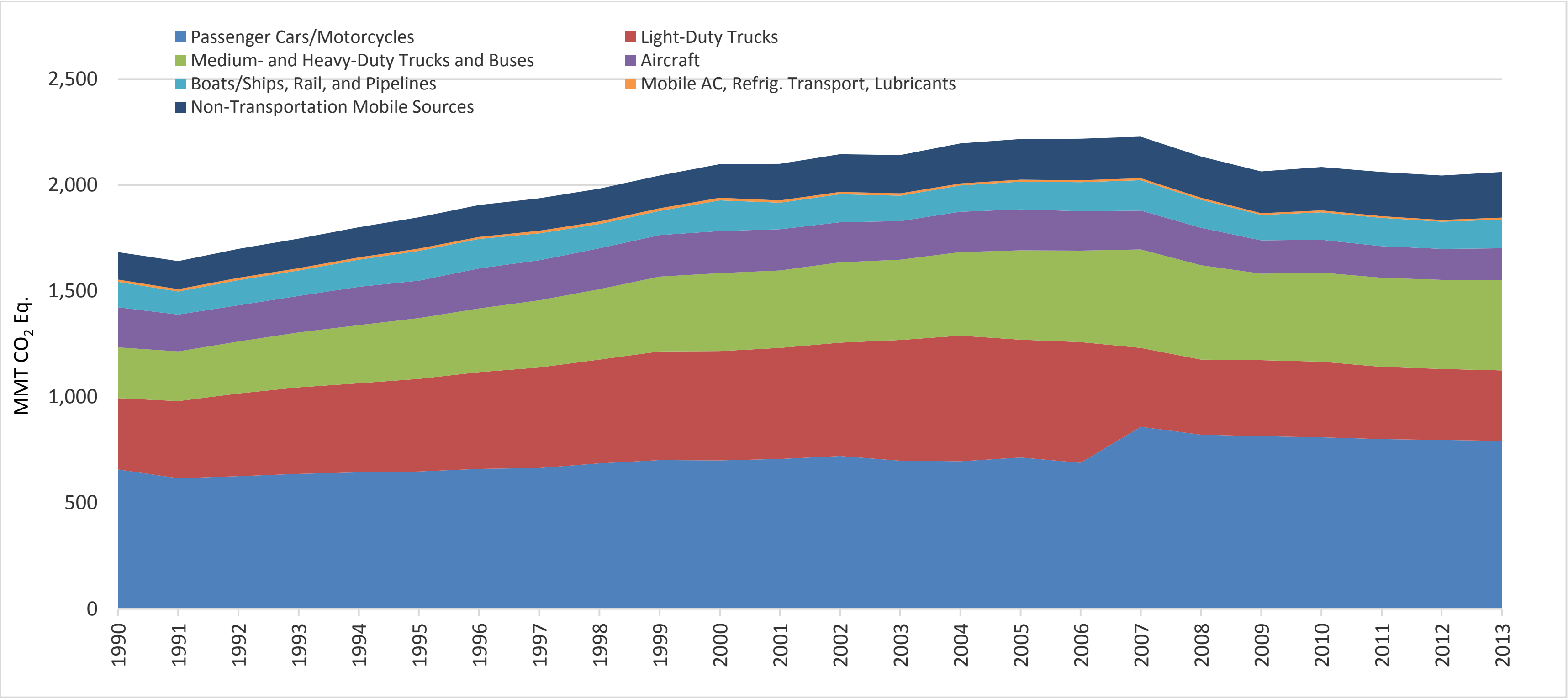


Table A-116: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Percent Change 1990-2013
On-Road Vehicles	**1,002.4**	**1,094.6**	**1,228.7**	**1,242.2**	**1,266.2**	**1,279.0**	**1,300.7**	**1,278.3**	**1,264.5**	**1,234.6**	**1,173.0**	**1,164.9**	**1,152.3**	**1,127.0**	**1,116.3**	**1,108.9**	**11%**
Passenger Cars	656.6	646.7	699.6	706.1	719.8	697.0	692.9	711.2	684.7	844.9	802.8	792.9	783.6	774.3	768.0	763.3	16%
Light-Duty Trucks	335.6	436.8	516.0	523.5	534.7	569.4	591.0	553.3	565.6	367.7	348.8	351.6	349.0	332.1	326.2	323.4	-4%
Buses	8.4	9.2	11.2	10.3	10.0	10.9	15.1	12.1	12.2	17.7	17.1	16.2	15.9	16.9	18.0	18.3	118%
Motorcycles	1.8	1.8	1.9	1.7	1.7	1.7	1.8	1.7	1.9	4.3	4.4	4.2	3.7	3.7	4.2	4.0	123%
Aircraft	**134.6**	**132.0**	**152.2**	**147.7**	**146.3**	**139.4**	**146.8**	**152.7**	**146.6**	**144.9**	**140.9**	**125.2**	**124.8**	**122.1**	**118.5**	**123.1**	**-9%**
General Aviation[a]	42.9	35.8	35.9	43.7	45.1	36.9	41.9	40.1	30.1	24.4	30.5	21.2	26.7	22.5	19.9	23.6	-45%
Commercial Aircraft	91.7	96.2	116.3	104.0	101.2	102.6	104.9	112.6	116.5	120.4	110.4	103.9	98.0	99.6	98.6	99.5	8%
Recreational Boats	**14.3**	**16.4**	**13.0**	**17.4**	**17.4**	**17.4**	**17.4**	**17.3**	**17.3**	**17.1**	**16.8**	**16.6**	**16.4**	**16.3**	**16.3**	**12.6**	**-12%**
Passenger Rail	**4.4**	**4.5**	**5.2**	**5.4**	**5.1**	**5.8**	**6.0**	**6.2**	**6.0**	**6.6**	**6.3**	**6.2**	**6.2**	**6.0**	**5.5**	**5.7**	**30%**
Total	**1,155.7**	**1,247.5**	**1,399.1**	**1,412.7**	**1,435.1**	**1,441.6**	**1,470.9**	**1,454.5**	**1,434.3**	**1,403.2**	**1,337.0**	**1,312.9**	**1,299.6**	**1,271.4**	**1,256.6**	**1,250.2**	**8%**

Note: Data from DOE (1993 through 2013) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

Note: The current Inventory includes updated vehicle population data based on the MOVES 2014 Model.

Note that updates to heat content data from EIA for years 1993 through present resulted in changes to the time series for energy consumption and emissions compared to the previous Inventory. Similarly, new data from Oak Ridge National Laboratory's Transportation Energy Book (Edition 33) for transit buses impacted the distribution of energy consumption and emissions between vehicle classes for the time series starting in 2006.

Table A-117: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Percent Change 1990-2013
Trucking	231.1	278.1	355.8	355.1	369.5	367.3	379.1	409.8	420.1	445.9	428.0	389.6	403.0	401.3	401.4	407.7	74%
Freight Rail	34.5	39.2	43.2	43.5	43.5	44.0	46.5	47.0	49.3	48.1	44.7	37.5	40.3	42.1	41.2	41.8	19%
Ships and Other Boats	30.6	42.1	48.3	25.4	30.1	19.9	22.7	27.8	31.1	37.9	28.8	22.3	28.6	30.3	24.1	15.7	-21%
Pipelines	36.0	38.2	35.2	34.4	36.4	32.5	31.1	32.2	32.3	34.2	35.6	36.7	37.1	37.8	40.3	47.7	12%
Commercial Aircraft	19.2	20.1	24.3	21.8	21.2	21.5	21.1	21.4	21.8	20.5	18.0	16.7	16.3	16.0	15.8	15.9	-18%
Total	**351.5**	**417.8**	**506.9**	**480.2**	**500.7**	**485.2**	**500.6**	**538.2**	**554.6**	**586.5**	**555.2**	**502.9**	**525.2**	**527.6**	**522.6**	**528.8**	**49%**

[a] Pipelines reflect CO_2 emissions from natural gas powered pipelines transporting natural gas

Note: Data from DOE (1993 through 2013) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption

IPCC Tier 3B Method: Commercial aircraft jet fuel burn and carbon dioxide (CO_2) emissions estimates were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2013 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

International Bunkers: The IPCC guidelines define international aviation (International Bunkers) as emissions from flights that depart from one country and arrive in a different country. Bunker fuel emission estimates for commercial aircraft were developed for this report for 2000 through 2013 using the same radar-informed data modeled with AEDT. Since this process builds estimates from flight-specific information, the emissions estimates for commercial aircraft can include emissions associated with the U.S. territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands). However, to allow for the alignment of emission estimates for commercial aircraft with other data that is provided without the U.S. territories, this annex includes emission estimates for commercial aircraft both with and without the U.S. territories included.

Time Series and Analysis Update: The FAA incrementally improves the consistency, robustness, and fidelity of the CO_2 emissions modeling for commercial aircraft, which is the basis of the Tier3B inventories presented in this report. While the FAA does not anticipate significant changes to the AEDT model in the future, recommended improvements are limited by budget and time constraints, as well as data availability. For instance, previous reports included reported annual CO_2 emission estimates for 2000 through 2005 that were modeled using the FAA's System for assessing Aviation's Global Emissions (SAGE). That tool and its capabilities were significantly improved after it was incorporated and evolved into AEDT. For this report, the AEDT model was used to generate annual CO_2 emission estimates for 2000, 2005, 2010, 2011, 2012, and 2013 only. The reported annual CO_2 emissions values for 2001 through 2004 were estimated from the previously reported SAGE data. Likewise, CO_2 emissions values for 2006 through 2009 were estimated by interpolation to preserve trends from past reports.

Commercial aircraft radar data sets are not available for years prior to 2000. Instead, the FAA applied a Tier3B methodology by developing Official Airline Guide (OAG) schedule-informed estimates modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. The ratios between the OAG schedule-informed and the radar-informed inventories for the years 2000 and 2010 were applied to the 1990 OAG scheduled-informed inventory to generate the best possible CO_2 inventory estimate for commercial aircraft in 1990. The resultant 1990 CO_2 inventory served as the reference for generating the additional 1991 through 1999 emission estimates, which were established using previously-available trends.

Notes on Revised 1990 CO_2 Emissions Inventory for Commercial Aircraft: There is a reduction in CO_2 emissions for the revised 1990 estimates for commercial aircraft, when compared to previous Inventory reports (Inventory reports published in 2000, 2002, 2007, 2010). The primary driver of modeling the 1990 emission estimate was to achieve time series consistency. The observed change in 1990 emissions is purely due to using a Tier3B methodology, and not reflective of revised industry performance and should not be used to infer or evaluate such performance.

To achieve time series consistency, the 1990 jet fuel burn was modeled with the latest AEDT version using great circle trajectories and OAG schedule information. There are uncertainties associated with the modeled 1990 data that do not exist for the modeled 2000 to 2013 data. Radar-based data is not available for 1990. The OAG schedule information generally includes fewer carriers than radar information, and this will result in a different fleet mix, and in turn, different CO_2 emissions than would be quantified using a radar-based data set. For this reason, the FAA adjusted the OAG-informed schedule for 1990 with a ratio based on radar-informed information. In addition, radar trajectories are also generally longer than great circle trajectories. While the 1990 fuel burn data was adjusted to address these differences, it inherently adds greater uncertainty to the revised 1990 commercial aircraft CO_2 emissions as compared to data from 2000 forward. Also, the revised 1990 CO_2 emission estimate now reflects only commercial aircraft jet fuel consumption, while previous reports may have aggregated jet fuel sales data from non-commercial aircraft into this category. Thus, it would be inappropriate to compare 1990 to future years for other than qualitative purposes.

The revised 1990 commercial aircraft CO_2 emissions estimate is approximately 4 percent lower than the 2013 CO_2 emissions estimate. It is important to note that the distance flown increased by more than 40 percent over this 24-year period and that fuel burn and aviation activity trends over the past two decades indicate significant improvements in commercial aviation's ability to provide increased service levels while using less fuel.[1]

Methane Emissions: Contributions of methane (CH_4) emissions from commercial aircraft are reported as zero. Years of scientific measurement campaigns conducted at the exhaust exit plane of commercial aircraft gas turbine engines have repeatedly indicated that CH_4 emissions are consumed over the full mission flight envelope (*Aircraft Emissions of Methane and Nitrous Oxide during the Alternative Aviation Fuel Experiment*, Santoni et al., Environ. Sci. Technol., 2011, 45, 7075-7082). As a result, the U.S. EPA published that "*...methane is no longer considered to be an emission from aircraft gas turbine engines burning Jet A at higher power settings and is, in fact, consumed in net at these higher powers.*"[2] In accordance with the following statements in the *2006 IPCC Guidelines* (IPCC 2006), the FAA does not calculate CH_4 emissions for either the domestic or international bunker commercial aircraft jet fuel emissions inventories. *"Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines." "Current scientific understanding does not allow other gases (e.g., N_2O and CH_4) to be included in calculation of cruise emissions." (IPCC 1999)*.

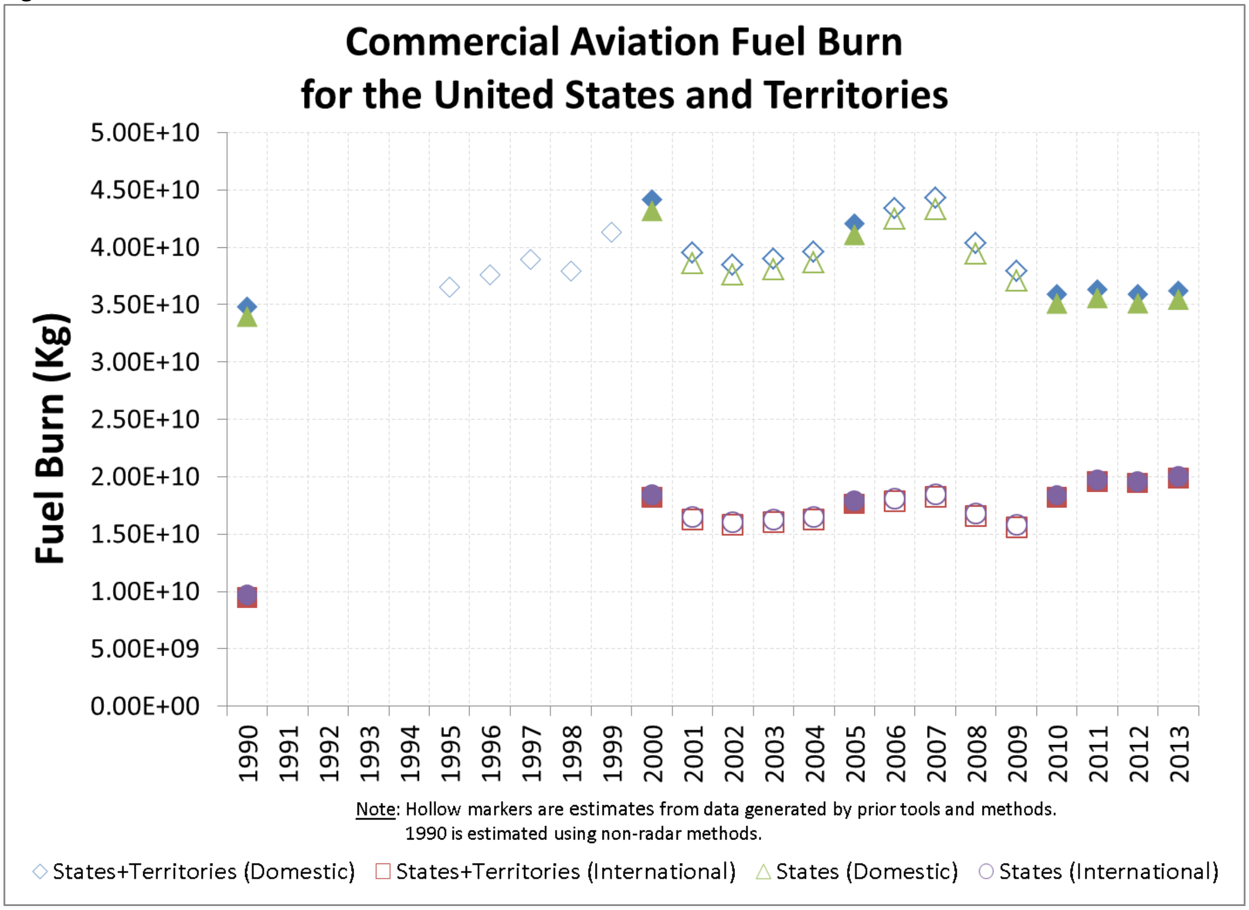
Results: The graph and table below, four jet fuel burn values are reported for each calendar year. These values are comprised of domestic and international fuel burn totals for the U.S. 50 States and the U.S. 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any commercial aircraft flight departing and landing in the U.S. 50 States and for the U.S. 50 States + Territories. The data presented as international is respective of the two different domestic definitions, and represents flights departing from the specified domestic area and landing anywhere in the world outside of that area.

Note that the graph and table present less fuel burn for the international U.S. 50 States + Territories than for the international U.S. 50 States. This is because the flights between the 50 states and U.S. Territories are "international" when only the 50 states are defined as domestic, but they are "domestic" for the U.S. 50 States + Territories definition.

[1] Additional information on the AEDT modeling process is available at: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/

[2] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines, EPA-420-R-09-901, May 27, 2009. See <http://www.epa.gov/otaq/aviation.html>.

Figure A-5: Commercial Aviation Fuel Burn for the United States and Territories



Note: Hollow markers are estimates from data generated by prior tools and methods.1990 is estimated using non-radar methods.

Table A- 118: Commercial Aviation Fuel Burn for the United States and Territories

Year	Region	Distance Flown (nmi)	Fuel Burn (M Gallon)	Fuel Burn (Tbtu)	Fuel Burn (Kg)	CO_2 (MMT)
1990	Domestic U.S. 50 States and U.S. Territories	4,057,195,988	11,568	1,562	34,820,800,463	109.9
	International U.S. 50 States and U.S. Territories	599,486,893	3,155	426	9,497,397,919	30.0
	Domestic U.S. 50 States	3,984,482,217	11,287	1,524	33,972,832,399	107.2
	International U.S. 50 States	617,671,849	3,228	436	9,714,974,766	30.7
1995	Domestic U.S. 50 States and U.S. Territories	N/A	12,136	1,638	36,528,990,675	115.2
1996	Domestic U.S. 50 States and U.S. Territories	N/A	12,492	1,686	37,600,624,534	118.6
1997	Domestic U.S. 50 States and U.S. Territories	N/A	12,937	1,747	38,940,896,854	122.9
1998	Domestic U.S. 50 States and U.S. Territories	N/A	12,601	1,701	37,930,582,643	119.7
1999	Domestic U.S. 50 States and U.S. Territories	N/A	13,726	1,853	41,314,843,250	130.3
2000	Domestic U.S. 50 States and U.S. Territories	5,994,679,944	14,672	1,981	44,161,841,348	139.3
	International U.S. 50 States and U.S. Territories	1,309,565,963	6,040	815	18,181,535,058	57.4
	Domestic U.S. 50 States	5,891,481,028	14,349	1,937	43,191,000,202	136.3
	International U.S. 50 States	1,331,784,289	6,117	826	18,412,169,613	58.1
2001	Domestic U.S. 50 States and U.S. Territories	5,360,977,447	13,121	1,771	39,493,457,147	124.6
	International U.S. 50 States and U.S. Territories	1,171,130,679	5,402	729	16,259,550,186	51.3
	Domestic U.S. 50 States	5,268,687,772	12,832	1,732	38,625,244,409	121.9
	International U.S. 50 States	1,191,000,288	5,470	739	16,465,804,174	51.9
2002	Domestic U.S. 50 States and U.S. Territories	5,219,345,344	12,774	1,725	38,450,076,259	121.3
	International U.S. 50 States and U.S. Territories	1,140,190,481	5,259	710	15,829,987,794	49.9
	Domestic U.S. 50 States	5,129,493,877	12,493	1,687	37,604,800,905	118.6
	International U.S. 50 States	1,159,535,153	5,326	719	16,030,792,741	50.6

2003	Domestic U.S. 50 States and U.S. Territories	5,288,138,079	12,942	1,747	38,956,861,262	122.9
	International U.S. 50 States and U.S. Territories	1,155,218,577	5,328	719	16,038,632,384	50.6
	Domestic U.S. 50 States	5,197,102,340	12,658	1,709	38,100,444,893	120.2
	International U.S. 50 States	1,174,818,219	5,396	728	16,242,084,008	51.2
2004	Domestic U.S. 50 States and U.S. Territories	5,371,498,689	13,146	1,775	39,570,965,441	124.8
	International U.S. 50 States and U.S. Territories	1,173,429,093	5,412	731	16,291,460,535	51.4
	Domestic U.S. 50 States	5,279,027,890	12,857	1,736	38,701,048,784	122.1
	International U.S. 50 States	1,193,337,698	5,481	740	16,498,119,309	52.1
2005	Domestic U.S. 50 States and U.S. Territories	6,476,007,697	13,976	1,887	42,067,562,737	132.7
	International U.S. 50 States and U.S. Territories	1,373,543,928	5,858	791	17,633,508,081	55.6
	Domestic U.S. 50 States	6,370,544,998	13,654	1,843	41,098,359,387	129.7
	International U.S. 50 States	1,397,051,323	5,936	801	17,868,972,965	56.4
2006	Domestic U.S. 50 States and U.S. Territories	5,894,323,482	14,426	1,948	43,422,531,461	137.0
	International U.S. 50 States and U.S. Territories	1,287,642,623	5,939	802	17,877,159,421	56.4
	Domestic U.S. 50 States	5,792,852,211	14,109	1,905	42,467,943,091	134.0
	International U.S. 50 States	1,309,488,994	6,015	812	18,103,932,940	57.1
2007	Domestic U.S. 50 States and U.S. Territories	6,009,247,818	14,707	1,986	44,269,160,525	139.7
	International U.S. 50 States and U.S. Territories	1,312,748,383	6,055	817	18,225,718,619	57.5
	Domestic U.S. 50 States	5,905,798,114	14,384	1,942	43,295,960,105	136.6
	International U.S. 50 States	1,335,020,703	6,132	828	18,456,913,646	58.2
2008	Domestic U.S. 50 States and U.S. Territories	5,475,092,456	13,400	1,809	40,334,124,033	127.3
	International U.S. 50 States and U.S. Territories	1,196,059,638	5,517	745	16,605,654,741	52.4
	Domestic U.S. 50 States	5,380,838,282	13,105	1,769	39,447,430,318	124.5
	International U.S. 50 States	1,216,352,196	5,587	754	16,816,299,099	53.1
2009	Domestic U.S. 50 States and U.S. Territories	5,143,268,671	12,588	1,699	37,889,631,668	119.5
	International U.S. 50 States and U.S. Territories	1,123,571,175	5,182	700	15,599,251,424	49.2
	Domestic U.S. 50 States	5,054,726,871	12,311	1,662	37,056,676,966	116.9
	International U.S. 50 States	1,142,633,881	5,248	709	15,797,129,457	49.8
2010	Domestic U.S. 50 States and U.S. Territories	5,652,264,576	11,931	1,611	35,912,723,830	113.3
	International U.S. 50 States and U.S. Territories	1,474,839,733	6,044	816	18,192,953,916	57.4
	Domestic U.S. 50 States	5,554,043,585	11,667	1,575	35,116,863,245	110.8
	International U.S. 50 States	1,497,606,695	6,113	825	18,398,996,825	58.0
2011	Domestic U.S. 50 States and U.S. Territories	5,767,378,664	12,067	1,629	36,321,170,730	114.6
	International U.S. 50 States and U.S. Territories	1,576,982,962	6,496	877	19,551,631,939	61.7
	Domestic U.S. 50 States	5,673,689,481	11,823	1,596	35,588,754,827	112.3
	International U.S. 50 States	1,596,797,398	6,554	885	19,727,043,614	62.2
2012	Domestic U.S. 50 States and U.S. Territories	5,735,605,432	11,932	1,611	35,915,745,616	113.3
	International U.S. 50 States and U.S. Territories	1,619,012,587	6,464	873	19,457,378,739	61.4
	Domestic U.S. 50 States	5,636,910,529	11,672	1,576	35,132,961,140	110.8
	International U.S. 50 States	1,637,917,110	6,507	879	19,587,140,347	61.8
2013	Domestic U.S. 50 States and U.S. Territories	5,808,034,123	12,031	1,624	36,212,974,471	114.3
	International U.S. 50 States and U.S. Territories	1,641,151,400	6,611	892	19,898,871,458	62.8
	Domestic U.S. 50 States	5,708,807,315	11,780	1,590	35,458,690,595	111.9
	International U.S. 50 States	1,661,167,498	6,657	899	20,036,865,038	63.2

*Estimates for these years were derived from previously reported tools and methods

3.4. Methodology for Estimating CH_4 Emissions from Coal Mining

The methodology for estimating CH_4 emissions from coal mining consists of two steps. The first step is to estimate emissions from underground mines. There are two sources of underground mine emissions: ventilation systems and degasification systems. These 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 from surface mines and post-mining activities. In contrast to the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

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 the generated CH_4, 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[3] 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 (MSHA 2014). Based on the four quarterly measurements, MSHA estimates average daily CH_4 liberated at each of the underground mines with detectable emissions.

For 1990 through 1999, average daily CH_4 emissions from MSHA 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 2013, the average daily CH_4 emissions from MSHA 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.

For the years 1990, 1993 through 1996, 1998 through 2006, and 2008 through 2012, 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 most years and at least 0.5 MMCFD for 1995 and 1996, as shown in Table A-119. Over 90 percent of all ventilation emissions were concentrated in these subsets of approximately 120-150 mines. No MSHA ventilation data exists for 1991 and 1992. For 1997, 2007, and 2013 the complete MSHA databases for all 495 mines (in 1997), 230 mines (in 2007), and 205 mines (in 2013) with detectable CH_4 emissions were obtained. These mines were assumed to account for 100 percent of CH_4 liberated from underground mine ventilation systems for those years. 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-119). The proportion was then applied to the years 1990 through 2006 to account for ventilation emissions coming from mines without MSHA data. The complete 2007 dataset was used to adjust the emissions proportion for 2008-2012.

EPA currently collects information on ventilation emissions from underground coal mines liberating greater than 36,500,000 actual cubic feet of CH_4 per year (about 14,700 metric tons CO_2 Eq.) through its Greenhouse Gas Reporting Program (GHGRP).[4] Many of the underground coal mines reporting to the GHGRP use the same quarterly MSHA samples. However, some mines use their own measurements and samples, which are taken either quarterly or monthly. The 2013 ventilation emissions were calculated using both GHGRP data from the mines that take their own measurements using 98.324(b)(1) monitoring methods and MSHA data 98.324 (b)(2) method for all other mines with reportable methane emissions. Since 2009, two coal mines have destroyed a portion of their CH_4 emissions from ventilation systems using

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[3] 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.

[4] See U.S. EPA Greenhouse Gas Reporting Program, <http://www.epa.gov/ghgreporting/>. Underground coal mines report to EPA under Subpart FF of the program.

thermal oxidation technology. The amount of CH_4 destroyed through these two projects was determined through publicly-available emission reduction project information (CAR 2014).

Table A-119: 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)**
2011	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2012	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2013	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% 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, degasification emissions were estimated on a mine-by-mine basis based on other sources of available data. For Alabama mines that sell CH_4 recovered from degasification systems to a pipeline, gas sales records were used to estimate CH_4 liberated from degasification systems (see Step 1.3). The well data was also used to estimate CH_4 collected from mined-through pre-drainage wells. For most other mines that either sold CH_4 to a pipeline, used CH_4 on site, or vented CH_4 from degasification systems, data on degasification emissions reported to the EPA's GHGRP (EPA 2014) were used.

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

In 2013, fifteen active coal mines had CH_4 recovery and use projects, of which thirteen mines sold the recovered CH_4 to a pipeline. One of the mines that sold gas to a pipeline also used CH_4 to fuel a thermal coal dryer. One mine used recovered CH_4 for electrical power generation, and two other mines used recovered CH_4 to heat mine ventilation air. For mines that utilize CH_4 on-site, either the GHGRP (EPA 2014) or project-specific information (CAR 2014) was used to estimate CH_4 liberated from degasification systems.

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. Alabama and West Virginia state agencies provided gas sales data (GSA 2014; WVGES 2014), which were used to estimate emissions avoided for these projects. Additionally, coal mine operators provided information on eligible pre-drainage wells drilled in advance of mining (JWR 2010, 2014). 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). The coal mine operators with the largest CH_4 recovery and use projects provided this information (Consol 2014; JWR 2010, 2014), which was then used to estimate emissions avoided for a particular year.

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, basin-specific coal production was multiplied by basin-specific gas contents and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions. This emission factor was revised downward since 2012 from 200 percent based on more recent studies (King 1994; Saghafi 2013). The 150 percent emission factor was applied to all inventory years since 1990, retroactively. For post-mining activities, basin-specific coal production was multiplied by basin-specific gas contents and a 32.5 percent emission factor accounting for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data was compiled from AAPG (1984) and USBM (1986). Beginning in 2006, revised data on in situ CH_4 content and emissions factors are taken from EPA (1996) and EPA (2005).

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-120, which presents coal basin definitions by basin and by state.

The Energy Information Administration's (EIA) Annual Coal Report (2014) 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-120. For two states—West Virginia and Kentucky—county-level production data was used for the basin assignments because coal production occurred in geologically distinct coal basins within these states. Table A-121 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 analyses conducted in Canada and Australia on coals similar to those present in the United States. (King 1994; Saghafi 2013), the surface mining emission factor used was conservatively estimated to be 150 percent of the *in situ* CH_4 content of 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-122 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 from surface mines and post-mining activities was calculated by multiplying the coal production in each basin by the appropriate emission factors.

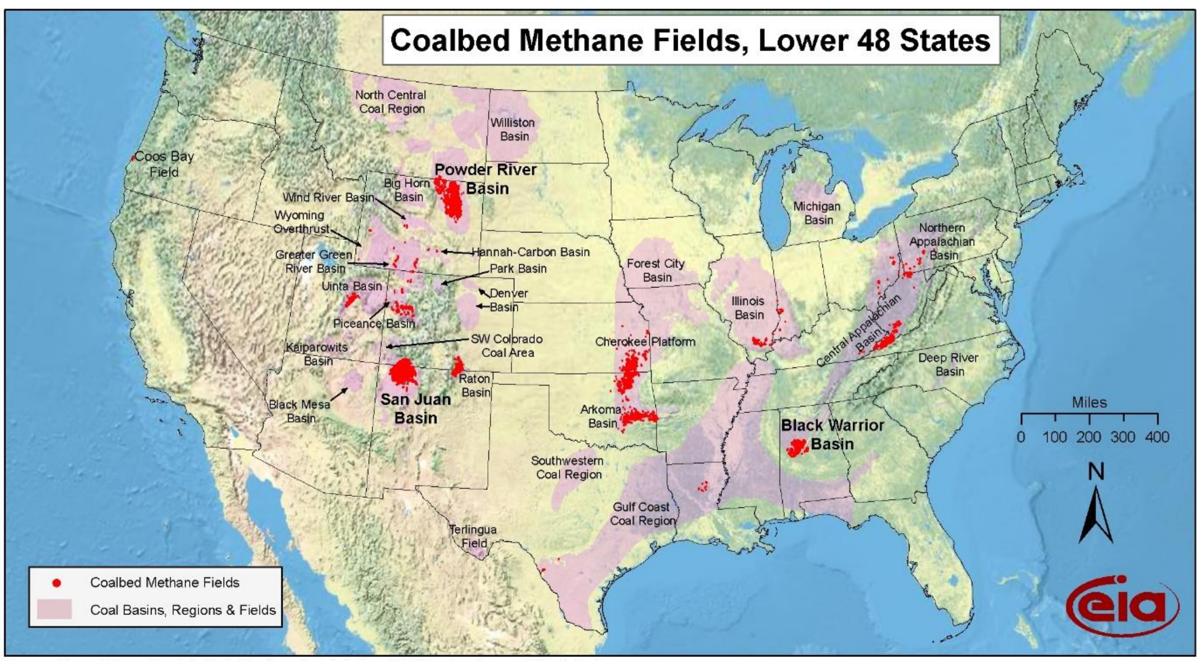
Table A-120 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-6, several coal basins span several states. Table A-121 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-122 shows the surface, post-surface, and post-underground emission factors used for estimating CH_4 emissions for each of the categories. Table A-123 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 used and emitted by underground coal mines. Table A-124 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities. Table A-125 provides the total net CH_4 emissions by state.

Table A-120: 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

Figure A-6: Locations of U.S Coal Basins



Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

Table A-121: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2008	2009	2010	2011	2012	2013
Underground Coal Production	**423,556**	**368,611**	**357,074**	**332,061**	**337,155**	**345,607**	**342,387**	**341,216**
N. Appalachia	103,865	111,151	105,228	99,629	103,109	105,752	103,408	104,198
Cent. Appalachia	198,412	123,083	114,998	98,689	96,354	94,034	78,067	70,440
Warrior	17,531	13,295	12,281	11,505	12,513	10,879	12,570	13,391
Illinois	69,167	59,180	64,609	67,186	72,178	81,089	92,500	98,331
S. West/Rockies	32,754	60,865	55,781	50,416	44,368	45,139	45,052	41,232
N. Great Plains	1,722	572	3,669	4,248	8,208	8,179	10,345	13,126
West Interior	105	465	508	388	425	535	445	498
Northwest	0	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,191**	**813,321**	**740,175**	**764,709**	**754,871**	**672,748**	**640,740**
N. Appalachia	60,761	28,873	30,413	26,552	26,082	26,382	21,411	19,339
Cent. Appalachia	94,343	112,222	118,962	97,778	89,788	90,778	69,721	57,173
Warrior	11,413	11,599	11,172	10,731	11,406	10,939	9,705	8,695
Illinois	72,000	33,702	34,266	34,837	32,911	34,943	34,771	33,798
S. West/Rockies	43,863	42,756	34,283	32,167	28,889	31,432	30,475	28,968
N. Great Plains	249,356	474,056	538,387	496,290	507,995	502,734	455,320	444,740
West Interior	64,310	52,263	44,361	39,960	46,136	55,514	49,293	46,477
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550
Total Coal Production	**1,026,309**	**1,130,802**	**1,170,395**	**1,072,236**	**1,101,864**	**1,100,478**	**1,015,135**	**981,956**
N. Appalachia	164,626	140,024	135,641	126,181	129,191	132,134	124,819	123,537
Cent. Appalachia	292,755	235,305	233,960	196,467	186,142	184,812	147,788	127,613
Warrior	28,944	24,894	23,453	22,236	23,919	21,818	22,275	22,086
Illinois	141,167	92,882	98,875	102,023	105,089	116,032	127,271	132,129
S. West/Rockies	76,617	103,621	90,064	82,583	73,257	76,571	75,527	70,200
N. Great Plains	251,078	474,628	542,056	500,538	516,203	510,913	465,665	457,866
West Interior	64,415	52,728	44,869	40,348	46,561	56,049	49,738	46,975
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550

Source for 1990-2013 data: EIA (1990 through 2013), Annual Coal Report. U.S. Department of Energy, Washington, DC, Table 1. Source for 2013 data: spreadsheet for the 2013 Annual Coal Report.
Note: Totals may not sum due to independent rounding.

Table A-122: Coal Underground, 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	89.3	19.3	45.0
Central Appalachia (WV)	24.9	136.8	37.4	8.1	44.5
Central Appalachia (VA)	24.9	399.1	37.4	8.1	129.7
Central Appalachia (E KY)	24.9	61.4	37.4	8.1	20.0
Warrior	30.7	266.7	46.1	10.0	86.7
Illinois	34.3	64.3	51.5	11.1	20.9
Rockies (Piceance Basin)	33.1	196.4	49.7	10.8	63.8
Rockies (Uinta Basin)	16.0	99.4	24.0	5.2	32.3
Rockies (San Juan Basin)	7.3	104.8	11.0	2.4	34.1
Rockies (Green River Basin)	33.1	247.2	49.7	10.8	80.3
Rockies (Raton Basin)	33.1	127.9	49.7	10.8	41.6
N. Great Plains (WY, MT)	20.0	15.8	30.0	6.5	5.1
N. Great Plains (ND)	5.6	15.8	8.4	1.8	5.1
West Interior (Forest City, Cherokee Basins)	34.3	64.3	51.5	11.1	20.9
West Interior (Arkoma Basin)	74.5	331.2	111.8	24.2	107.6
West Interior (Gulf Coast Basin)	11.0	127.9	16.5	3.6	41.6
Northwest (AK)	16.0	160.0	24.0	1.8	52.0
Northwest (WA)	16.0	47.3	24.0	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-123: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013
Ventilation Output	112	75	100	114	117	97	90	89
Adjustment Factor for Mine Data*	98%	98%	99%	99%	99%	99%	99%	100%
Adjusted Ventilation Output	114	77	101	115	118	98	91	89
Degasification System Liberated	54	48	49	49	58	48	45	48
Total Underground Liberated	168	124	150	163	177	147	137	137
Recovered & Used	(14)	(37)	(40)	(40)	(49)	(42)	(38)	(41)
Total	**154**	**87**	**110**	**123**	**128**	**104**	**98**	**96**

* Refer to Table A-119.
Note: Totals may not sum due to independent rounding

Table A-124: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013
Underground Mining	154	87	110	123	128	104	98	96
Surface Mining	22	25	27	24	24	24	21	20
Post-Mining (Underground)	19	16	15	14	14	14	14	14
Post-Mining (Surface)	5	5	6	5	5	5	5	4
Total	**200**	**132**	**157**	**166**	**171**	**148**	**138**	**134**

Note: Totals may not sum due to independent rounding.

Table A-125: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2008	2009	2010	2011	2012	2013
Alabama	32,097	15,789	20,992	22,119	21,377	18,530	18,129	17,486
Alaska	50	42	43	54	63	63	60	45
Arizona	151	161	107	100	103	108	100	101
Arkansas	5	+	237	119	130	348	391	214
California	1	+	+	+	+	+	+	+
Colorado	10,187	13,441	12,871	13,999	16,470	11,187	9,305	4,838
Illinois	10,180	6,488	7,568	7,231	8,622	7,579	9,763	8,920
Indiana	2,232	3,303	5,047	5,763	5,938	6,203	7,374	6,427
Iowa	24	+	+	+	+	+	+	+
Kansas	45	11	14	12	8	2	1	1

Kentucky	10,018		6,898		9,986	12,035	12,303	10,592	7,993	8,098
Louisiana	64		84		77	73	79	168	80	56
Maryland	474		361		263	219	238	263	197	166
Mississippi	-		199		159	193	224	154	165	200
Missouri	166		3		15	28	29	29	26	26
Montana	1,373		1,468		1,629	1,417	1,495	1,445	1,160	1,269
New Mexico	363		2,926		3,411	3,836	3,956	4,187	2,148	2,845
North Dakota	299		306		303	306	296	289	281	282
Ohio	4,406		3,120		3,686	4,443	3,614	3,909	3,389	3,182
Oklahoma	226		825		932	624	436	360	499	282
Pennsylvania	21,864		17,904		20,684	22,939	23,372	17,708	17,773	20,953
Tennessee	276		115		86	69	67	60	35	31
Texas	1,119		922		783	704	823	922	887	854
Utah	3,587		4,787		5,524	5,449	5,628	3,651	3,624	2,733
Virginia	46,041		8,649		9,223	8,042	9,061	8,526	6,516	8,141
Washington	146		154		+	+	+	+	+	+
West Virginia	48,335		29,745		36,421	40,452	40,638	35,709	33,608	32,998
Wyoming	6,671		14,745		16,959	15,627	16,032	15,916	14,507	14,025
Total	**200,399**		**132,481**		**157,112**	**165,854**	**171,000**	**147,908**	**138,012**	**134,173**

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.

3.5. 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 the production and the transportation segments of petroleum systems is generally based on the 1999 EPA 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). The refineries segment is based largely on EPA's Greenhouse Gas Reporting Program data (GHGRP) for 2010 through 2013. Sixty-four activities that emit CH_4 and thirty activities that emit non-combustion CO_2 from petroleum systems were examined from these reports and the GHGRP data. Most of the activities analyzed involve crude oil production field operations, which accounted for 96 percent of total oil industry CH_4 emissions. Crude transportation and refining accounted for the remaining CH_4 emissions of approximately 0.7 and slightly above 3 percent, respectively. Non-combustion CO_2 emissions were analyzed for production operations and asphalt blowing, flaring, and process vents 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: Calculate Potential Methane and Carbon Dioxide

Activity Data

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 production and transportation sources, activity data for 1995 found in EPA/GRI 1996a are extrapolated to other years using publicly-available data sources. For refining sources, emissions data were directly available from the GHGRP for 2010 through 2013. For the remaining sources, the activity data are obtained directly from publicly-available data.

For all sets of available 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 (BOEM), 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 2013. Data used include total domestic crude oil production, 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 (i.e., refinery feed in 1000 bbl/year) was used also for the transportation sector. The number of domestic crude oil wells was obtained from a data set licensed by DrillingInfo, Inc. In the few cases where no data were 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. In some instances, where 2013 data are not yet available 2012 data has been used as proxy.

Potential methane factors and emission factors

The CH_4 emission factors for the majority of the activities 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 controllers 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 2015; BOEM 2014). The emission factors were assumed to be representative of emissions from each source type over the period 1990 through 2013. Therefore, the same emission factors are used for each year throughout this period.

In general, 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-130. The exceptions are the emissions factor for storage tanks, which are estimated using API E&P Tank Calc simulation runs of tank emissions for crude oil of different gravities less than 45 API degrees; emission factors for shallow water and deep water platforms, which are estimated from analysis of the *2011 Gulf-Wide Emission Inventory Study* (BOEM 2014) and the emissions estimates for refineries, which are estimated using the data from U.S. EPA's GHGRP.

Step 2: Compile Reductions Data

The methane emissions calculated in Step 1 above generally represent expected emissions from an activity in the absence of emissions controls, and do not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies, data were collected on voluntary reductions. Voluntary reductions included in the Petroleum Sector calculations were those reported to Natural Gas STAR for the following activities: Artificial lift: gas lift, Artificial lift: use compression, Artificial lift: use pumping unit, Consolidate crude oil prod and water storage tanks, Lower heater- treater temperature, Re-inject gas for enhanced oil recovery, Re-inject gas into crude, and Route casing head gas to VRU or compressor. In addition, a portion of the total Gas STAR reductions from pneumatics in the production sector are applied to potential emissions in the petroleum sector.

Industry partners report CH_4 emission reductions by project to the Natural Gas STAR Program. The reductions from the implementation of specific technologies and practices 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 Inventory uses aggregated Natural Gas STAR reductions for the petroleum sector.

Step 3: Calculate Net 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, except for petroleum refineries segment. Emissions from refineries were obtained directly from the GHGRP data for 2010 through 2013; these three years of data were used to develop emission factors and activity data that are applied for the reminder of the time-series (i.e., 1990 through 2009). These annual emissions for each activity were then summed to estimate the total annual CH_4 and CO_2 emissions, respectively. Natural Gas STAR reductions data is summed for each year and deducted from the potential CH_4 calculated in Step 1 to estimate net CH_4 emissions for the Inventory.

Table A-126, Table A-127, Table A-128, and Table A-131 provide 2013 activity data, emission factors, and emission estimates and Table A-129 and Table A-132 provide a summary of emission estimates for the years 1990, 1995, 2000, and 2005 through 2013. Table A-130 provides the CO_2 content in natural gas for equipment in different crude streams to estimate CO_2 emission factors using CH_4 emission factors.

The tables provide references for emission factors and activity data in footnotes (the lettered footnotes). The tables also provide information on which method was used for supplying activity data for 2013 (the numbered footnotes).

<u>Key to table notations on methods for supplying activity data for 2013 for all tables</u>:

1. Ratios relating other factors for which activity data are available. For example, EPA (1996) found that the number of heater treaters (a source of CH_4 emissions) is related to both number of producing wells and annual production. To estimate the activity data for heater treaters, reported statistics for wells and production were used, along with the ratios developed for EPA (1996).
2. Activity data for 2013 available from source.
3. Activity data were held constant from 1990 through 2013 based on EPA (1999).
4. 2009, 2010, 2011, or 2012 activity data are used to determine some or all of the 2013 activity data.

Table A-126: 2013 CH_4 Emissions from Petroleum Production Field Operations

	2013 EPA Inventory Values					
Activity/Equipment	**Emission Factor**		**Activity Data**		**Emissions (Bcf/yr)**	**Emissions (kt/yr)**
Vented Emissions					**54.533**	**1,048.7**
Oil Tanks	7.4	scf of CH_4/bbl crude[a]	2,233	MMbbl/yr (non stripper wells)[b,c,d,1]	16.508	317.5
Pneumatic controllers, High Bleed	330	scfd CH_4/controller[f]	158,259	No. of high-bleed controllers[c,e,g,q,1]	19.085	367.0**
Pneumatic controllers, Low Bleed	52	scfd CH_4/controller[f]	293,910	No. of low-bleed controllers[c,e,g,q,1]	5.578	107.3**
Chemical Injection Pumps	248	scfd CH_4/pump[h,i]	31,066	No. of pumps[g,i,p,q,1]	2.813	54.1

Activity/Equipment	2013 EPA Inventory Values Emission Factor		Activity Data		Emissions (Bcf/yr)	Emissions (kt/yr)
Vessel Blowdowns	78	scfy CH_4/vessel[h]	206,898	No. of vessels[c,g,i,q,1]	0.016	0.3
Compressor Blowdowns	3,775	scf/yr of CH_4/compressor[h]	2,820	No. of compressors[c,g,i,q,1]	0.011	0.2
Compressor Starts	8,443	scf/yr of CH_4/compressor[h]	2,820	No. of compressors[c,g,i,1]	0.024	0.5
Stripper wells	2,345	scf/yr of CH_4/stripper well[f]	315,213	No. of stripper wells vented[f,d,1]	0.739	14.2
Well Completion Venting	733	scf/completion[h]	15,753	Oil well completions[c,4]	0.012	0.2
Well Workovers	96	scf CH_4/workover[i]	64,793	Oil well workovers[g,i,1,4]	0.006	0.1
Pipeline Pigging	2.4	scfd of CH_4/pig station[j]	0	No. of crude pig stations[e,3]	0.000	0.0
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	16,552	scfd CH_4/platform[q]	1,447	No. of shallow water oil platforms[l,4]	8.739	168.1
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	93,836	scfd CH_4/platform[q]	29	No. of deep water oil platforms[l,4]	1.001	19.3
Fugitive Emissions					**4.750**	**91.4**
Oil Wellheads (heavy crude)	0.13	scfd/well[e,m]	38,682	No. of hvy. Crude wells[d,g,i,1,4]	0.002	0.0*
Oil Wellheads (light crude)	17	scfd/well[e,m]	510,005	No. of lt. crude wells[d,g,i,1,4]	3.096	59.5
Separators (heavy crude)	0.15	scfd CH_4/separator[e,m]	12,141	No. of hvy. Crude seps.[c,g,i,1]	0.001	0.0*
Separators (light crude)	14	scfd CH_4/separator[e,m]	110,495	No. of lt. crude seps.[c,g,i,1]	0.559	10.7
Heater/Treaters (light crude)	19	scfd CH_4/heater[e,m]	84,262	No. of heater treaters[c,g,i,1]	0.590	11.4
Headers (heavy crude)	0.08	scfd CH_4/header[e,m]	22,535	No. of hvy. Crude hdrs.[g,i,1]	0.001	0.0*
Headers (light crude)	11	scfd CH_4/header[e,m]	69,861	No. of lt. crude hdrs.[g,i,1]	0.277	5.3
Floating Roof Tanks	338,306	scf CH_4/floating roof tank/yr[m,n]	24	No. of floating roof tanks[e,3]	0.008	0.2
Compressors	100	scfd CH_4/compressor[e]	2,820	No. of compressors[c,g,i,1]	0.103	2.0
Large Compressors	16,360	scfd CH_4/compressor[e]	0	No. of large comprs.[e,3]	0.000	0.0
Sales Areas	41	scf CH_4/loading[e]	2,265,983	Loadings/year[c,1]	0.092	1.8
Pipelines	NE	scfd of CH_4/mile of pipeline	14,590	Miles of gathering line[o,2]	NE	NE
Well Drilling	NE	scfd of CH_4/oil well drilled	17,774	No. of oil wells drilled[c,2]	NE	NE
Battery Pumps	0.24	scfd of CH_4/pump[m]	259,170	No. of battery pumps[g,e,1]	0.023	0.4
Combustion Emissions					**5.731**	**110.2**
Gas Engines	0.24	scf CH_4/HP-hr[h]	17,764	MMHP-hr[c,g,i,1]	4.263	82.0
Heaters	0.52	scf CH_4/bbl[n]	2,720	MMbbl/yr[c,2]	1.417	27.3
Well Drilling	2,453	scf CH_4/well drilled[m]	17,774	Oil wells drilled[c,4]	0.044	0.8
Flares	20	scf CH_4/Mcf flared[j]	363,184	Mcf flared/yr[b,c,d,1,4]	0.007	0.1
Process Upset Emissions					**0.156**	**3.0**
Pressure Relief Valves	35	scf/yr/PR valve[h]	227,169	No. of PR valves[c,e,1]	0.008	0.2
Well Blowouts Onshore	2.5	MMscf/blowout[f]	59	No. of blowouts/yr[c,e,1]	0.148	2.8
Voluntary Reductions					**14.799**	**284.6**
Total Potential Emissions					**65.171**	**1,253.3**
Total Net Emissions					**50.372**	**968.7**

[a] TankCALC
[b] EPA / ICF International (1999)
[c] Energy Information Administration (EIA) Monthly Energy Review
[d] Interstate Oil & Gas Compact Commission (IOGCC) Marginal Wells Report
[e] Consensus of Industrial Review Panel
[f] Expert Judgment
[g] EIA Annual Energy Review
[h] Gas Research Institute (GRI) / EPA (1996)
[i] Radian (1999)
[j] Canadian Association of Petroleum Producers (CAPP) (1992)
[k] Adapted from the Minerals Management Service (MMS) Gulfwide Offshore Activities Data System (GOADS) by ICF (2005)
[l] Bureau of Ocean Energy Management (BOEM)
[m] American Petroleum Institute (API) (1996)
[n] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[o] Oil and Gas Journal (OGJ) Petroleum Economics Issue

[p] Percentage of chemical injection pumps (CIPs) that are gas-driven was determined through based on an estimate provided in 1997 by Ron Rayman. From Dresser Texsteam, a major manufacturer of CIPs at the time.
[q] BOEM 2011 Gulf-wide Emissions Inventory Study (2014)
- Zero Emissions
* Emissions are not actually 0, but too small to show at this level of precision.
**Values shown in this table for pneumatic controllers are potential emissions. Net 2013 emissions for all pneumatic controllers are 220.6 kt CH_4.

Table A-127: 2013 CH_4 Emissions from Petroleum Transportation

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)	Emissions (kt/yr)
Vented Emissions					**0.305**	**5.9**
Tanks	0.021	scf CH_4/yr/bbl of crude delivered to refineries[a]	5,589	MMbbl crude feed/yr[b,2]	0.115	2.2
Truck Loading	0.520	scf CH_4/yr/bbl of crude transported by truck[c]	145.4	MMbbl crude trans. By truck[d,2]	0.076	1.5
Marine Loading	2.544	scf CH_4/1000 gal crude marine loadings[c]	23,838,944	1,000 gal/yr loaded[e,1,4]	0.061	1.2
Rail Loading	0.520	scf CH_4/yr/bbl of crude transported by rail[c]	76.2	MMbbl Crude by rail/yr[d,2]	0.040	0.8
Pump Station Maintenance	36.80	scf CH_4/station/yr[f]	500	No. of pump stations[g,1]	0.000*	0.0*
Pipeline Pigging	39	scfd of CH_4/pig station[h]	999	No. of pig stations[g,1]	0.014	0.3
Fugitive Emissions					**0.050**	**1.0**
Pump Stations	25	scf CH_4/mile/yr[f]	49,974	No. of miles of crude p/l[g,2]	0.001	0.0*
Pipelines	NE	scf CH_4/bbl crude transported by pipeline[f]	8,122	MMbbl crude piped[g,2]	NE	NE
Floating Roof Tanks	58,965	scf CH_4/floating roof tank/yr[i]	824	No. of floating roof tanks[3]	0.049	0.9
Combustion Emissions					**NE**	**NE**
Pump Engine Drivers	0.24	scf CH_4/hp-hr[j]	NE	No. of hp-hrs	NE	NE
Heaters	0.521	scf CH_4/bbl burned[k]	NE	No. of bbl Burned	NE	NE
Total					**0.355**	**6.8**

[a] API (1992)
[b] Energy Information Administration (EIA) Petroleum Supply Annual, Volume 1.
[c] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[d] EIA Refinery Capacity Report
[e] EIA Monthly Energy Review
[f] Radian (1996)
[g] OGJ Petroleum Economics Issue
[h] CAPP (1992)
[i] API TANK
[j] GRI / EPA (1996)
[k] EPA / ICF International (1999)
* Emissions are not actually 0, but too small to show at this level of precision.
NE: Not estimated for lack of data

Table A-128: 2013 CH_4 Emissions from Petroleum Refining

Activity/Equipment	2013 EPA Inventory Values: Emission Factor	Activity Factor	Emissions (Bcf/yr)	Emissions (kt/yr)
Vented Emissions			**0.467**	**9.0**
Uncontrolled Blowdowns	0.000970 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.282	5.4
Asphalt Blowing	0.000053 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.015	0.3
Process Vents	0.000581 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.169	3.2
CEMS	0.000003 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.001	0.0*
Fugitive Emissions			**0.238**	**4.6**
Equipment Leaks	0.000498 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.145	2.8
Storage Tanks	0.000235 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.068	1.3
Wastewater Treating	0.00798 lb VOC/bbl[b,c]	5,589,006 Mbbl/year refinery feed[a]	0.011	0.2

Activity/Equipment	2013 EPA Inventory Values: Emission Factor	Activity Factor	Emissions (Bcf/yr)	Emissions (kt/yr)
Cooling Towers	0.010 lb VOC/bbl[b,c]	5,589,006 Mbbl/year refinery feed[a]	0.013	0.3
Loading Operations	0.000004 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.001	0.0*
Combustion Emissions			**1.061**	**20.4**
Catalytic Cracking, Coking, Reforming	0.000256 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.075	1.4
Flares	0.002960 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.860	16.5
Delay Cokers	0.000429 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.125	2.4
Coke Calcining	0.000004 MT CH_4/Mbbl[d]	5,589,006 Mbbl/year refinery feed[a]	0.001	0.0*
Total			**1.766**	**34.0**

[a] EIA Petroleum Supply Annual, Volume 1.
[b] Radian (1996)
[c] Assuming methane is 1% of total hydrocarbons (AP-42)
[d] GHGRP data
Note: The methodology for year 2013 is to use GHGRP emissions data as-reported (rather than an EFxAF approach, per se). The emission factors in this table were populated by dividing 2013 emissions by 2013 refinery feed rate.
* Emissions are not actually 0, but too small to show at this level of precision.

Table A-129: Summary of CH_4 Emissions from Petroleum Systems (kt)

Activity	1990	1995	2000	2007	2008	2009	2010	2011	2012	2013
Production Field Operations	**1,230**	**1,137**	**1,056**	**1,025**	**1,038**	**1,053**	**1,077**	**1,106**	**1,184**	**1,253**
Pneumatic controller venting*	489	454	415	409	423	425	433	443	463	474
Tank venting	250	226	214	193	185	202	210	222	267	317
Combustion & process upsets	115	105	95	92	95	95	98	101	107	113
Misc. venting & fugitives	317	300	285	283	282	279	282	284	287	289
Wellhead fugitives	58	53	48	49	54	52	54	56	59	60
Crude Oil Transportation	**7**	**6**	**5**	**5**	**5**	**5**	**5**	**5**	**6**	**7**
Refining	**27**	**29**	**31**	**31**	**30**	**29**	**27**	**30**	**32**	**34**
Voluntary Reductions	**3**	**12**	**59**	**170**	**208**	**227**	**255**	**263**	**290**	**285**
Total Potential Emissions	**1,264**	**1,172**	**1,093**	**1,061**	**1,073**	**1,087**	**1,109**	**1,141**	**1,221**	**1,294**
Total Net Emissions	**1,261**	**1,160**	**1,033**	**891**	**865**	**860**	**854**	**878**	**931**	**1,009**

Note: Totals may not sum due to independent rounding.
*Values shown in this table for pneumatic controllers are potential emissions. Net 2013 emissions for all pneumatic controllers are 220.6 kt CH4.

Table A-130: 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-131: 2013 CO_2 Emissions from Petroleum Production Field Operations and Petroleum Refining

Activity/Equipment	2013 EPA Inventory Values: Emission Factor	Activity Factor	Emissions (Bcf/yr)	Emissions (kt/yr)
Vented Emissions			**8.608**	**455.2**
Oil Tanks	3.528 scf of CO_2/bbl crude[a]	2,233 MMbbl/yr (non stripper wells)[b,c,d,1,4]	7.876	416.5
Pneumatic controllers, High Bleed	6.704 scfd CO_2/controller[f]	158,259 No. of high-bleed controllers[c,e,g,1]	0.387	20.4
Pneumatic controllers, Low Bleed	1.055 scfd CO_2/controller[f]	293,910 No. of low-bleed controllers[c,e,g,1]	0.113	6.0
Chemical Injection Pumps	5.033 scfd CO_2/pump[h]	31,066 No. of pumps[g,i,1]	0.057	3.0
Vessel Blowdowns	1.583 scfy CO_2/vessel[h]	206,898 No. of vessels[c,g,i,1]	0.000*	0.0*

Activity/Equipment	2013 EPA Inventory Values: Emission Factor		Activity Factor		Emissions (Bcf/yr)	Emissions (kt/yr)
Compressor Blowdowns	77	scf/yr of CO_2/compressor[h]	2,820	No. of compressors[c,g,i,1]	0.000*	0.0*
Compressor Starts	171	scf/yr of CO_2/compressor[h]	2,820	No. of compressors[c,g,i,1]	0.000*	0.0*
Stripper wells	48	scf/yr of CO_2/stripper well[f]	315,213	No. of stripper wells vented[f,1,4]	0.015	0.8
Well Completion Venting	14.87	scf/completion[h]	15,753	Oil well completions[c,2]	0.000*	0.0*
Well Workovers	1.95	scf CO_2/workover[i]	64,793	Oil well workovers[g,i,1]	0.000*	0.0*
Pipeline Pigging	NE	scfd of CO_2/pig station	0	No. of crude pig stations	NE	NE
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	276	scfd CO_2/platform[k]	1,447	No. of shallow water oil platforms[l,4]	0.146	7.7
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	1,100	scfd CO_2/platform[k]	29	No. of deep water oil platforms[l,4]	0.012	0.6
Fugitive Emissions					**0.098**	**5.2**
Oil Wellheads (heavy crude)	0.003	scfd/well[e,m]	38,682	No.ofhvy.Crudewells[d,g,i,1,4]	0.000*	0.0*
Oil Wellheads (light crude)	0.337	scfd/well[e,m]	510,005	No.oflt.crudewells[d,g,i,1,4]	0.063	3.3
Separators (heavy crude)	0.003	scfd CO_2/separator[e,m]	12,141	No.ofhvy.Crudeseps.[c,g,i,1]	0.000*	0.0*
Separators (light crude)	0.281	scfd CO_2/separator[e,m]	110,495	No.oflt.crudeseps.[c,g,i,1]	0.011	0.6
Heater/Treaters (light crude)	0.319	scfd CO_2/heater[e,m]	84,262	No.ofheatertreaters[c,g,i,1]	0.010	0.5
Headers (heavy crude)	0.002	scfd CO_2/header[e,m]	22,535	No.ofhvy.Crudehdrs.[g,i,1]	0.000*	0.0*
Headers (light crude)	0.220	scfd CO_2/header[e,m]	69,861	No.oflt.crudehdrs.[g,i,1]	0.006	0.3
Floating Roof Tanks	17,490	scf CO_2/floating roof tank/yr[m,n]	24	No.offloatingrooftanks[e,3]	0.000*	0.0*
Compressors	2.029	scfd CO_2/compressor[e]	2,820	No.ofcompressors[c,g,i,1]	0.002	0.1
Large Compressors	332	scfd CO_2/compressor[e]	-	No.oflargecomprs.[e,3]	0.000	0.0
Sales Areas	2.096	scf CO_2/loading[e]	2,265,983	Loadings/year[c,1]	0.005	0.3
Pipelines	NE	scfd of CO_2/mile of pipeline	14,590	Milesofgatheringline[o,2]	NE	NE
Well Drilling	NE	scfd of CO_2/oil well drilled	17,774	No.ofoilwellsdrilled[c,2]	NE	NE
Battery Pumps	0.012	scfd of CO_2/pump[m]	259,170	No.ofbatterypumps[g,e,1]	0.001	0.1
Process Upset Emissions					**0.003**	**0.2**
Pressure Relief Valves	1.794	scf/yr/PR valve[h]	227,169	No.ofPRvalves[c,e,1]	0.000*	0.0*
Well Blowouts Onshore	0.051	MMscf/blowout[e]	59	No.ofblowouts/yr[c,e,1]	0.003	0.2
Refining Emissions[1]					**104.763**	**5,540.4**
Asphalt Blowing	0.022	MT CO_2/Mbbl[q]	5,589,006	Mbbl/yearrefineryfeed[p]	2.355	124.6
Flaring	0.944	MT CO_2/Mbbl[q]	5,589,006	Mbbl/year refinery feed[p]	99.811	5,278.5
Process Vents	0.025	MT CO_2/Mbbl[q]	5,589,006	Mbbl/year refinery feed[p]	2.597	137.3
Total					**113.472**	**6,000.9**

[a] TankCALC
[b] EPA / ICF International (1999)
[c] EIA Monthly Energy Review
[d] IOGCC Marginal Wells Report
[e] Consensus of Industrial Review Panel

[1] The methodology for year 2013 is to use GHGRP emissions data as-reported (rather than an EFxAF approach, per se). The emission factors in this table were populated by dividing 2013 emissions by 2013 refinery feed rate.

[f] Expert Judgment
[g] EIA Annual Energy Review
[h] GRI / EPA (1996)
[i] Radian (1996)
[j] CAPP (1992)
[k] Adapted from the GOADS 2011 Study by ERG (2015)
[l] BOEM
[m] API (1996)
[n] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[o] OGJ Petroleum Economics Issue
[p] EIA Petroleum Supply Annual, Volume 1
[q] GHGRP data
* Emissions are not actually 0, but 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-132: Summary of CO_2 Emissions from Petroleum Systems (kt)

Activity	1990	1995	2000	2007	2008	2009	2010	2011	2012	2013
Production Field Operations	**375**	**339**	**321**	**293**	**283**	**305**	**317**	**333**	**394**	**461**
Pneumatic controller venting	27	25	23	23	24	24	24	25	26	26
Tank venting	328	296	281	253	243	265	276	291	351	417
Misc. venting & fugitives	16	15	14	14	14	14	14	14	14	14
Wellhead fugitives	3	3	3	3	3	3	3	3	3	3
Refining	**4,070**	**4,241**	**4,586**	**4,600**	**4,458**	**4,351**	**3,836**	**4,134**	**4,666**	**5,540**
Asphalt Blowing	95	99	107	107	104	101	97	84	117	125
Flaring	3,901	4,065	4,395	4,409	4,273	4,171	3,687	3,967	4,490	5,278
Process Vents	74	77	84	84	81	79	52	83	59	137
Total	**4,445**	**4,581**	**4,907**	**4,893**	**4,742**	**4,656**	**4,153**	**4,467**	**5,060**	**6,001**

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

As described in the main body text on Natural Gas Systems, the Inventory methodology involves the calculation of CH_4 and CO_2 emissions for over 100 emissions sources, and then the summation of emissions for each natural gas sector stage.

Step 1: Calculate Potential Methane

Potential Methane Factors

The primary basis for potential CH_4 factors and emission factors for non-combustion-related CO_2 emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. Since the time of this study, practices and technologies have changed. While this study still represents best available data in many cases, using these emission factors alone to represent actual emissions without adjusting for emissions controls would in many cases overestimate emissions. For this reason, "potential methane" is calculated using the data, and then recent data on voluntary and regulatory emission reduction activities (step 3) is deducted to calculate actual emissions. See Section 3.7 of the main document on Natural Gas Systems for more information.

For certain CH_4 emissions sources, new data and information allows for net emissions to be calculated directly: gas well completions and workovers with hydraulic fracturing, liquids unloading, condensate storage tanks, and centrifugal compressors. For these sources, EPA developed emissions factors that directly reflect the use of control technologies. For gas well completions and workovers with hydraulic fracturing, separate emissions estimates were developed for hydraulically fractured completions and workovers that vent, flared hydraulic fracturing completions and workovers, hydraulic fracturing completions and workovers with reduced emissions completions (RECs), and hydraulic fracturing completions and workovers with RECs that flare. For liquids unloading, separate emissions estimates were developed for wells with plunger lifts and wells without plunger lifts. Likewise, for condensate tanks, emissions estimates were developed for tanks with and without control devices. Finally, for centrifugal compressors, separate emissions estimates were developed for compressors with wet and dry seals.

For potential CH_4 factors and emission factors used in the Inventory, see Table A-133 to Table A-138. Methane compositions from GTI 2001 are adjusted year to year using gross production for National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA. These adjusted region-specific annual CH_4 compositions are presented in Table A-139 (for general sources), Table A-140 (for gas wells without hydraulic fracturing), and Table A-141 (for gas wells with hydraulic fracturing). Therefore, emission factors may vary from year to year due to slight changes in the CH_4 composition between each NEMS oil and gas supply module region.

1990-2013 Inventory updates to potential emission factors and emission factors

The current Inventory includes an update to emission factors for gas well completions and workovers with hydraulic fracturing. Technology-specific national emission factors were developed based on 2011, 2012, and 2013 GHGRP data. The emission factors used for gas well completions and workovers with hydraulic fracturing are not potential factors, but are factors for actual emissions because control technologies are taken into account through the use of separate emission factors for each of the aforementioned categories. The updated factors are included in Table A-133. The current Inventory also includes revised emission factors for offshore production platforms. Previously, the Inventory relied on the Bureau of Ocean Energy Management's (BOEM's) Gulf Offshore Activity Data System (GOADS) year 2000 inventory to develop emission factors for offshore platforms; the methodology has been updated to use more recent GOADS inventory data to develop emission factors.

Activity Data

Activity data were taken from the following sources: DrillingInfo, Inc. (DrillingInfo 2014); American Gas Association (AGA 1991–1998); Bureau of Ocean Energy Management, Regulation and Enforcement (previous Minerals and Management Service) (BOEMRE 2011a, 2011b, 2011c, 2011d); Monthly Energy Review (EIA 2012f, 2012g, 2012h, 2011a, 2011b, 2011c, 2011d); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2012c, 2012d, 2012e, 2013a, 2013b, 2013c); the Natural Gas STAR Program annual emissions savings (EPA 2012a, 2013c); Oil and Gas Journal (OGJ 1997–2014); Pipeline and Hazardous Materials Safety Administration (PHMSA 2014); Federal Energy Regulatory Commission (FERC 2014); GHGRP data for natural gas systems (40 CFR 98, subpart W); and other Energy Information Administration publications (EIA 2001, 2004, 2010, 2011, 2012i, 2014). Data for estimating emissions from hydrocarbon production tanks were incorporated (EPA 1999). Coalbed CH_4 well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2014) and the Alabama State Oil and Gas Board (Alabama 2014). Activity data are presented in Table A-133 through Table A-138.

For a few sources, recent direct activity data were not available. For these sources, either 2012 data were used as proxy for 2013 data or a set of industry activity data drivers was developed and was used to update activity data. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. For example, recent data on various types of field separation equipment in the production stage (i.e., heaters, separators, and dehydrators) were unavailable. EPA determined that each of these types of field separation equipment relate to the number of non-associated gas wells. Using the number of each type of field separation equipment estimated by GRI/EPA in 1992, and the number of non-associated gas wells in 1992, EPA developed a factor that is used to estimate the number of each type of field separation equipment throughout the time series. The key activity drivers are presented in Table A-142.

EPA used DI Desktop, a production database maintained by DrillingInfo, Inc. (DrillingInfo 2014), covering U.S. oil and natural gas wells to populate activity data for non-associated gas wells, oil wells, associated gas wells, gas wells with hydraulic fracturing, and completions with hydraulic fracturing. EPA queried DI Desktop for relevant data on an individual well basis—including location, natural gas and liquids (i.e., oil and condensate) production by year, drill type (e.g., horizontal or vertical), and date of completion or first production. Non-associated gas wells were classified as any well within DI Desktop that had non-zero gas production in a given year, and with a gas-to-oil ratio (GOR) of greater than 100 mcf/bbl in that year. Oil wells were classified as any well that had non-zero liquids production in a given year, and with a GOR of less than or equal to 100 mcf/bbl in that year. Associated gas wells were identified as a subset of oil wells with nonzero gas production in a given year. Both oil and condensate are included in the liquids production data in DI Desktop; therefore, the count of associated gas wells may include wells that produce gas and condensate only. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in DI Desktop referenced against a formation type crosswalk developed by EIA (EIA 2012a).

For 1990 through 2010, gas well completions with hydraulic fracturing were identified as a subset of the gas wells with hydraulic fracturing that had a date of completion or first production in the specified year. To calculate workovers for 1990 through 2010, EPA applied a refracture rate of 1 percent (i.e., 1 percent of all wells with hydraulic fracturing are assumed to be refractured in a given year) to the total counts of wells with hydraulic fracturing from the DrillingInfo data. For 2011 through 2013, EPA used GHGRP data for the total number of well completions and workovers. The GHGRP data represents a subset of the national completions and workovers, due to the reporting threshold, and therefore using this data without scaling it up to national level results in an underestimate. However, because EPA's GHGRP counts of completions and workovers were higher than national counts of completions and workovers, obtained using DI Desktop data, EPA directly used the GHGRP data for completions and workovers for 2011 through 2013.

EPA calculated the percentage of gas well completions and workovers with hydraulic fracturing in the each of the four control categories using 2011 through 2013 Subpart W data. EPA assumed 0 percent RECs use from 1990 through 2000, used GHGRP RECs percentage for 2011 through 2013, and then used linear interpolation between the 2000 and 2011 percentages. For flaring, EPA used an assumption of 10 percent (the average of the percent of completions and workovers that were flared in 2011 through 2013 GHGRP data) flaring from 1990 through 2010 to recognize that some flaring has occurred over that time period. For 2011 through 2013, EPA used the GHGRP data on flaring.

Step 2: Compile Reductions Data

The emissions calculated in Step 1 above represent expected emissions from an activity in the absence of emissions controls (with the exceptions of gas well completions and workovers with hydraulic fracturing, liquids unloading, centrifugal compressors, and condensate tanks, as noted above), and do not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies, data were collected on voluntary and regulatory reductions. Voluntary reductions included in the Inventory were those reported to Gas STAR for activities such as replacing a high bleed pneumatic controllers with a low bleed controller and replacing wet seals with dry seals at reciprocating compressors. Regulatory actions reducing emissions include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents and condensate tanks.

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 and practices (e.g., vapor recovery units, centrifugal compressors, etc.) are calculated by the reporting partners using actual measurement data or equipment-specific emission factors. 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. The reductions undergo quality assurance and quality control checks to identify errors, inconsistencies, or irregular data before being incorporated into the Inventory. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). However, aggregate emissions reductions data by Gas STAR technology are provided for several sources, as shown in Table A-143. For those sources, EPA has also used data on potential emissions, and the Gas STAR data on reductions, to calculate net emissions, as shown in Table A-149. Many of the activities reported to Gas STAR are cross-cutting and apply to more than one emissions source and therefore cannot be assigned to one emissions source, but instead are included in the "other" category. For Inventory sources with emission factors that already take into account the use of control technologies (i.e., gas well completions and workovers with hydraulic fracturing, liquids unloading, and condensate storage tanks) Natural Gas STAR reported reductions for those activities are not incorporated into the Inventory, as this would double count reductions. CH_4 emission reductions from the Natural Gas STAR Program are summarized in Table A-143.

Federal regulations. The 1990 Clean Air Act (CAA) sets 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 (MACT), giving the operators flexibility to 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 incidentally 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 threshold, 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 Repair (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. CH_4 emission reductions from federal regulations, such as NESHAP, are summarized in Table A-144. In addition to the NESHAP applicable to natural gas, future Inventories will reflect the 2012 New Source Performance Standards (NSPS) for oil and gas. By separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors for each category, EPA is implicitly accounting for NSPS reductions from hydraulically fractured gas wells. The rule also has VOC reduction requirements for compressors, storage vessels, pneumatic controllers, and equipment leaks at processing plants, which will also impact CH_4 emissions in future Inventories.

Step 3: Calculate Net Emissions

For CH_4, the reductions described above in Step 2 are summed and deducted from the potential CH_4 emissions calculated in Step 1. These net emissions are reported in the Natural Gas Systems inventory text.

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

Produced natural gas is composed of primarily CH_4, but as shown in Table A-150, 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. The emission factors used to estimate CH_4 were also used to calculate non-combustion CO_2 emissions. The Gas Technology Institute's (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. Additional information about CO_2 content in transmission quality natural gas was obtained from numerous U.S. transmission companies to help further develop the non-combustion CO_2 emission factors. For the CO_2 content used to develop CO_2 emission factors from CH_4 potential factors, see Table A-150. The detailed source emission estimates for CH_4 and CO_2 from the production sector are presented in Table A-145 and Table A-154, 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-146 and Table A-152, respectively.

For the transmission sector, CO_2 content in natural gas transmission pipelines was estimated for the top 20 transmission pipeline companies in the United States (separate analyses identified the top 20 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-147 and Table A-153, 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 to transmission segment contents 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-148 and Table A-154, respectively.

Three exceptions to this methodology are CO_2 emissions from flares, CO_2 from acid gas removal units, and CO_2 from 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, including associated gas. 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 were 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.

Table A-133 through Table A-138 display the 2012 activity data, CH_4 emission factors, and calculated potential CH_4 emissions for each stage.

The tables provide references for emission factors and activity data in footnotes (i.e., lettered footnotes). The tables also provide information on which method was used for supplying activity data for 2013 (i.e., numbered footnotes).

Table A-133: 2013 Data and Calculated CH_4 Potential Emissions (Mg) for the Natural Gas Production Stage, by NEMS Region

	2013 EPA Inventory Values		
Activity	**Activity Data**	**Emission Factor (Potential)[aa]**	**Calculated Potential (Mg)[bb]**
North East			
Gas Wells			
NE - Associated Gas Wells[cc,dd]	42,454 wells[a,1]	NA	0.0
NE - Non-associated Gas Wells (less wells with hydraulic fracturing)	72,422 wells[a,1]	7.55 scfd/well[b]	3,844.6
NE - Gas Wells with Hydraulic Fracturing	80,193 wells[a,1]	7.59 scfd/well[b]	4,277.4
Field Separation Equipment			
Heaters	305 heaters[b,2]	15.19 scfd/heater[b]	32.6
Separators	108,357 separators[b,2]	0.96 scfd/separator[b]	731.4
Dehydrators	21,277 dehydrators [b,2]	23.24 scfd/dehydrator[b]	3,475.8
Meters/Piping	7,803 meters [c,2]	9.63 scfd/meter[b]	528.1
Gathering Compressors			
Small Reciprocating Compressors	153 compressors [b,2]	286.09 scfd/compressor[b]	306.9
Large Reciprocating Compressors	24 compressors [b,2]	16,246.46 scfd/compressor[b]	2,741.1
Large Reciprocating Stations	3 stations [b,2]	8,811.42 scfd/station[b]	185.8
Pipeline Leaks	75,413 miles [c,2]	56.79 scfd/mile[b]	30,108.2
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	252 completions/yr [d,2]	778.57 scf/completion[b]	3.8
Gas Well Workovers without Hydraulic Fracturing	3,150 workovers/yr [a,1]	2,606.55 scf/workover[b]	158.2
Gas Well Completions and Workovers with Hydraulic Fracturing	1,093 completions/yr[o] 384 workovers/yr[o]	See Table A-134	17,456.0
Well Drilling	6,370 wells[f,1]	2,717.18 scf/well[g]	333.4
Normal Operations			
Pneumatic Controllers Vents	74,171 controllers [b,2]	368.63 scfd/controller[b]	192,209.1
Chemical Injection Pumps	763 active pumps [b,2]	264.99 scfd/pump[b]	1,421.5
Kimray Pumps	6,227,750 MMscf/yr [b,2]	1,059.95 scf/MMscf[b]	127,136.8
Dehydrator Vents	6,989,618 MMscf/yr [b,2]	294.48 scf/MMscf[b]	39,642.5
Condensate Tank Vents			
Condensate Tanks without Control Devices	2.5 MMbbl/yr [h,1]	21.87 scf/bbl[i,ff]	1,053.0
Condensate Tanks with Control Devices	2.5 MMbbl/yr [h,1]	4.37 scf/bbl[i,ff]	210.6
Compressor Exhaust Vented			
Gas Engines	0.00 MMHPhr [b,2]	0.26 scf/HPhr[b]	0.0
Liquids Unloading			
Liquids Unloading (with plunger lifts)	6,647 venting wells[a,j,2a,j,2]	264,906.76 scfy/venting well[j,gg]	33,913.7
Liquids Unloading (without plunger lifts)	17,190 venting wells[a,j,2]	139,914.11 scfy/venting well[j,gg]	46,322.7
Blowdowns			
Vessel Blowdown	129,939 vessels [b,2]	83.34 scfy/vessel[b]	208.6
Pipeline Blowdown	75,413 miles (gathering) [c,2]	330.16 scfy/mile[b]	479.5
Compressor Blowdown	153 compressors [b,2]	4,032.50 scfy/compressor[b]	11.9
Compressor Starts	153 compressors [b,2]	9,021.30 scfy/compressor[b]	26.5
Upsets			
Pressure Relief Valves	333,087 PRV [b,2]	36.33 scfy/PRV[b]	233.1
Mishaps	18,853 miles [c,2]	714.82 scf/mile[b]	259.6
Midcontinent			
Gas Wells			
MC - Associated Gas Wells[cc,dd]	47,930 wells[a,1]	NA	0.0
MC - Non-associated Gas Wells (less wells with hydraulic fracturing)	74,442 wells[a,1]	7.44 scfd/well[b]	3,891.5
MC - Gas Wells with Hydraulic Fracturing	26,699 wells[a,1]	8.35 scfd/well[b]	1,567.6
Field Separation Equipment			
Heaters	41,063 heaters [b,2]	14.87 scfd/heater[b]	4,293.2
Separators	43,996 separators [b,2]	0.94 scfd/separator[b]	290.8
Dehydrators	14,101 dehydrators [b,2]	95.35 scfd/dehydrator[b]	9,452.0
Meters/Piping	135,554 meters [c,2]	9.43 scfd/meter[b]	8,984.7
Gathering Compressors			
Small Reciprocating Compressors	11,429 compressors [b,2]	280.16 scfd/compressor[b]	22,509.0

Large Reciprocating Compressors	24 compressors [b,2]	15,909.56 scfd/compressor[b]	2,684.2
Large Reciprocating Stations	3 stations [b,2]	8,628.70 scfd/station[b]	182.0
Pipeline Leaks	77,074 miles [c,2]	55.61 scfd/mile[b]	30,133.2
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	167 completions/yr [d,2]	766.66 scf/completion[b]	2.5
Gas Well Workovers without Hydraulic Fracturing	3,238 workovers/yr [a,1]	2,566.70 scf/workover[b]	160.1
Gas Well Completions and Workovers with Hydraulic Fracturing	1,186 completions/yr[o] 143 workovers/yr[o]	See Table A-134	14,737.1
Well Drilling	4,222 wells [f,1]	2,660.84 scf/well[g]	216.4
Normal Operations			
Pneumatic Controllers Vents	156,870 controllers [b,2]	360.99 scfd/controller[b]	398,087.8
Chemical Injection Pumps	14,362 active pumps [b,2]	259.49 scfd/pump[b]	26,199.2
Kimray Pumps	4,127,254 MMscf/yr [b,2]	1,037.97 scf/MMscf[b]	82,508.9
Dehydrator Vents	4,632,159 MMscf/yr [b,2]	288.37 scf/MMscf[b]	25,727.1
Condensate Tank Vents			
Condensate Tanks without Control Devices	26 MMbbl/yr [h,1]	302.75 scf/bbl[i,ff]	151,607.4
Condensate Tanks with Control Devices	26 MMbbl/yr [h,1]	60.55 scf/bbl[i,ff]	30,321.5
Compressor Exhaust Vented			
Gas Engines	17,473 MMHPhr [b,2]	0.25 scf/HPhr[b]	84,508.1
Liquids Unloading			
Liquids Unloading (with plunger lifts)	2,356 venting wells [a,j,2]	1,137,794.18 scfy/venting well[j,gg]	51,629.2
Liquids Unloading (without plunger lifts)	4,183 venting wells [a,j,2]	189,802.21 scfy/venting well[j,gg]	15,291.3
Blowdowns			
Vessel Blowdown	99,161 vessels [b,2]	81.61 scfy/vessel[b]	155.9
Pipeline Blowdown	77,074 miles (gathering) [c,2]	323.32 scfy/mile[b]	479.9
Compressor Blowdown	11,429 compressors [b,2]	3,948.88 scfy/compressor[b]	869.2
Compressor Starts	11,429 compressors [b,2]	8,834.22 scfy/compressor[b]	1,944.6
Upsets			
Pressure Relief Valves	220,743 PRV [b,2]	35.58 scfy/PRV[b]	151.2
Mishaps	19,269 miles [c,2]	700.00 scf/mile[b]	259.8
Rocky Mountain			
Gas Wells			
RM - Associated Gas Wells[cc,dd]	50,533 wells [a,1]	NA	0.0
RM - Non-associated Gas Wells (less wells with hydraulic fracturing)	10,069 wells [a,1]	35.33 scfd/well[b]	2,500.5
RM - Gas Wells with Hydraulic Fracturing	66,750 wells [a,1]	40.64 scfd/well[b]	19,072.0
Field Separation Equipment			
Heaters	35,029 heaters [b,2]	57.09 scfd/heater[b]	14,057.8
Separators	38,333 separators [b,2]	120.69 scfd/separator[b]	32,522.4
Dehydrators	10,710 dehydrators [b,2]	90.14 scfd/dehydrator[b]	6,786.4
Meters/Piping	90,791 meters [c,2]	52.33 scfd/meter[b]	33,398.6
Gathering Compressors			
Small Reciprocating Compressors	8,527 compressors [b,2]	264.84 scfd/compressor[b]	15,875.1
Large Reciprocating Compressors	32 compressors [b,2]	15,039.44 scfd/compressor[b]	3,383.2
Large Reciprocating Stations	4 stations [b,2]	8,156.78 scfd/station[b]	229.4
Pipeline Leaks	100,404 miles [c,2]	52.57 scfd/mile[b]	37,107.5
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	127 completions/yr [d,2]	710.51 scf/completion[b]	1.7
Gas Well Workovers without Hydraulic Fracturing	438 workovers/yr [a,1]	2,378.69 scf/workover[b]	20.1
Gas Well Completions and Workovers with Hydraulic Fracturing	604 completions/yr[o] 275 workovers/yr[o]	See Table A-134	25,723.4
Well Drilling	3,206 wells [f,1]	2,515.31 scf/well[g]	155.3
Normal Operations			
Pneumatic Controllers Vents	112,463 controllers [b,2]	341.24 scfd/controller[b]	269,788.4
Chemical Injection Pumps	13,674 active pumps [b,2]	245.30 scfd/pump[b]	23,579.5
Kimray Pumps	3,134,748 MMscf/yr [b,2]	981.20 scf/MMscf[b]	59,240.1
Dehydrator Vents	3,518,235 MMscf/yr [b,2]	272.60 scf/MMscf[b]	18,471.6
Condensate Tank Vents			
Condensate Tanks without Control Devices	18 MMbbl/yr [h,1]	21.87 scf/bbl[i,ff]	7,371.3
Condensate Tanks with Control Devices	18 MMbbl/yr [h,1]	4.37 scf/bbl[i,ff]	1,474.3

Compressor Exhaust Vented			
Gas Engines	13,271 MMHPhr [b,2]	0.24 scf/HPhr[b]	60,675.5
Liquids Unloading			
Liquids Unloading (with plunger lifts)	9,891 venting wells [a,j,2]	120,264.50 scfy/venting well[j,gg]	22,910.5
Liquids Unloading (without plunger lifts)	1,167 venting wells [a,j,2]	2,010,470.06 scfy/venting well[j,gg]	45,188.2
Blowdowns			
Vessel Blowdown	84,072 vessels [b,2]	77.15 scfy/vessel[b]	124.9
Pipeline Blowdown	100,404 miles (gathering) [c,2]	305.64 scfy/mile[b]	591.0
Compressor Blowdown	8,527 compressors [b,2]	3,732.91 scfy/compressor[b]	613.0
Compressor Starts	8,527 compressors [b,2]	8,351.07 scfy/compressor[b]	1,371.5
Upsets			
Pressure Relief Valves	167,660 PRV b,2	33.63 scfy/PRV[b]	108.6
Mishaps	25,101 miles c,2	661.72 scf/mile[b]	319.9
Produced Water from Coal Bed Methane			
	gallons produced	kt/gallon	
Powder River	20,596,530,150 water [k,1]	0.00 water drainage [k]	47,138.6
South West			
Gas Wells			
SW - Associated Gas Wells[cc,dd]	237,237 wells [a,1]	NA	0.0
SW - Non-associated Gas Wells (less wells with hydraulic fracturing)	22,250 wells [a,1]	37.23 scfd/well[b]	5,823.9
SW - Gas Wells with Hydraulic Fracturing	26,903 wells [a,1]	37.23 scfd/well[b]	7,041.9
Field Separation Equipment			
Heaters	13,320 heaters [b,2]	58.97 scfd/heater[b]	5,521.7
Separators	27,624 separators [b,2]	124.66 scfd/separator[b]	24,208.4
Dehydrators	6,853 dehydrators [b,2]	93.10 scfd/dehydrator[b]	4,485.3
Meters/Piping	69,076 meters [c,2]	54.05 scfd/meter[b]	26,247.0
Gathering Compressors			
Small Reciprocating Compressors	6,685 compressors [b,2]	273.55 scfd/compressor[b]	12,855.3
Large Reciprocating Compressors	16 compressors [b,2]	15,534.58 scfd/compressor[b]	1,747.3
Large Reciprocating Stations	2 stations [b,2]	8,425.33 scfd/station[b]	118.5
Pipeline Leaks	69,418 miles [c,2]	54.30 scfd/mile[b]	26,500.3
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	81 completions/yr [d,2]	748.89 scf/completion[b]	1.2
Gas Well Workovers without Hydraulic Fracturing	968 workovers/yr [a,1]	2,507.19 scf/workover[b]	46.7
Gas Well Completions and Workovers with Hydraulic Fracturing	253 completions/yr[o] 116 workovers/yr[o]	See Table A-134	4,860.6
Well Drilling	2,052 wells [f,1]	2,598.12 scf/well[g]	102.7
Normal Operations			
Pneumatic Controllers Vents	65,275 controllers [b,2]	352.48 scfd/controller[b]	161,744.4
Chemical Injection Pumps	2,998 active pumps [b,2]	253.38 scfd/pump[b]	5,340.6
Kimray Pumps	2,005,783 MMscf/yr [b,2]	1,013.50 scf/MMscf[b]	39,153.0
Dehydrator Vents	2,251,159 MMscf/yr [b,2]	281.57 scf/MMscf[b]	12,208.3
Condensate Tank Vents			
Condensate Tanks without Control Devices	12 MMbbl/yr [h,1]	302.75 scf/bbl[i,ff]	67,057.1
Condensate Tanks with Control Devices	12 MMbbl/yr [h,1]	60.55 scf/bbl[i,ff]	13,411.4
Compressor Exhaust Vented			
Gas Engines	8,491 MMHPhr [b,2]	0.25 scf/HPhr[b]	40,101.7
Liquids Unloading			
Liquids Unloading (with plunger lifts)	1,634 venting wells [a,j,2]	2,855.62 scfy/venting well[j,gg]	89.9
Liquids Unloading (without plunger lifts)	9,571 venting wells [a,j,2]	77,889.92 scfy/venting well[j,gg]	14,358.0
Blowdowns			
Vessel Blowdown	47,797 vessels [b,2]	79.69 scfy/vessel[b]	73.4
Pipeline Blowdown	69,418 miles (gathering) [c,2]	315.70 scfy/mile[b]	422.1
Compressor Blowdown	6,685 compressors [b,2]	3,855.80 scfy/compressor[b]	496.4
Compressor Starts	6,685 compressors [b,2]	8,626.01 scfy/compressor[b]	1,110.6
Upsets			
Pressure Relief Valves	107,278 PRV [b,2]	34.74 scfy/PRV[b]	71.8
Mishaps	17,355 miles [c,2]	683.50 scf/mile[b]	228.5
West Coast			
Gas Wells			
WC - Associated Gas Wells[cc,dd]	30,507 wells [a,1]	NA	0.0

WC - Non-associated Gas Wells (less wells with hydraulic fracturing)	2,190 wells [a,1]	42.49 scfd/well[b]	654.2
WC - Gas Wells with Hydraulic Fracturing	369 wells [a,1]	42.49 scfd/well[b]	110.2
Field Separation Equipment			
Heaters	2,559 heaters [b,2]	67.29 scfd/heater[b]	1,210.6
Separators	1,868 separators [b,2]	142.27 scfd/separator[b]	1,868.3
Dehydrators	357 dehydrators [b,2]	106.25 scfd/dehydrator[b]	266.5
Meters/Piping	4,569 meters [c,2]	61.68 scfd/meter[b]	1,981.4
Gathering Compressors			
Small Reciprocating Compressors	2,971 compressors [b,2]	312.19 scfd/compressor[b]	6,520.3
Large Reciprocating Compressors	8 compressors [b,2]	17,728.38 scfd/compressor[b]	997.0
Large Reciprocating Stations	1 stations [b,2]	9,615.15 scfd/station[b]	67.6
Pipeline Leaks	17,233 miles [c,2]	61.97 scfd/mile[b]	7,507.7
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	4 completions/yr [d,2]	854.65 scf/completion[b]	0.1
Gas Well Workovers without Hydraulic Fracturing	95 workovers/yr [a,1]	2,861.26 scf/workover[b]	5.2
Gas Well Completions and Workovers with Hydraulic Fracturing	5 completions/yr[o] 1 workovers/yr[o]	See Table A-134	0.0
Well Drilling	107 wells [f,1]	2,965.03 scf/well[g]	6.1
Normal Operations			
Pneumatic Controllers Vents	2,564 controllers [b,2]	402.26 scfd/controller[b]	7,250.8
Chemical Injection Pumps	1,738 active pumps [b,2]	289.16 scfd/pump[b]	3,532.0
Kimray Pumps	104,425 MMscf/yr [b,2]	1,156.63 scf/MMscf[b]	2,326.2
Dehydrator Vents	117,200 MMscf/yr [b,2]	321.34 scf/MMscf[b]	725.3
Condensate Tank Vents			
Condensate Tanks without Control Devices	9 MMbbl/yr [h,1]	21.87 scf/bbl[i,ff]	3,790.9
Condensate Tanks with Control Devices	9 MMbbl/yr [h,1]	4.37 scf/bbl[i,ff]	758.2
Compressor Exhaust Vented			
Gas Engines	442 MMHPhr [b,2]	0.28 scf/HPhr[b]	2,382.6
Liquids Unloading			
Liquids Unloading (with plunger lifts)	194 wells [a,j,2]	317,292.27 scfy/venting well[j,gg]	1,185.5
Liquids Unloading (without plunger lifts)	174 wells [a,j,2]	279,351.48 scfy/venting well[j,gg]	936.2
Blowdowns			
Vessel Blowdown	4,784 vessels [b,2]	90.94 scfy/vessel[b]	8.4
Pipeline Blowdown	17,233 miles (gathering) [c,2]	360.28 scfy/mile[b]	119.6
Compressor Blowdown	2,971 compressors [b,2]	4,400.32 scfy/compressor[b]	251.8
Compressor Starts	2,971 compressors [b,2]	9,844.18 scfy/compressor[b]	563.3
Upsets			
Pressure Relief Valves	5,585 PRV [b,2]	39.64 scfy/PRV[b]	4.3
Mishaps	4,308 miles [c,2]	780.03 scf/mile[b]	64.7
Gulf Coast			
Gas Wells			
GC - Associated Gas Wells[cc,dd]	68,362 wells [a,1]	NA	0.0
GC - Non-associated Gas Wells (less wells with hydraulic fracturing)	25,906 wells [a,1]	7.96 scfd/well[b]	1,449.3
GC - Gas Wells with Hydraulic Fracturing	43,103 wells [a,1]	7.96 scfd/well[b]	2,411.8
Field Separation Equipment			
Heaters	15,458 heaters [b,2]	64.61 scfd/heater[b]	7,021.5
Separators	45,408 separators [b,2]	136.60 scfd/separator[b]	43,604.9
Dehydrators	9,621 dehydrators [b,2]	102.02 scfd/dehydrator[b]	6,900.3
Meters/Piping	82,792 meters [c,2]	59.23 scfd/meter[b]	34,471.6
Gathering Compressors			
Small Reciprocating Compressors	5,590 compressors [b,2]	299.75 scfd/compressor[b]	11,778.9
Large Reciprocating Compressors	24 compressors [b,2]	17,022.46 scfd/compressor[b]	2,872.0
Large Reciprocating Stations	3 stations [b,2]	9,232.29 scfd/station[b]	194.7
Pipeline Leaks	91,657 miles [c,2]	59.50 scfd/mile[b]	38,341.3
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	114 completions/yr [d,2]	820.51 scf/completion[b]	1.8
Gas Well Workovers without Hydraulic Fracturing	1,127 workovers/yr [a,1]	2,746.96 scf/workover[b]	59.6

Gas Well Completions and Workovers with Hydraulic Fracturing	933 completions/yr[o] 279 workovers/yr[o]	See Table A-134	23,614.9
Well Drilling	2,880 wells [f,1]	2,846.97 scf/well[g]	157.9
Normal Operations			
Pneumatic Controllers Vents	47,961 controllers [b,2]	386.24 scfd/controller[b]	130,225.1
Chemical Injection Pumps	2,277 active pumps [b,2]	277.64 scfd/pump[b]	4,444.8
Kimray Pumps	2,816,046 MMscf/yr [b,2]	1,110.57 scf/MMscf[b]	60,234.2
Dehydrator Vents	3,160,545 MMscf/yr [b,2]	308.54 scf/MMscf[b]	18,781.6
Condensate Tank Vents			
Condensate Tanks without Control Devices	71 MMbbl/yr [h,1]	21.87 scf/bbl[i,ff]	29,695.7
Condensate Tanks with Control Devices	71 MMbbl/yr [h,1]	4.37 scf/bbl[i,ff]	5,939.1
Compressor Exhaust Vented			
Gas Engines	11,922 MMHPhr [b,2]	0.27 scf/HPhr[b]	61,693.7
Liquids Unloading			
Liquids Unloading (with plunger lifts)	1,601 venting wells [a,j,2]	61,771.81 scfy/venting well[j,gg]	1,904.7
Liquids Unloading (without plunger lifts)	4,887 venting wells [a,j,2]	265,179.21 scfy/venting well[j,gg]	24,959.6
Blowdowns			
Vessel Blowdown	70,487 vessels [b,2]	87.32 scfy/vessel[b]	118.5
Pipeline Blowdown	91,657 miles (gathering) [c,2]	345.93 scfy/mile[b]	610.7
Compressor Blowdown	5,590 compressors [b,2]	4,225.11 scfy/compressor[b]	454.9
Compressor Starts	5,590 compressors [b,2]	9,452.19 scfy/compressor[b]	1,017.6
Upsets			
Pressure Relief Valves	150,614 PRV [b,2]	38.06 scfy/PRV[b]	110.4
Mishaps	22,914 miles [c,2]	748.97 scf/mile[b]	330.5
Produced Water from Coal Bed Methane Wells			
Black Warrior	5,480 wells [l,1]	0.00 kt/well [l]	12,695.3
Offshore Platforms			
Shallow water Gas Platforms (GoM and Pacific)	shallow water gas 1,973 platforms [m,3]	8,899.00 scfd/platform [n]	123,460.0
Deepwater Gas Platforms (GoM and Pacific)	deepwater gas 41 platforms [m,3]	93,836.00 scfd/platform [n]	27,105.3
Regulatory Reductions (kt)			**(120.8)**
Voluntary Reductions (kt)			**(1,422.9)**
Total Reductions (kt)			**(1,543.7)**
Total Potential Emissions (kt)			**3,423.1**
Total Net Emissions (kt)			**1,879.5**

[a] DI Desktop (2014)
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (1996), Estimation of Activity Factors for the Natural Gas Exploration and Production Industry in the U.S.
[d] API/ICF memo (1997)
[e] EPA NSPS Technical Support Document (2012)
[f] EIA Monthly Energy Review
[g] Radian (1992), Global Emissions of Methane Sources
[h] EIA U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves Annual Report
[I] EP&P/API Tank Calc runs
[j] API/ANGA (2012), Characterizing Pivotal Sources of Methane Emissions from Natural Gas Production – Summary and Analysis of API and ANGA Survey Responses
[k] Wyoming Oil and Gas Conservation Commission (2014)
[l] Alabama State Oil and Gas Board (2014)
[m] Bureau of Ocean Energy Management, Regulation and Enforcement (2011)
[n] MMS (2000), 2000 Gulfwide Offshore Activity Data System
[o] 2013 GHGRP - Subpart W data
[p] Emissions for hydraulic fracturing completions and workovers are split into 4 categories and the same emission factors (shown in Table A-2) are used for all NEMS regions. For more details, refer to EPA memo "Updating GHG Inventory Estimate for Hydraulically Fractured Gas Well Completions and Workovers." The factors for hydraulically fractured completions and workovers in Table A-135 represent actual emissions and can be used to calculate emissions directly.
[q] Emissions for hydraulic fracturing completions and workovers are calculated together.
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[bb] Totals may not sum due to independent rounding.
[cc] Emissions from oil wells that produce associated gas are estimated in the Petroleum Systems model. In the Natural Gas Systems model, the oil wells counts are used as a driver only.
[dd] NA = not applicable (i.e., this data is not applicable for the Natural Gas Systems model).
[ff] Emission factors for condensate tanks represent actual emissions and can be used to calculate emissions directly.
[gg] Emission factors for liquids unloading represent actual emissions and can be used to calculate emissions directly.

[1] Activity data for 2013 available from source.
[2] Ratios relating other factors for which activity data are available.
[3] 2012 activity data are used to determine some or all of the 2013 activity.

Table A-134: 2013 National Activity Data and Emission Factors, and Emissions (Mg), by category for Hydraulically Fractured Gas Well Completions and Workovers

	2013 EPA Inventory Values		
Activity	Activity Data	Emission Factor	Emissions (Mg)[aa]
Hydraulic Fracturing Completions and Workovers that vent	1,677 completions and workovers/year[a]	36.8 Mg/comp or workover[b]	61,737
Hydraulic Fracturing Completions and Workovers that flare	835 completions and workovers/year[a]	4.9 Mg/comp or workover[b]	4,100
Hydraulic Fracturing Completions and Workovers with RECs	3,156 completions and workovers/year[a]	3.2 Mg/comp or workover[b]	10,229
Hydraulic Fracturing Completions and Workovers with RECs that flare	2,117 completions and workovers/year[a]	4.9 Mg/comp or workover[b]	10,326

[a] 2013 GHGRP - Subpart W data. The GHGRP data represents a subset of national completions and workovers, due to the reporting threshold. Please see the section on "Activity Data" above for more information and the Planned Improvements section of the Inventory report.
[b] Emissions for hydraulic fracturing completions and workovers are split into 4 categories and the same emission factors are used for all NEMS regions. For more details, refer to EPA memo "Updating GHG Inventory Estimate for Hydraulically Fractured Gas Well Completions and Workovers."
[aa] Totals may not sum due to independent rounding.

Table A-135: U.S. Activity Data for Hydraulic Fracturing Completions and Workovers split by 4 categories

Activity	1990	1995	2000	2005	2011[a]	2012[a]	2013[a]
Hydraulic Fracturing Completions and Workovers that vent	3,951	3,548	7,121	10,436	4,640	3,109	1,677
Hydraulic Fracturing Completions and Workovers that flare	439	394	791	1,513	1,386	703	835
Hydraulic Fracturing Completions and Workovers with RECs	0	0	0	2,383	3,884	3,413	3,156
Hydraulic Fracturing Completions and Workovers with RECs that flare	0	0	0	794	1,295	1,911	2,117
Total	**4,391**	**3,942**	**7,912**	**15,127**	**11,204**	**9,136**	**7,785**

[a] 2011, 2012, and 2013 GHGRP - Subpart W data

Table A-136: 2013 Data and CH_4 Emissions (Mg) for the Natural Gas Processing Stage

	2013 EPA Inventory Values				
Activity	Activity Data		Emission Factor (Potential)[aa]		Calculated Potential Emissions (Mg)
Normal Fugitives					
Plants	650	plants[a,1]	7,906.00	scfd/plant[b]	36,126.0
Reciprocating Compressors	5,679	compressors[c,2]	11,196.00	scfd/compressor[b]	446,972.3
Centrifugal Compressors (wet seals)	659	compressors[d,2]	51,369.86	scfd/compressor[d]	238,045.0
Centrifugal Compressors (dry seals)	256	compressors[d,2]	25,189.04	scfd/compressor[d]	45,352.6
Vented and Combusted					
Gas Engines	40,799	MMHPhr[c,2]	0.24	scf/HPhr[b]	188,591.2
Gas Turbines	48,376	MMHPhr[c,2]	0.01	scf/HPhr[b]	5,310.8
AGR Vents	329	AGRunits[b,2]	6,083.00	scfd/AGR[b]	14,087.8
Kimray Pumps	1,478,022	MMscf/yr[c,2]	177.75	scf/MMscf[b]	5,060.0
Dehydrator Vents	13,315,517	MMscf/yr[c,2]	121.55	scf/MMscf[b]	31,172.3
Pneumatic Controllers	650	gasplants[a,1]	164,721.00	scfy/plant[b]	2,062.1
Routine Maintenance					
Blowdowns/Venting	650	gasplants[a,1]	4,060.00	Mscfy/plant[b]	50,827.1
Regulatory Reductions (kt)					**(16.5)**
Voluntary Reductions (kt)					**(140.7)**
Total Reductions (kt)					**(157.2)**
Total Potential Emissions (kt)					**1,063.6**
Total Net Emissions (kt)					**906.4**

[a] Oil and Gas Journal
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2008), Natural Gas Model Activity Factor Basis Change
[d] ICF (2010), Emissions from Centrifugal Compressors
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[1] Activity data for 2013 available from source.
[2] Ratios relating other factors for which activity data are available.

Table A-137: 2013 Data and CH_4 Emissions (Mg) for the Natural Gas Transmission Stage

	2013 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor (Potential)[aa]**		**Calculated Potential Emissions (Mg)**
Fugitives					
Pipeline Leaks	302,825	miles[a,1]	1.55	scfd/mile[b]	3,308.1
Compressor Stations (Transmission)					
Station	1,798	stations[c,2]	8,778.00	scfd/station[b]	110,926.8
Reciprocating Compressor	7,227	compressors[c,2]	15,205.00	scfd/compressor[b]	772,526.5
Centrifugal Compressor (wet seals)	659	compressors[d,2]	50,221.92	scfd/compressor[d]	232,509.0
Centrifugal Compressor (dry seals)	66	compressors[d,2]	32,208.22	scfd/compressor[d]	15,011.9
Compressor Stations (Storage)					
Station	407	stations[e,2]	21,507.00	scfd/station[b]	61,482.6
Reciprocating Compressor	1,196	compressors[e,2]	21,116.00	scfd/compressor[b]	177,538.3
Centrifugal Compressor (wet seals)	72	compressors[d,2]	45,441.10	scfd/compressor[d]	22,921.7
Centrifugal Compressor (dry seals)	45	compressors[d,2]	31,989.04	scfd/compressor[d]	10,174.8
Wells (Storage)	18,962	wells[b,2]	114.50	scfd/well[b]	15,263.0
M&R (Trans. Co. Interconnect)	2,696	stations[c,2]	3,984.00	scfd/station[b]	75,498.5
M& R (Farm Taps + Direct Sales)	79,930	stations[c,2]	31.20	scfd/station[b]	17,531.3
Vented and Combusted					
Dehydrator vents (Transmission)	1,145,852	MMscf/year[b,2]	93.72	scf/MMscf[b]	2,068.3
Dehydrator vents (Storage)	2,107,008	MMscf/year[b,2]	117.18	scf/MMscf[b]	4,755.3
Compressor Exhaust					
Engines (Transmission)	51,976	MMHPhr[b,2]	0.24	scf/HPhr[b]	240,252.0
Turbines (Transmission)	12,402	MMHPhr[b,2]	0.01	scf/HPhr[b]	1,361.5
Engines (Storage)	5,185	MMHPhr[b,2]	0.24	scf/HPhr[b]	23,968.7
Turbines (Storage)	1,822	MMHPhr[b,2]	0.01	scf/HPhr[b]	200.0
Generators (Engines)	2,543	MMHPhr[b,2]	0.24	scf/HPhr[b]	11,756.8
Generators (Turbines)	30	MMHPhr[b,2]	0.01	scf/HPhr[b]	3.3
Pneumatic Controllers Transmission + Storage					
Pneumatic Controllers Transmission	70,756	controllers[f,2]	162,197.00	scfy/controller[b]	221,037.2
Pneumatic Controllers Storage	16,007	controllers[e,2]	162,197.00	scfy/controller[b]	50,004.5
Routine Maintenance/Upsets					
Pipeline venting	302,825	miles[a,1]	31.65	Mscfy/mile[b]	184,595.8
Station Venting Transmission + Storage					
Station Venting Transmission	1,798	compressor stations[c,2]	4,359.00	Mscfy/station[b]	150,915.9
Station Venting Storage	407	compressor stations[e,2]	4,359.00	Mscfy/station[b]	34,140.2
LNG Storage					-
LNG Stations	70	stations[f,g,3]	21,507.00	scfd/station[b]	10,622.8
LNG Reciprocating Compressors	270	compressors[f,g,3]	21,116.00	scfd/comp[b]	40,146.5
LNG Centrifugal Compressors	64	compressors[f,g,3]	30,573.00	scfd/comp[b]	13,766.0
LNG Compressor Exhaust					
LNG Engines	579	MMHPhr[f,g,3]	0.24	scf/HPhr[b]	2,677.7
LNG Turbines	113	MMHPhr[f,g,3]	0.01	scf/HPhr[b]	12.4
LNG Station Venting	70	stations[f,g,3]	4,359.00	Mscfy/station[b]	5,898.6
LNG Import Terminals					
LNG Stations	8	stations[f,g,3]	21,507.00	scfd/station[b]	1,164.2
LNG Reciprocating Compressors	37	compressors[f,g,3]	21,116.00	scfd/compressor[b]	5,551.8
LNG Centrifugal Compressors	7	compressors[f,g,3]	30,573.00	scfd/compressor[b]	1,418.5
LNG Compressor Exhaust					
LNG Engines	457	MMHPhr[f,g,3]	0.24	scf/HPhr[b]	2,110.7
LNG Turbines	99	MMHPhr[f,g,3]	0.01	scf/HPhr[b]	10.8
LNG Station Venting	8	stations[f,g,3]	4,359.00	Mscfy/station[b]	646.4
Regulatory Reductions (kt)					-
Voluntary Reductions (kt)					(347.4)
Total Reductions (kt)					**(347.4)**
Total Potential Emissions (kt)					**2,523.8**
Total Net Emissions (kt)					**2,176.4**

[a] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2014)
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2008), Natural Gas Model Activity Factor Basis Change
[d] ICF (2010), Emissions from Centrifugal Compressors

[e] ICF (1997), Additional Changes to Activity Factors for Portions of the Gas Industry
[f] ICF (1996), Estimation of Activity Factors for the Natural Gas Exploration and Production Industry in the U.S.
[g] EIA (2004), U.S. LNG Markets and Uses
[1] Activity data for 2013 available from source.
[2] Ratios relating other factors for which activity data are available.
[3] 2012 activity data are used to determine some or all of the 2013 activity (to be updated).
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.

Table A-138: 2013 Data and CH_4 Emissions (Mg) for the Natural Gas Distribution Stage

	2013 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor (Potential)[aa]**		**Calculated Potential Emissions (Mg)**
Pipeline Leaks					
Mains—Cast Iron	30,904	miles[a,1]	238.70	Mscf/mile-yr[b]	142,076.9
Mains—Unprotected steel	60,633	miles[a,1]	110.19	Mscf/mile-yr[b]	128,678.8
Mains—Protected steel	486,521	miles[a,1]	3.07	Mscf/mile-yr[b]	28,738.1
Mains—Plastic	674,808	miles[a,1]	9.91	Mscf/mile-yr[c]	128,798.3
Services—Unprotected steel	3,668,842	services[a,1]	1.70	Mscf/service[b]	120,179.5
Services Protected steel	14,751,424	services[a,1]	0.18	Mscf/service[b]	50,144.6
Services—Plastic	46,153,036	services[a,1]	0.01	Mscf/service[b]	8,265.2
Services—Copper	973,107	services[a,1]	0.25	Mscf/service[b]	4,766.6
Meter/Regulator (City Gates)					
M&R >300	4,095	stations[d,2]	179.80	scfh/station[b]	124,235.7
M&R 100-300	14,946	stations[d,2]	95.60	scfh/station[b]	241,063.4
M&R <100	7,988	stations[d,2]	4.31	scfh/station[b]	5,809.0
Reg >300	4,478	stations[d,2]	161.90	scfh/station[b]	122,305.5
R-Vault >300	2,630	stations[d,2]	1.30	scfh/station[b]	576.8
Reg 100-300	13,545	stations[d,2]	40.50	scfh/station[b]	92,556.1
R-Vault 100-300	6,086	stations[d,2]	0.18	scfh/station[b]	184.8
Reg 40-100	40,648	stations[d,2]	1.04	scfh/station[b]	7,132.3
R-Vault 40-100	36,046	stations[d,2]	0.09	scfh/station[b]	526.1
Reg <40	17,236	stations[d,2]	0.13	scfh/station[b]	386.8
Customer Meters					
Residential	42,192,085	Outdoor meters[b,2]	143.27	scfy/meter[b]	116,424.6
Commercial/Industry	4,797,283	meters[b,2]	47.90	scfy/meter[b]	4,425.8
Routine Maintenance					
Pressure Relief Valve Releases	1,252,866	milemain[a,1]	0.05	Mscf/mile[b]	1,206.5
Pipeline Blowdown	1,366,993	miles[b,2]	0.10	Mscfy/mile[b]	2,685.5
Upsets					
Mishaps (Dig-ins)	1,366,993	miles[b,2]	1.59	Mscfy/mile[b]	41,862.0
Regulatory Reductions (kt)					-
Voluntary Reductions (kt)					(40.5)
Total Reductions (kt)					**(40.5)**
Total Potential Emissions (kt)					**1,373.0**
Total Net Emissions (kt)					**1,332.5**

[a] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2013)
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2005), Plastic Pipe Emission Factors
[d] ICF (2008), Natural Gas Model Activity Factor Basis Change
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[1] Activity data for 2013 available from source.
[2] Ratios relating other factors for which activity data are available.

Table A-139: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (General Sources)

	U.S. Region						
Year	North East	Midcontinent	Rocky Mountain	South West	West Coast	Gulf Coast	Lower 48 States
1990	84.0%	78.3%	67.4%	64.4%	75.3%	79.8%	n/a
1991	83.8%	78.7%	69.1%	67.1%	78.1%	80.1%	n/a
1992	83.5%	79.1%	71.4%	75.4%	80.8%	82.7%	n/a
1993	82.9%	79.9%	73.4%	76.1%	83.6%	84.1%	n/a
1994	82.0%	80.7%	75.5%	77.4%	86.4%	85.6%	n/a
1995	81.5%	81.6%	77.6%	79.0%	89.1%	87.2%	n/a
1996	81.2%	82.6%	80.5%	80.5%	91.9%	88.7%	84.2%
1997	80.3%	82.5%	80.4%	80.5%	91.9%	88.6%	84.1%
1998	81.0%	82.5%	80.5%	80.5%	91.9%	88.6%	84.2%
1999	80.5%	82.5%	80.4%	80.5%	91.9%	88.7%	84.2%
2000	80.8%	82.5%	80.2%	80.5%	91.9%	88.7%	84.0%
2001	80.3%	82.5%	79.5%	80.5%	91.9%	88.7%	83.8%
2002	80.4%	82.5%	79.3%	80.5%	91.9%	88.6%	83.5%
2003	76.4%	82.6%	79.1%	80.5%	91.9%	88.6%	83.2%
2004	80.4%	82.7%	79.0%	80.5%	91.9%	88.6%	83.4%
2005	80.1%	82.7%	79.0%	80.5%	91.9%	88.6%	83.4%
2006	79.5%	83.0%	78.9%	80.5%	91.9%	88.6%	83.4%
2007	85.8%	82.7%	77.5%	80.5%	91.9%	88.6%	83.9%
2008	86.0%	82.7%	77.7%	80.5%	91.9%	88.5%	83.9%
2009	85.1%	82.7%	77.5%	80.5%	91.9%	88.5%	83.6%
2010	84.3%	82.8%	77.4%	80.5%	91.9%	88.3%	83.4%
2011	85.2%	82.6%	77.5%	80.5%	91.9%	88.2%	83.3%
2012	84.8%	82.5%	78.2%	80.5%	91.9%	88.2%	83.0%
2013	84.2%	82.5%	77.9%	80.5%	91.9%	88.2%	82.9%

Table A-140: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells Without Hydraulic Fracturing)

	U.S. Region						
Year	North East	Midcontinent	Rocky Mountain	South West	West Coast	Gulf Coast	Lower 48 States
1990	84.0%	78.3%	67.0%	64.4%	75.3%	79.8%	n/a
1991	83.8%	78.7%	69.1%	67.1%	78.1%	80.1%	n/a
1992	83.5%	79.1%	71.4%	75.4%	80.8%	82.7%	n/a
1993	82.9%	79.9%	73.4%	76.1%	83.6%	84.1%	n/a
1994	82.0%	80.7%	75.5%	77.4%	86.4%	85.6%	n/a
1995	81.5%	81.6%	77.6%	79.0%	89.1%	87.2%	n/a
1996	81.2%	82.5%	79.6%	80.5%	91.9%	88.6%	84.0%
1997	80.5%	82.5%	79.5%	80.5%	91.9%	88.6%	83.9%
1998	81.2%	82.5%	79.6%	80.5%	91.9%	88.6%	84.0%
1999	80.7%	82.5%	79.5%	80.5%	91.9%	88.7%	83.9%
2000	81.0%	82.5%	79.2%	80.5%	91.9%	88.7%	83.8%
2001	80.4%	82.5%	78.3%	80.5%	91.9%	88.6%	83.5%
2002	80.5%	82.5%	78.1%	80.5%	91.9%	88.6%	83.2%
2003	76.5%	82.6%	77.9%	80.5%	91.9%	88.6%	82.9%
2004	80.5%	82.6%	77.8%	80.5%	91.9%	88.6%	83.1%
2005	80.3%	82.7%	77.7%	80.5%	91.9%	88.6%	83.1%
2006	79.6%	83.0%	77.7%	80.5%	91.9%	88.6%	83.1%
2007	85.6%	82.7%	75.8%	80.5%	91.9%	88.6%	83.5%
2008	85.6%	82.7%	76.0%	80.5%	91.9%	88.5%	83.5%
2009	84.7%	82.7%	75.8%	80.5%	91.9%	88.5%	83.2%
2010	83.8%	82.8%	75.7%	80.5%	91.9%	88.3%	82.9%
2011	85.0%	82.6%	75.8%	80.5%	91.9%	88.2%	82.8%
2012	84.4%	82.5%	76.7%	80.5%	91.9%	88.2%	82.5%
2013	83.7%	82.4%	76.4%	80.5%	91.9%	88.2%	82.4%

Table A-141: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)

	U.S. Region						
Year	North East	Midcontinent	Rocky Mountain	South West	West Coast	Gulf Coast	Lower 48 States
1990	84.0%	78.3%	67.0%	64.4%	75.3%	79.8%	n/a
1991	83.8%	78.7%	69.1%	67.1%	78.1%	80.1%	n/a
1992	83.5%	79.1%	71.4%	75.4%	80.8%	82.7%	n/a

1993	82.9%	79.9%	73.4%	76.1%	83.6%	84.1%	n/a
1994	82.0%	80.7%	75.5%	77.4%	86.4%	85.6%	n/a
1995	81.5%	81.6%	77.6%	79.0%	89.1%	87.2%	n/a
1996	83.2%	92.6%	74.4%	80.5%	91.9%	88.7%	82.1%
1997	83.1%	92.6%	74.9%	80.5%	91.9%	88.6%	82.1%
1998	83.1%	92.6%	75.5%	80.5%	91.9%	88.6%	82.3%
1999	83.1%	92.6%	75.3%	80.5%	91.9%	88.7%	81.9%
2000	83.0%	92.6%	76.4%	80.5%	91.9%	88.7%	82.5%
2001	83.0%	92.6%	78.9%	80.5%	91.9%	88.7%	83.6%
2002	83.0%	92.6%	80.5%	80.5%	91.9%	88.6%	84.4%
2003	83.1%	92.6%	81.4%	80.5%	91.9%	88.6%	84.9%
2004	83.0%	92.6%	81.7%	80.5%	91.9%	88.6%	85.2%
2005	83.0%	92.6%	82.0%	80.5%	91.9%	88.6%	85.3%
2006	83.0%	92.6%	82.6%	80.5%	91.9%	88.6%	85.6%
2007	83.5%	92.6%	86.5%	80.5%	91.9%	88.6%	88.7%
2008	84.1%	92.6%	86.3%	80.5%	91.9%	88.5%	88.4%
2009	84.1%	92.6%	86.8%	80.5%	91.9%	88.5%	88.7%
2010	84.3%	92.6%	86.8%	80.5%	91.9%	88.3%	89.0%
2011	83.6%	92.6%	87.9%	80.5%	91.9%	88.2%	89.4%
2012	84.0%	92.6%	87.6%	80.5%	91.9%	88.2%	89.1%
2013	84.1%	92.6%	87.9%	80.5%	91.9%	88.2%	89.3%

Table A-142: Key Activity Data Drivers

Variable	Units	1990	1995	2000	2005	2011	2012	2013
Transmission Pipelines Length	**miles**	**291,925**	**296,947**	**298,957**	**300,468**	**305,036**	**303,332**	**302,825**
Wells								
NE—Associated Gas Wells[a,1]	# wells	28,574	26,831	27,898	33,088	43,105	45,919	42,454
NE—Non-associated Gas Wells [a,1]	# wells	66,772	92,615	105,734	131,167	161,330	161,408	152,615
MC—Associated Gas Wells [a,1]	# wells	50,506	45,284	44,005	43,628	46,001	48,580	47,930
MC—Non-associated Gas Wells [a,1]	# wells	62,496	67,858	72,575	85,580	102,499	101,228	101,141
RM—Associated Gas Wells [a,1]	# wells	23,417	25,780	25,804	29,435	43,432	47,494	50,533
RM—Non-associated Gas Wells [a,1]	# wells	22,734	26,925	37,281	61,839	79,423	78,920	76,819
SW—Associated Gas Wells [a,1]	# wells	299,608	230,647	213,059	213,341	227,544	235,575	237,237
SW—Non-associated Gas Wells [a,1]	# wells	33,537	33,349	39,089	43,329	49,918	49,303	49,153
WC—Associated Gas Wells [a,1]	# wells	17,535	14,451	16,179	18,998	29,362	29,679	30,507
WC—Non-associated Gas Wells [a,1]	# wells	2,160	1,945	2,021	2,332	2,806	2,802	2,559
GC—Associated Gas Wells [a,1]	# wells	139,642	100,634	73,985	61,780	61,527	65,570	68,362
GC—Non-associated Gas Wells [a,1]	# wells	35,144	35,906	40,205	54,017	71,137	70,786	69,009
Platforms[aa]								
Gulf of Mexico and Pacific OCS Off-shore Platforms [b,2]	# platforms	3,941	3,978	4,016	3,909	3,432	3,432	3,432
GoM and Pacific OCS Deep Water Platforms [b,2]	# platforms	17	23	38	59	70	70	70
Gas Plants[c,1]	**# gas plants**	**761**	**675**	**585**	**566**	**606**	**606**	**650**
Distribution Services	**# of services**	**47,883,083**	**54,644,033**	**56,761,042**	**61,832,574**	**64,771,088**	**65,051,457**	**65,546,409**
Steel—Unprotected [d,1]	# of services	7,633,526	6,151,653	5,675,520	5,507,356	4,142,842	3,916,899	3,668,842
Steel—Protected [d,1]	# of services	19,781,581	21,002,455	17,855,560	16,529,118	15,274,865	14,952,619	14,751,424
Plastic [d,1]	# of services	18,879,865	26,044,545	31,795,871	38,549,089	44,296,786	45,172,684	46,153,036
Copper [d,1]	# of services	1,588,111	1,445,380	1,434,091	1,247,011	1,056,595	1,009,255	973,107
Distribution Mains	**miles**	**944,157**	**1,001,706**	**1,048,485**	**1,162,560**	**1,236,947**	**1,245,316**	**1,252,866**
Cast Iron [d,1]	miles	58,292	50,625	44,750	39,645	33,670	32,406	30,904
Steel—Unprotected [d,1]	miles	108,941	94,058	82,800	72,458	64,980	63,702	60,633
Steel—Protected [d,1]	miles	465,538	503,288	471,510	490,156	488,719	487,484	486,521
Plastic [d,1]	miles	311,386	353,735	449,425	560,301	649,578	661,724	674,808

[a] DI Desktop (2014)

[b] Bureau of Ocean Energy Management, Regulation and Enforcement (2011)

[c] Oil and Gas Journal

[d] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2014)

[1] Activity data for 2013 available from source.

[2] 2012 activity data are used to determine some or all of the 2013 activity (to be updated).

[aa] Number of platforms include both oil and gas platforms

Table A-143: CH_4 Reductions Derived from the Natural Gas STAR Program (kt)

Process	1990	1995	2000	2005	2011	2012	2013
Production	**(6.4)**	**(75.8)**	**(260.6)**	**(512.0)**	**(1,384.3)**	**(1,392.7)**	**(1,422.9)**
Pipeline Leaks	(0.0)	(0.0)	-	(2.4)	-	-	-
Pneumatic Controllers Vents	(2.8)	(15.2)	(76.5)	(159.5)	(588.0)	(627.6)	(620.2)
Chemical Injection Pumps	-	-	-	(0.0)	(2.1)	(2.8)	(3.3)
Gas Engines	(0.0)	(13.8)	(53.2)	(97.9)	(137.2)	(140.0)	(140.5)
Compressor Starts	-	(0.0)	(0.1)	(0.2)	(0.5)	(0.5)	(0.5)
Other Production	(3.5)	(46.8)	(130.9)	(251.9)	(656.5)	(621.8)	(658.5)
Processing	**(1.5)**	**(21.8)**	**(42.8)**	**(155.5)**	**(140.4)**	**(140.4)**	**(140.7)**
Fugitives Reciprocating Compressors	-	-	-	-	-	-	(0.1)
Gas Engines	-	-	(0.1)	(1.1)	(6.1)	(6.1)	(6.1)
AGR Vents	-	-	-	-	-	-	-
Dehydrator Vents	(1.3)	-	(0.2)	(2.1)	(9.3)	(9.3)	(9.3)
Other Processing	(0.2)	(21.8)	(42.6)	(152.2)	(125.0)	(125.0)	(125.2)
Transmission and Storage	**-**	**(107.7)**	**(264.0)**	**(506.8)**	**(355.2)**	**(390.2)**	**(347.4)**
Fugitives Reciprocating Compressors	-	(0.6)	-	(0.2)	(0.2)	(0.7)	(1.0)
Engines	-	(12.5)	(49.3)	(83.2)	(121.7)	(124.0)	(126.9)
Pneumatic Controllers Vents (Transmission)	-	(5.4)	(8.9)	(10.5)	(13.0)	(14.1)	(14.5)
Pipeline Vents	-	(36.3)	(33.3)	(124.9)	(58.9)	(100.1)	(59.4)
Other Transmission	-	(52.8)	(172.5)	(288.1)	(161.3)	(151.2)	(145.5)
Distribution	**-**	**(19.7)**	**(29.9)**	**(48.4)**	**(58.1)**	**(45.2)**	**(40.5)**
Fugitives Cast Iron	-	(0.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mishaps (Dig-ins)	-	-	-	(0.3)	(4.7)	(0.7)	(0.8)
Other Distribution	-	(19.7)	(29.9)	(48.0)	(53.3)	(44.4)	(39.6)
Total	**(7.9)**	**(225.0)**	**(597.4)**	**(1,222.7)**	**(1,937.8)**	**(1,968.5)**	**(1,951.5)**

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. This table presents aggregate Gas STAR reduction data for each natural gas system stage, and also presents reductions for select technologies for which disaggregated Gas STAR data can be matched to an Inventory source category. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). In some cases, emissions reductions reported to Gas STAR have been matched to potential emissions calculated in the Inventory, to provide a net emissions number for specific emissions sources. This table presents sources for which Gas STAR reductions can be matched to Inventory emissions sources. Net emissions values for these sources are presented in Table A-149. Some reported Gas STAR reduction activities are cross-cutting and cover multiple Inventory sources. It is not possible to attribute those reductions to specific Inventory source categories, and they are included in the "Other" category.

Table A-144: CH_4 Reductions Derived from Regulations (kt)

Process	1990	1995	2000	2005	2011	2012	2013
Production	**NA**	**NA**	**(45.9)**	**(62.6)**	**(99.9)**	**(107.7)**	**(120.8)**
Dehydrator vents (NESHAP)	NA	NA	(24.2)	(30.6)	(38.5)	(38.3)	(37.1)
Condensate tanks (NESHAP)	NA	NA	(21.7)	(31.9)	(61.4)	(69.4)	(83.7)
Processing	**(0.0)**	**(0.0)**	**(12.9)**	**(12.1)**	**(15.5)**	**(16.3)**	**(16.5)**
Dehydrator vents (NESHAP)	(0.0)	(0.0)	(12.9)	(12.1)	(15.5)	(16.3)	(16.5)
Transmission and Storage	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Distribution	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Total	**(0.0)**	**(0.0)**	**(58.8)**	**(74.7)**	**(115.4)**	**(124.0)**	**(137.3)**

NA Not applicable
Note: Totals may not sum due to independent rounding.

Table A-145: National CH_4 Potential Emission Estimates from the Natural Gas Production Stage, and Reductions from the Natural Gas STAR Program and Regulations (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Normal Fugitives							
Associated Gas Wells	IE	IE	IE	IE	IE	IE	IE
Non-Associated Gas Wells (less wells with hydraulic fracturing)	13.1	14.6	16.1	17.3	19.0	18.7	18.2
Gas Wells with Hydraulic Fracturing	7.9	11.7	15.7	25.5	35.3	35.2	34.5
Field Separation Equipment							
Heaters	13.2	16.0	19.6	26.6	33.0	32.9	32.1
Separators	43.4	51.9	63.2	84.7	106.1	105.6	103.2
Dehydrators	14.6	17.4	20.3	26.0	32.3	32.0	31.4
Meters/ Piping	50.0	57.4	67.2	87.2	107.6	107.5	105.6
Gathering Compressors							
Small Reciprocating Compressors	34.3	40.1	46.6	58.8	71.8	71.3	69.8
Large Reciprocating Compressors	7.3	9.8	10.0	11.7	14.4	14.5	14.4
Large Reciprocating Stations	0.5	0.7	0.7	0.8	1.0	1.0	1.0
Pipeline Leaks	90.9	107.0	120.7	146.0	174.2	173.3	169.7
Vented and Combusted							
Drilling, Well Completion, and Well Workover							
Gas Well Completions without Hydraulic Fracturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Well Workovers without Hydraulic Fracturing	0.3	0.4	0.4	0.4	0.5	0.5	0.4
Hydraulic Fracturing Completions and Workovers that vent	145.5	130.6	262.2	384.3	170.9	114.5	61.7
Flared Hydraulic Fracturing Completions and Workovers	2.2	1.9	3.9	7.4	6.8	3.4	4.1
Hydraulic Fracturing Completions and Workovers with RECs	0.0	0.0	0.0	7.7	12.6	11.1	10.2
Hydraulic Fracturing Completions and Workovers with RECs that flare	0.0	0.0	0.0	3.9	6.3	9.3	10.3
Well Drilling	0.7	0.5	1.0	1.6	1.0	1.0	1.0
Produced Water from Coal Bed Methane Wells							
Powder River	0.0	1.5	31.4	50.0	47.2	47.0	47.1
Black Warrior	2.7	6.3	6.8	9.9	12.7	12.8	12.7
Normal Operations							
Pneumatic Controllers Vents	539.5	651.2	759.1	966.6	1,193.7	1,185.0	1,159.3
Chemical Injection Pumps	29.4	34.9	41.2	54.1	66.2	65.8	64.5
Kimray Pumps	169.7	208.9	241.6	306.3	385.1	382.6	370.6
Dehydrator Vents	52.9	65.1	75.3	95.5	120.1	119.3	115.6
Condensate Tank Vents							
Condensate Tanks without Control Device	77.7	58.1	67.5	99.3	191.1	215.9	260.6
Condensate Tanks with Control Device	15.5	11.6	13.5	19.9	38.2	43.2	52.1
Compressor Exhaust Vented							
Gas Engines	117.0	137.4	160.9	207.2	255.1	253.2	249.4
Liquids Unloading							
Liquids Unloading (with plunger lifts)	0.0	16.0	36.6	69.7	115.6	114.8	111.6
Liquids Unloading (without plunger lifts)	809.8	814.8	758.1	639.0	152.9	152.2	147.1
Blowdowns							
Vessel Blowdown	0.3	0.4	0.4	0.6	0.7	0.7	0.7
Pipeline Blowdown	1.4	1.7	1.9	2.3	2.8	2.8	2.7
Compressor Blowdown	1.3	1.5	1.8	2.3	2.8	2.8	2.7
Compressor Starts	3.0	3.5	4.0	5.1	6.2	6.2	6.0

Upsets							
Pressure Relief Valves	0.3	0.4	0.4	0.6	0.7	0.7	0.7
Mishaps	0.8	0.9	1.0	1.3	1.5	1.5	1.5
Offshore							
Offshore Water Gas Platforms (Gulf of Mexico & Pacific)	134.8	142.6	150.2	149.3	123.5	123.5	123.5
Deepwater Gas Platforms (Gulf of Mexico & Pacific)	6.2	8.7	15.1	24.1	27.1	27.1	27.1
Regulatory Reductions	**-**	**-**	**(45.9)**	**(62.6)**	**(99.9)**	**(107.7)**	**(120.8)**
Voluntary Reductions	**(6.4)**	**(75.8)**	**(260.6)**	**(512.0)**	**(1,384.3)**	**(1,392.7)**	**(1,422.9)**
Total Reductions	**(6.4)**	**(75.8)**	**(306.5)**	**(574.6)**	**(1,484.2)**	**(1,500.3)**	**(1,543.7)**
Total Potential Emissions	**2,386.3**	**2,625.4**	**3,014.6**	**3,593.0**	**3,535.8**	**3,488.8**	**3,423.1**
Total Net Emissions	**2,379.9**	**2,549.6**	**2,708.1**	**3,018.4**	**2,051.7**	**1,988.5**	**1,879.5**

Note: Totals may not sum due to independent rounding.
IE: Included Elsewhere. These emissions are included in the Petroleum Systems estimates.

Table A-146: Potential CH_4 Emission Estimates from the Natural Gas Processing Plants, and Reductions from the Natural Gas STAR Program and Regulations (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Normal Fugitives							
Plants	42.3	37.5	32.5	31.5	33.7	33.7	36.1
Reciprocating Compressors	324.9	338.4	349.5	327.9	420.9	442.5	447.0
Centrifugal Compressors (wet seals)	240.3	248.6	251.3	229.2	236.1	237.7	238.0
Centrifugal Compressors (dry seals)	-	0.8	3.5	6.5	36.8	43.9	45.4
Vented and Combusted							
Compressor Exhaust							
Gas Engines	137.1	142.8	147.5	138.3	177.6	186.7	188.6
Gas Turbines	3.9	4.0	4.2	3.9	5.0	5.3	5.3
AGR Vents	16.5	14.6	12.7	12.3	13.1	13.1	14.1
Kimray Pumps	3.7	3.8	4.0	3.7	4.8	5.0	5.1
Dehydrator Vents	22.7	23.6	24.4	22.9	29.4	30.9	31.2
Pneumatic Controllers	2.4	2.1	1.9	1.8	1.9	1.9	2.1
Routine Maintenance							
Blowdowns/Venting	59.5	52.8	45.7	44.3	47.4	47.4	50.8
Regulatory Reductions	**-**	**-**	**(12.9)**	**(12.1)**	**(15.5)**	**(16.3)**	**(16.5)**
Voluntary Reductions	**(1.5)**	**(21.8)**	**(42.8)**	**(155.5)**	**(140.4)**	**(140.4)**	**(140.7)**
Total Reductions	**(1.5)**	**(21.8)**	**(55.7)**	**(167.6)**	**(155.9)**	**(156.8)**	**(157.2)**
Total Potential Emissions	**853.2**	**869.2**	**877.1**	**822.2**	**1,006.6**	**1,048.1**	**1,063.6**
Total Net Emissions	**851.8**	**847.3**	**821.3**	**654.6**	**850.7**	**891.4**	**906.4**

Note: Totals may not sum due to independent rounding.

Table A-147: Potential CH_4 Emission Estimates from the Natural Gas Transmission and Storage, and Reductions from the Natural Gas STAR Program and Regulations (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Fugitives							
Pipelines Leaks	3.2	3.2	3.3	3.3	3.3	3.3	3.3
Compressor Stations (Transmission)							
Station	106.9	108.8	109.5	110.1	111.7	111.1	110.9
Recip Compressor	744.7	757.5	762.7	766.5	778.2	773.8	772.5
Centrifugal Compressor (wet seals)	246.7	249.7	243.0	234.1	234.4	232.9	232.5
Centrifugal Compressor (dry seals)	-	0.8	6.2	12.7	15.0	15.0	15.0
Compressor Stations (Storage)							
Station	54.6	60.4	62.2	60.1	58.7	51.6	61.5
Recip Compressor	157.8	174.3	179.6	173.5	169.4	149.2	177.5
Centrifugal Compressor (wet seals)	33.2	36.6	34.4	30.9	26.5	22.3	22.9
Centrifugal Compressor (dry seals)	-	0.1	2.5	4.1	6.5	6.5	10.2
Wells (Storage)	13.6	15.0	15.4	14.9	14.6	12.8	15.3
M&R (Trans. Co. Interconnect)	72.8	74.0	74.5	74.9	76.0	75.6	75.5
M&R (Farm Taps + Direct Sales)	16.9	17.2	17.3	17.4	17.7	17.6	17.5
Vented and Combusted							
Normal Operation							

Dehydrator Vents (Transmission)	2.0	2.0	2.0	2.1	2.1	2.1	2.1
Dehydrator Vents (Storage)	4.2	4.7	4.8	4.6	4.5	4.0	4.8
Compressor Exhaust							
Engines (Transmission)	176.9	204.9	215.3	203.1	225.9	235.6	240.3
Turbines (Transmission)	1.0	1.2	1.2	1.2	1.3	1.3	1.4
Engines (Storage)	21.3	23.5	24.2	23.4	22.9	20.1	24.0
Turbines (Storage)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Generators (Engines)	8.7	10.0	10.5	9.9	11.1	11.5	11.8
Generators (Turbines)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pneumatic Controllers Transmission + Storage							
Pneumatic Controllers Trans	213.1	216.7	218.2	219.3	222.7	221.4	221.0
Pneumatic Controllers Storage	44.4	49.1	50.6	48.8	47.7	42.0	50.0
Routine Maintenance/Upsets							
Pipeline Venting	178.0	181.0	182.2	183.2	185.9	184.9	184.6
Station venting Transmission + Storage							
Station Venting Transmission	145.5	148.0	149.0	149.7	152.0	151.2	150.9
Station Venting Storage	30.3	33.5	34.5	33.4	32.6	28.7	34.1
LNG Storage							
LNG Stations	9.2	9.8	10.3	10.6	10.6	10.6	10.6
LNG Reciprocating Compressors	34.5	36.7	38.8	40.1	40.1	40.1	40.1
LNG Centrifugal Compressors	11.8	12.5	13.3	13.8	13.8	13.8	13.8
LNG Compressor Exhaust							
LNG Engines	2.6	2.6	2.7	2.7	2.7	2.7	2.7
LNG Turbines	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LNG Station Venting	5.1	5.4	5.7	5.9	5.9	5.9	5.9
LNG Import Terminals							
LNG Stations	0.2	0.2	0.2	0.4	1.2	1.2	1.2
LNG Reciprocating Compressors	1.0	1.0	1.0	2.0	5.6	5.6	5.6
LNG Centrifugal Compressors	0.3	0.3	0.3	0.5	1.4	1.4	1.4
LNG Compressor Exhaust							
LNG Engines	1.7	0.5	4.4	12.2	6.9	3.6	2.1
LNG Turbines	0.0	0.0	0.0	0.1	0.0	0.0	0.0
LNG Station Venting	0.1	0.1	0.1	0.2	0.6	0.6	0.6
Regulatory Reductions	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Voluntary Reductions	**-**	**(107.7)**	**(264.0)**	**(506.8)**	**(355.2)**	**(390.2)**	**(347.4)**
Total Reductions	**-**	**(107.7)**	**(264.0)**	**(506.8)**	**(355.2)**	**(390.2)**	**(347.4)**
Total Potential Emissions	**2,342.6**	**2,441.6**	**2,480.4**	**2,470.0**	**2,509.5**	**2,460.4**	**2,523.8**
Total Net Emissions	**2,342.6**	**2,333.9**	**2,216.4**	**1,963.2**	**2,154.4**	**2,070.1**	**2,176.4**

Note: Totals may not sum due to independent rounding.

Table A-148: Potential CH_4 Emission Estimates from the Natural Gas Distribution Stage, and Reductions from the Natural Gas STAR Program, and Regulations (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Pipeline Leaks							
Mains—Cast Iron	268.0	232.7	205.7	182.3	154.8	149.0	142.1
Mains—Unprotected steel	231.2	199.6	175.7	153.8	137.9	135.2	128.7
Mains—Protected steel	27.5	29.7	27.9	29.0	28.9	28.8	28.7
Mains—Plastic	59.4	67.5	85.8	106.9	124.0	126.3	128.8
Services—Unprotected steel	250.0	201.5	185.9	180.4	135.7	128.3	120.2
Services Protected steel	67.2	71.4	60.7	56.2	51.9	50.8	50.1
Services—Plastic	3.4	4.7	5.7	6.9	7.9	8.1	8.3
Services—Copper	7.8	7.1	7.0	6.1	5.2	4.9	4.8
Meter/Regulator (City Gates)							
M&R >300	110.4	122.0	125.6	121.4	118.5	104.3	124.2
M&R 100-300	214.2	236.6	243.8	235.5	230.0	202.4	241.1
M&R <100	5.2	5.7	5.9	5.7	5.5	4.9	5.8

Reg >300	108.7	120.1	123.7	119.5	116.7	102.7	122.3
R-Vault >300	0.5	0.6	0.6	0.6	0.6	0.5	0.6
Reg 100-300	82.3	90.9	93.6	90.4	88.3	77.7	92.6
R-Vault 100-300	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Reg 40-100	6.3	7.0	7.2	7.0	6.8	6.0	7.1
R-Vault 40-100	0.5	0.5	0.5	0.5	0.5	0.4	0.5
Reg <40	0.3	0.4	0.4	0.4	0.4	0.3	0.4
Customer Meters							
Residential	103.5	114.3	117.7	113.7	111.1	97.8	116.4
Commercial/Industry	4.0	4.8	4.7	3.9	4.2	4.2	4.4
Routine Maintenance							
Pressure Relief Valve Releases	0.9	1.0	1.0	1.1	1.2	1.2	1.2
Pipeline Blowdown	2.4	2.6	2.7	2.6	2.6	2.3	2.7
Upsets							
Mishaps (Dig-ins)	37.2	41.1	42.3	40.9	39.9	35.2	41.9
Regulatory Reductions	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Voluntary Reductions	**-**	**(19.7)**	**(29.9)**	**(48.4)**	**(58.1)**	**(45.2)**	**(40.5)**
Total Reductions	**-**	**(19.7)**	**(29.9)**	**(48.4)**	**(58.1)**	**(45.2)**	**(40.5)**
Total Potential Emissions	**1,591.1**	**1,561.9**	**1,524.3**	**1,464.9**	**1,372.7**	**1,271.4**	**1,373.0**
Total Net Emissions	**1,591.1**	**1,542.1**	**1,494.4**	**1,416.5**	**1,314.6**	**1,226.2**	**1,332.5**

Note: Totals may not sum due to independent rounding.

Table A-149: Net Emissions for Select Sources (kt)

Stage/Activity	1990	1995	2000	2005	2011	2012	2013
Production	**2,379.9**	**2,549.6**	**2,708.1**	**3,018.4**	**2,051.7**	**1,988.5**	**1,879.5**
Hydraulic Fracturing Completions Workovers	147.7	132.6	266.1	403.3	196.6	138.3	86.4
Liquids Unloading	809.8	830.8	794.7	708.6	268.5	267.0	258.7
Dehydrator Vents	52.9	65.1	51.2	64.9	81.6	81.0	78.5
Condensate Tanks	93.2	69.7	59.3	87.3	167.9	189.8	229.0
Pipeline Leaks	90.9	107.0	120.7	143.6	174.2	173.3	169.7
Pneumatic Controllers Vents	536.7	636.0	682.6	807.1	605.7	557.4	539.1
Chemical Injection Pumps	29.4	34.9	41.2	54.0	64.1	63.1	61.3
Gas Engines	117.0	123.6	107.7	109.3	117.9	113.3	108.9
Compressor Starts	3.0	3.5	3.9	4.9	5.7	5.7	5.5
Other Production	499.4	546.4	580.7	635.5	369.5	399.8	342.4
Processing	**851.8**	**847.3**	**821.3**	**654.6**	**850.7**	**891.4**	**906.4**
Fugitives Reciprocating Compressors	324.9	338.4	349.5	327.9	420.9	442.5	446.8
Gas Engines	137.1	142.8	147.4	137.2	171.5	180.6	182.5
AGR Vents	16.5	14.6	12.7	12.3	13.1	13.1	14.1
Dehydrator Vents	21.3	23.6	11.3	8.6	4.5	5.2	5.3
Other Processing	351.9	327.9	300.5	168.6	240.8	249.9	257.6
Transmission and Storage	**2,342.6**	**2,333.9**	**2,216.4**	**1,963.2**	**2,154.4**	**2,070.1**	**2,176.4**
Fugitives Reciprocating Compressors	744.7	756.9	762.7	766.3	778.0	773.1	771.5
Engines	176.9	192.4	166.0	119.9	104.2	111.6	113.3
Pneumatic Controllers Vents (Transmission)	213.1	211.4	209.3	208.9	209.7	207.3	206.5
Pipeline Vents	178.0	144.7	149.0	58.3	127.0	84.8	125.2
Other Transmission and Storage	1,030.0	1,028.6	929.4	809.8	935.6	893.4	959.9
Distribution	**1,591.1**	**1,542.1**	**1,494.4**	**1,416.5**	**1,314.6**	**1,226.2**	**1,332.5**
Fugitives Cast Iron	268.0	232.7	205.7	182.2	154.7	148.9	142.0
Mishaps (Dig-ins)	37.2	41.1	42.3	40.6	35.3	34.4	41.0
Other Distribution	1,285.9	1,268.3	1,246.3	1,193.7	1,124.6	1,042.8	1,149.5
Total	**7,165.4**	**7,272.9**	**7,240.1**	**7,052.7**	**6,371.4**	**6,176.3**	**6,294.7**

Note: This table presents net emissions for each natural gas system stage, and also presents net emissions for select emissions sources for which disaggregated Gas STAR data and/or regulation reduction data can be matched to an Inventory source category, and sources for which emissions are calculated using net emission factors. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). In some cases, emissions reductions reported to Gas STAR have been matched to potential emissions calculated in the Inventory, to provide a net emissions number for specific emissions sources. This table presents sources for which Gas STAR reductions and/or regulatory reductions can be matched to Inventory emissions sources. Net emission values presented here were calculated by deducting the voluntary reductions (Table A-143) and the regulatory reductions

(Table A-144) from the potential emissions values in Table A-145 through Table A-148. Some reported Gas STAR reduction activities are cross-cutting and cover multiple Inventory sources. It is not possible to attribute those reductions to specific Inventory source categories, and they are included in the "Other" category.

Table A-150: U.S. Production Sector CO_2 Content in Natural Gas by NEMS Region and Formation Type for all years

	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- 151: CO_2 Emission Estimates from the Natural Gas Production Stage (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Normal Fugitives							
Gas Wells							
Non-Associated Gas Wells	1.4	1.3	1.5	1.6	1.8	1.8	1.8
Gas Wells with Hydraulic Fracturing	0.4	0.6	0.9	1.2	1.5	1.5	1.4
Field Separation Equipment							
Heaters	1.9	2.1	2.7	4.1	5.1	5.1	5.0
Separators	6.1	6.6	8.3	11.9	15.0	14.9	14.6
Dehydrators	1.4	1.6	2.0	2.8	3.5	3.5	3.4
Meters/ Piping	6.8	7.0	8.6	12.0	15.0	15.0	14.7
Gathering Compressors							
Small Reciprocating Compressors	3.1	3.4	4.2	6.0	7.4	7.4	7.2
Large Reciprocating Compressors	0.7	1.0	1.0	1.3	1.6	1.6	1.6
Large Reciprocating Stations	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Pipeline Leaks	10.0	10.9	12.7	16.5	19.9	19.8	19.4
Vented and Combusted							
Drilling, Well Completion, and Well Workover							
Gas Well Completions without Hydraulic Fracturing[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Well Workovers without Hydraulic Fracturing[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Well Completions with Hydraulic Fracturing	73.9	64.7	195.0	314.7	146.7	85.8	70.1
Gas Well Workovers with Hydraulic Fracturing	15.4	21.3	29.2	44.5	44.1	26.1	26.1
Well Drilling	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Produced Water from Coal Bed Methane Wells							
Powder River[1]	NE	NE	NE	NE	NE	NE	NE
Black Warrior[a]	NE	NE	NE	NE	NE	NE	NE
Normal Operations							
Pneumatic Controllers Vents	53.9	61.5	76.1	106.6	133.2	132.3	129.0
Chemical Injection Pumps	2.9	3.3	4.3	6.5	8.2	8.2	8.0
Kimray Pumps	16.8	19.8	23.9	32.5	40.5	40.3	39.0
Dehydrator Vents	5.2	6.2	7.5	10.1	12.6	12.6	12.2
Condensate Tank Vents							
Condensate Tanks without Control Device	10.3	8.8	9.3	10.3	17.2	21.0	25.1
Condensate Tanks with Control Device	2.1	1.8	1.9	2.1	3.4	4.2	5.0
Compressor Exhaust Vented							
Gas Engines[a]	NE	NE	NE	NE	NE	NE	NE
Liquids Unloading							

Liquids Unloading – Vent with plunger Lifts	0.0	1.6	4.0	8.5	14.2	14.1	13.7
Liquids Unloading – Vent without plunger Lifts	236.2	211.9	197.3	170.7	26.6	26.5	25.7
Blowdowns							
Vessel Blowdowns[b]	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Pipeline Blowdowns	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Compressor Blowdowns	0.1	0.1	0.2	0.2	0.3	0.3	0.3
Compressor Starts	0.3	0.3	0.4	0.5	0.6	0.6	0.6
Upsets							
Pressure Relief Valves[b]	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Mishaps	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Flaring Emissions – Onshore Production and Processing	9,092.7	17,167.8	5,525.0	7,193.0	13,084.7	12,401.1	15,171.2
Offshore							
Shallow water Gas Platforms (Gulf of Mexico & Pacific)	2.5	2.7	2.8	2.8	2.3	2.3	2.3
Deepwater Gas Platforms (Gulf of Mexico & Pacific)[b]	0.1	0.1	0.2	0.3	0.3	0.3	0.3
Flaring Emissions – Offshore	230.4	197.2	204.3	180.7	373.7	348.5	348.5
Total	**9,775.1**	**17,804.4**	**6,323.9**	**8,142.1**	**13,980.5**	**13,195.5**	**15,947.0**

[a] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.
[b] 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-152: CO_2 Emission Estimates from the Natural Gas Processing Stage (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Normal Fugitives							
Plants – Before CO_2 removal	2.6	2.3	2.0	1.9	2.0	2.0	2.2
Plants – After CO_2 removal	0.6	0.5	0.4	0.4	0.5	0.5	0.5
Reciprocating Compressors – Before CO_2 removal	19.7	20.5	21.2	19.8	25.5	26.8	27.1
Reciprocating Compressors – After CO_2 removal	4.4	4.5	4.7	4.4	5.7	5.9	6.0
Centrifugal Compressors (wet seals) – Before CO_2 removal	14.5	15.0	15.2	13.9	14.3	14.4	14.4
Centrifugal Compressors (wet seals) – After CO_2 removal	3.2	3.3	3.4	3.1	3.2	3.2	3.2
Centrifugal Compressors (dry seals) – Before CO_2 removal	-	0.0	0.2	0.4	2.2	2.7	2.7
Centrifugal Compressors (dry seals) – After CO_2 removal	-	0.0	0.0	0.1	0.5	0.6	0.6
Vented and Combusted							
Compressor Exhaust							
Gas Engines[a]	NE	NE	NE	NE	NE	NE	NE
Gas Turbines[a]	NE	NE	NE	NE	NE	NE	NE
AGR Vents	27,708.2	24,576.9	23,288.2	21,694.3	21,403.6	21,403.6	21,690.3
Kimray Pumps	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Dehydrator Vents	2.4	2.5	2.6	2.4	3.1	3.3	3.3
Pneumatic Controllers	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Routine Maintenance							
Blowdowns/Venting	6.4	5.6	4.9	4.7	5.1	5.1	5.4
Total	**27,762.6**	**24,632.0**	**23,343.5**	**21,746.1**	**21,466.3**	**21,468.8**	**21,756.6**

[a] 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-153: CO_2 Emission Estimates from the Natural Gas Transmission and Storage Stage (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Fugitives							
Pipelines Leaks	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Compressor Stations (Transmission) Station	3.1	3.1	3.2	3.2	3.2	3.2	3.2

Reciprocating Compressor	21.5	21.9	22.0	22.1	22.4	22.3	22.3
Centrifugal Compressor (wet seals)	7.1	7.2	7.0	6.8	6.8	6.7	6.7
Centrifugal Compressor (dry seals)	-	0.0	0.2	0.4	0.4	0.4	0.4
Compressor Stations (Storage)							
Station	1.6	1.7	1.8	1.7	1.7	1.5	1.8
Reciprocating Compressor	4.6	5.0	5.2	5.0	4.9	4.3	5.1
Centrifugal Compressor (wet seals)	1.0	1.1	1.0	0.9	0.8	0.6	0.7
Centrifugal Compressor (dry seals)	-	0.0	0.1	0.1	0.2	0.2	0.3
Wells (Storage)	0.4	0.4	0.4	0.4	0.4	0.4	0.4
M&R (Trans. Co. Interconnect)	2.1	2.1	2.1	2.2	2.2	2.2	2.2
M&R (Farm Taps + Direct Sales)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Vented and Combusted							
Normal Operation							
Dehydrator Vents (Transmission)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dehydrator Vents (Storage)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Compressor Exhaust							
Engines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE
Turbines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE
Engines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE
Turbines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE
Engines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE
Turbines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE
Generators (Engines)[1]	NE	NE	NE	NE	NE	NE	NE
Generators (Turbines)[1]	NE	NE	NE	NE	NE	NE	NE
Pneumatic Controllers Transmission + Storage							
Pneumatic Controllers Transmission	6.1	6.3	6.3	6.3	6.4	6.4	6.4
Pneumatic Controllers Storage	1.3	1.4	1.5	1.4	1.4	1.2	1.4
Routine Maintenance/Upsets							
Pipeline Venting	5.1	5.2	5.3	5.3	5.4	5.3	5.3
Station Venting Transmission + Storage							
Station Venting Transmission	4.2	4.3	4.3	4.3	4.4	4.4	4.4
Station Venting Storage	0.9	1.0	1.0	1.0	0.9	0.8	1.0
LNG Storage							
LNG Stations	0.3	0.3	0.3	0.4	0.4	0.4	0.4
LNG Reciprocating Compressors	1.2	1.2	1.3	1.3	1.3	1.3	1.3
LNG Centrifugal Compressors	0.4	0.4	0.4	0.5	0.5	0.5	0.5
LNG Compressor Exhaust							
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting	0.2	0.2	0.2	0.2	0.2	0.2	0.2
LNG Import Terminals							
LNG Stations	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LNG Reciprocating Compressors	0.0	0.0	0.0	0.1	0.2	0.2	0.2
LNG Centrifugal Compressors	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LNG Compressor Exhaust							
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting[2]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**61.7**	**63.7**	**64.4**	**64.3**	**64.9**	**63.4**	**65.0**

[a] 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-154: CO_2 Emission Estimates from the Natural Gas Distribution Stage (kt)

Activity	1990	1995	2000	2005	2011	2012	2013
Pipeline Leaks							
Mains—Cast Iron	7.7	6.7	5.9	5.3	4.5	4.3	4.1
Mains—Unprotected steel	6.7	5.8	5.1	4.4	4.0	3.9	3.7

Mains—Protected steel	0.8	0.9	0.8	0.8	0.8	0.8	0.8
Mains—Plastic	1.7	1.9	2.5	3.1	3.6	3.6	3.7
Total Pipeline Miles							
Services—Unprotected steel	7.2	5.8	5.4	5.2	3.9	3.7	3.5
Services Protected steel	1.9	2.1	1.8	1.6	1.5	1.5	1.4
Services—Plastic	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Services—Copper	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Meter/Regulator (City Gates)							
M&R >300	3.2	3.5	3.6	3.5	3.4	3.0	3.6
M&R 100-300	6.2	6.8	7.0	6.8	6.6	5.8	7.0
M&R <100	0.1	0.2	0.2	0.2	0.2	0.1	0.2
Reg >300	3.1	3.5	3.6	3.4	3.4	3.0	3.5
R-Vault >300	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reg 100-300	2.4	2.6	2.7	2.6	2.5	2.2	2.7
R-Vault 100-300	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reg 40-100	0.2	0.2	0.2	0.2	0.2	0.2	0.2
R-Vault 40-100	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reg <40	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Customer Meters							
Residential	3.0	3.3	3.4	3.3	3.2	2.8	3.4
Commercial/Industry	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Routine Maintenance							
Pressure Relief Valve Releases	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pipeline Blowdown	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Upsets							
Mishaps (Dig-ins)	1.1	1.2	1.2	1.2	1.2	1.0	1.2
Total	**45.9**	**45.1**	**44.0**	**42.3**	**39.6**	**36.7**	**39.6**

Note: Totals may not sum due to independent rounding.

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3.7. 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 2014), the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2013, the quantity generated, recovered, and discarded for each resin is shown in Table A-155. The data set for 1990 through 2013 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), Themelis and Shin (in press) and Shin (2014). 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-155: 2013 Plastics in the Municipal Solid Waste Stream by Resin (kt)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	4,101	5,017	789	6,668	6,523	2,032	3,629	**28,758**
Recovery	798	517	0	354	36	18	816	**2,540**
Discard	3,302	4,500	789	6,314	6,486	2,014	2,812	**26,218**
Landfill	3,051	4,158	729	5,834	5,994	1,861	2,599	**24,226**
Combustion	251	342	60	480	493	153	214	**1,993**
Recovery*	19%	10%	0%	5%	1%	1%	23%	**9%**
Discard*	81%	90%	100%	95%	99%	99%	78%	**91%**
Landfill*	74%	83%	92%	87%	92%	92%	72%	**84%**
Combustion*	6%	7%	8%	7%	8%	8%	6%	**7%**

*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-156). 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-156: 2013 Plastics Incinerated (kt), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (kt)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	251	342	60	480	493	153	214	1,993
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%	-
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	-
Carbon in Resin Combusted	154	287	23	403	414	138	138	1,557
Emissions (MMT CO_2 Eq.)	**0.6**	**1.1**	**0.1**	**1.5**	**1.5**	**0.5**	**0.5**	**5.7**

[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. "2013 U.S. Scrap Tire Management Summary" (RMA 2014a) reports that 2,120 thousand of the 3,667 thousand tons of scrap tires generated in 2013 (approximately 58 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.[1] Table A-157 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- 158. The disposal rate of rubber in tires (0.3 MMT C/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-155 (1.3 MMT/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 2014 were taken from RMA 2006, RMA 2009, RMA 2011; RMA 2014a; 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, 2014b).

Table A-157: Elastomers Consumed in 2002 (kt)

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.

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

Table A- 158: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Incineration in 2013

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	1.2
Carbon Black	0.4	98%	100%	1.4
Total	**0.7**	**-**	**-**	**2.6**

- Not applicable

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[2] provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2014) 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 (2014) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009 through 2013. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009 through 2013 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-159.[3] 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-159: Rubber and Leather in Municipal Solid Waste in 2013

Product Type	Incinerated (kt)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (MMT CO_2 Eq.)
Durables (not Tires)	254	70%	85%	98%	0.8
Non-Durables	73	-	-	-	0.2
Clothing and Footwear	56	70%	85%	98%	0.2
Other Non-Durables	17	70%	85%	98%	0.1
Containers and Packaging	2	70%	85%	98%	0.0
Total	**330**	**-**	**-**	**-**	**1.0**

+ Less than 0.05 MMT 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 2014) 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-160). 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), Themelis and Shin (in press), and Shin (2014). 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

[2] Discards = Generation minus recycling.

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

of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 1999 (see Table A-161). The equation relating CO_2 emissions to the amount of textiles combusted is shown below.

$$CO_2 \text{ Emissions from the Incineration of Synthetic Fibers} = \text{Annual Textile Incineration (kt)} \times \text{(Percent of Total Fiber that is Synthetic)} \times \text{(Average C Content of Synthetic Fiber)} \times (44\text{g } CO_2/12 \text{ g C})$$

Table A-160: Synthetic Textiles in MSW (kt)

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	6,305	968	5,337	470
2009	6,424	978	5,446	458
2010	6,508	998	5,510	441
2011	6,513	1,003	5,510	419
2012	7,114	1,117	5,997	456
2013	7,114	1,117	5,997	456

Table A-161: Synthetic Fiber Production in 1999

Fiber	Production (MMT)	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 2014) 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 results of the bi-annual national survey of Municipal Solid Waste (MSW) Generation and Disposition in the U.S., published in *BioCycle* (van Haaren et al. 2010), Themelis and Shin (in press), and Shin (2014). 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 1990 through 2008. Data for 2011 were derived from information forthcoming in Themelis and Shin (in press) and Shin (2014). For waste incineration in the United States, an emission factor of 0.20 kg CH_4/kt 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 for 2012 and 2013, so these values were assumed to be equal to the 2011 value.

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-162).

Table A-162: 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
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	22,714,122[e]
2010	26,544,672	21,741,734[e]
2011	26,544,672	20,756,870
2012	26,544,672	20,756,870[f]
2013	26,544,672[g]	20,756,870[f]

[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
[e] Interpolated between 2011 and 2008 values
[f] Set equal to the 2011 value
[g] Set equal to the 2012 value.

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

Bunker fuel emissions estimates for the Department of Defense (DoD) were developed using data generated by the Defense Logistics Agency Energy (DLA Energy) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2013 fuel sales in the Continental United States (CONUS).[4] The following steps outline the methodology used for estimating emissions from international bunker fuels used by the U.S. Military.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS data set for each year, the first step in quantifying DoD-related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as 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[5] and NATO[6] 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 of 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 Military Service data and expert judgment, a small fraction of the total JP8 use (i.e., between 1.78 and 2.7 times the quantity of diesel fuel used, depending on the Service) was reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. As a result of this reallocation, the JP8 use reported for aviation was reduced and the total fuel use for land-based equipment increased. DoD's total fuel use did not change.

Table A- 163 displays DoD's consumption of transportation fuels, summarized by fuel type, that remain at the completion of Step 1, and 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 omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- **Aviation:** jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).
- **Marine:** naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).

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[4] FAS contains data for 1995 through 2013, but the dataset was not complete for years prior to 1995. Using DLA aviation and marine fuel procurement data, fuel quantities from 1990 to 1994 were estimated based on a back-calculation of the 1995 data in the legacy database, the Defense Fuels Automated Management System (DFAMS). 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.

[5] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2004.

[6] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipments Using Compression Ignition or Turbine Engines, 2012.

Step 4: Omit Fuel Transactions Received by Military Services that are not considered to be International Bunker Fuels

Only Navy and Air Force were deemed to be users of military international bunker fuels after sorting the data by Military Service and applying the following assumptions regarding fuel use by Service.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a bunker fuel.
- Based on previous discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of Army 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 research, Army bunker fuel emissions were assumed to be zero.
- Marine Corps aircraft operating while embarked consumed fuel that was 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

It was necessary to determine what percent of the aviation and marine 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). Methods for quantifying aviation and marine bunker fuel percentages are described below.

- **Aviation:** The Air Force Aviation bunker fuel percentage was determined to be 13.2 percent. 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. 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 was calculated to be 40.4 percent by 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. This Naval Aviation bunker fuel percentage was then multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.

- **Marine:** For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. The Navy maritime bunker fuel percentage was determined to be 79 percent because the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside) in the year 2000.[7]

Table A- 164 and Table A-165 display DoD bunker fuel use totals for the Navy and Air Force.

[7] Note that 79 percent is used because it is based on Navy data, but the percentage of time underway may vary from year-to-year depending on vessel operations. For example, for years prior to 2000, the bunker fuel percentage was 87 percent.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas (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- 164 and Table A-165, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-168, and are based on emissions from fuels tallied in Table A- 164 and Table A-165.

Table A- 163: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Aviation	**4,598.4**	**4,562.8**	**3,734.5**	**3,610.8**	**3,246.2**	**3,099.9**	**2,941.9**	**2,685.6**	**2,741.4**	**2,635.2**	**2,664.4**	**2,900.6**
Total Jet Fuels	4,598.4	4,562.8	3,734.5	3,610.8	3,246.2	3,099.9	2,941.9	2,685.6	2,741.4	2,635.2	2,664.4	2,900.6
JP8	285.7	283.5	234.5	989.4	1,598.1	2,182.8	2,253.1	2,072.0	2,122.5	2,066.5	2,122.7	2,326.2
JP5	1,025.4	1,017.4	832.7	805.1	723.8	691.2	615.8	552.8	515.6	505.5	472.1	503.2
Other Jet Fuels	3,287.3	3,261.9	2,667.3	1,816.3	924.3	225.9	72.9	60.9	103.3	63.3	69.6	71.2
Aviation Gasoline	+	+	+	+	+	+	+	+	+	+	+	+
Marine	**686.8**	**632.6**	**646.2**	**589.4**	**478.6**	**438.9**	**493.3**	**639.8**	**674.2**	**598.9**	**454.4**	**418.4**
Middle Distillate (MGO)	+	+	+	+	+	+	38.5	47.5	51.1	49.2	48.3	33.0
Naval Distillate (F76)	686.8	632.6	646.2	589.4	478.6	438.9	449.0	583.4	608.4	542.9	398.0	369.1
Intermediate Fuel Oil (IFO)[b]	+	+	+	+	+	+	5.9	9.0	14.7	6.7	8.1	16.3
Other[c]	**717.1**	**590.4**	**491.7**	**415.1**	**356.1**	**310.9**	**276.9**	**263.3**	**256.8**	**256.0**	**248.2**	**109.8**
Diesel	93.0	97.9	103.0	108.3	113.9	119.9	126.1	132.6	139.5	146.8	126.6	26.6
Gasoline	624.1	492.5	388.7	306.8	242.1	191.1	150.8	119.0	93.9	74.1	74.8	24.7
Jet Fuel[d]	+	+	+	+	+	+	+	11.7	23.4	35.0	46.7	58.4
Total (Including Bunkers)	**6,002.4**	**5,785.9**	**4,872.3**	**4,615.3**	**4,080.9**	**3,849.8**	**3,712.1**	**3,588.8**	**3,672.4**	**3,490.1**	**3,367.0**	**3,428.8**

Vehicle Type/Fuel	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Aviation	**2,609.8**	**2,615.0**	**2,703.1**	**2,338.1**	**2,092.0**	**2,081.0**	**2,067.8**	**1,814.5**	**1,663.9**	**1,405.0**	**1,449.7**	**1,336.4**
Total Jet Fuels	2,609.6	2,614.9	2,703.1	2,338.0	2,091.9	2,080.9	2,067.7	1,814.3	1,663.7	1,404.8	1,449.5	1,336.2
JP8	2,091.4	2,094.3	2,126.2	1,838.8	1,709.3	1,618.5	1,616.2	1,358.2	1,100.1	882.8	865.2	718.0
JP5	442.2	409.1	433.7	421.6	325.5	376.1	362.2	361.2	399.3	372.3	362.5	316.4
Other Jet Fuels	76.1	111.4	143.2	77.6	57.0	86.3	89.2	94.8	164.3	149.7	221.8	301.7
Aviation Gasoline	0.1	0.1	+	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.2
Marine	**455.8**	**609.1**	**704.5**	**604.9**	**531.6**	**572.8**	**563.4**	**485.8**	**578.8**	**489.9**	**490.4**	**390.4**
Middle Distillate (MGO)	41.2	88.1	71.2	54.0	45.8	45.7	55.2	56.8	48.4	37.3	52.9	40.9
Naval Distillate (F76)	395.1	460.9	583.5	525.9	453.6	516.0	483.4	399.0	513.7	440.0	428.4	345.7
Intermediate Fuel Oil (IFO)[b]	19.5	60.2	49.9	25.0	32.2	11.1	24.9	30.0	16.7	12.5	9.1	3.8
Other[c]	**211.1**	**221.2**	**170.9**	**205.6**	**107.3**	**169.0**	**173.6**	**206.8**	**224.0**	**208.6**	**193.8**	**180.6**
Diesel	57.7	60.8	46.4	56.8	30.6	47.3	49.1	58.3	64.1	60.9	57.9	54.9
Gasoline	27.5	26.5	19.4	24.3	11.7	19.2	19.7	25.2	25.5	22.0	19.6	16.9
Jet Fuel[d]	125.9	133.9	105.1	124.4	65.0	102.6	104.8	123.3	134.4	125.6	116.2	108.8
Total (Including Bunkers)	**3,276.7**	**3,445.3**	**3,578.5**	**3,148.6**	**2,730.9**	**2,822.8**	**2,804.9**	**2,507.1**	**2,466.7**	**2,103.5**	**2,133.9**	**1,907.5**

[a] Includes fuel distributed 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. Datasets 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. Since 2001, other gasoline and diesel fuel totals were generated by DLA Energy.
[d] The fraction of jet fuel consumed in land-based vehicles was estimated based on DLA Energy data as well as Military Service and expert judgment.
Note: Totals may not sum due to independent rounding.

+ indicates value does not exceed 0.05 million gallons.

Table A- 164: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Jet Fuels												
JP8	**56.7**	**56.3**	**46.4**	**145.3**	**224.0**	**300.4**	**308.8**	**292.0**	**306.4**	**301.4**	**307.6**	**341.2**
Navy	56.7	56.3	46.1	44.6	40.1	38.3	39.8	46.9	53.8	55.5	53.4	73.8
Air Force	+	+	0.3	100.8	183.9	262.2	269.0	245.1	252.6	245.9	254.2	267.4
JP5	**370.5**	**367.7**	**300.9**	**291.0**	**261.6**	**249.8**	**219.4**	**194.2**	**184.4**	**175.4**	**160.3**	**169.7**
Navy	365.3	362.5	296.7	286.8	257.9	246.3	216.1	191.2	181.4	170.6	155.6	163.7
Air Force	5.3	5.2	4.3	4.1	3.7	3.5	3.3	3.0	3.0	4.8	4.7	6.1
JP4	**420.8**	**417.5**	**341.4**	**229.6**	**113.1**	**21.5**	**1.1**	**0.1**	**+**	**+**	**+**	**+**
Navy	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	420.8	417.5	341.4	229.6	113.1	21.5	1.1	0.1	+	+	+	+
JAA	**13.7**	**13.6**	**11.1**	**10.8**	**9.7**	**9.2**	**10.3**	**9.4**	**10.8**	**10.8**	**12.5**	**12.6**
Navy	8.5	8.4	6.9	6.6	6.0	5.7	6.6	5.9	6.6	6.3	7.9	8.0
Air Force	5.3	5.2	4.3	4.1	3.7	3.5	3.7	3.5	4.2	4.5	4.5	4.6
JA1	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**0.1**
Navy	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	+	+	+	0.1
JAB	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air Force	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Navy Subtotal	**430.5**	**427.2**	**349.6**	**338.1**	**303.9**	**290.2**	**262.5**	**244.0**	**241.8**	**232.4**	**216.9**	**245.5**
Air Force Subtotal	**431.3**	**427.9**	**350.2**	**338.6**	**304.4**	**290.7**	**277.0**	**251.7**	**259.9**	**255.2**	**263.5**	**278.1**
Total	**861.8**	**855.1**	**699.9**	**676.7**	**608.4**	**580.9**	**539.5**	**495.6**	**501.7**	**487.5**	**480.4**	**523.6**

Fuel Type/Service	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Jet Fuels												
JP8	**309.5**	**305.1**	**309.8**	**285.6**	**262.5**	**249.1**	**229.4**	**211.4**	**182.5**	**143.4**	**141.2**	**122.0**
Navy	86.6	76.3	79.2	70.9	64.7	62.7	59.2	55.4	60.8	47.1	50.4	48.9
Air Force	222.9	228.7	230.6	214.7	197.8	186.5	170.3	156.0	121.7	96.2	90.8	73.0
JP5	**158.3**	**146.1**	**157.9**	**160.6**	**125.0**	**144.5**	**139.2**	**137.0**	**152.5**	**144.9**	**141.2**	**124.9**
Navy	153.0	141.3	153.8	156.9	122.8	141.8	136.5	133.5	149.7	143.0	139.5	123.6
Air Force	5.3	4.9	4.1	3.7	2.3	2.7	2.6	3.5	2.8	1.8	1.7	1.3
JP4	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**0.1**	**0.0**	**0.0**	**+**
Navy	+	+	+	+	+	+	+	+	+	0.0	0.0	+
Air Force	+	+	+	+	+	+	+	+	0.1	0.0	0.0	+
JAA	**13.7**	**21.7**	**30.0**	**15.5**	**11.7**	**15.6**	**16.8**	**18.1**	**31.4**	**31.1**	**38.6**	**46.5**
Navy	9.8	15.5	21.5	11.6	9.1	11.7	12.5	12.3	13.7	14.6	14.8	13.4
Air Force	3.8	6.2	8.6	3.9	2.6	3.9	4.3	5.9	17.7	16.5	23.8	33.1

JA1	**0.6**	**0.2**	**0.5**	**0.5**	**0.4**	**1.1**	**1.0**	**0.6**	**0.3**	**(-+)**	**(-+)**	**0.6**
Navy	+	+	+	+	+	0.1	0.1	0.1	0.1	(-+)	(-+)	0.6
Air Force	0.6	0.2	0.5	0.5	0.4	1.0	0.8	0.5	0.1	(-+)	(-+)	+
JAB	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air Force	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Navy Subtotal	**249.4**	**233.1**	**254.4**	**239.4**	**196.6**	**216.3**	**208.3**	**201.3**	**224.4**	**204.3**	**204.5**	**186.5**
Air Force Subtotal	**232.7**	**239.9**	**243.7**	**222.9**	**203.1**	**194.0**	**178.1**	**165.9**	**142.4**	**114.5**	**116.3**	**107.4**
Total	**482.1**	**473.0**	**498.1**	**462.3**	**399.7**	**410.3**	**386.3**	**367.2**	**366.7**	**318.8**	**320.8**	**293.9**

The negative values in this table represent returned products.
Note: Totals may not sum due to independent rounding.
+ indicates value does not exceed 0.05 million gallons.

Table A-165: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Navy – MGO	0.0	0.0	0.0	0.0	0.0	0.0	30.3	35.6	31.9	39.7	23.8	22.5
Navy – F76	522.4	481.2	491.5	448.3	364.0	333.8	331.9	441.7	474.2	466.0	298.6	282.6
Navy – IFO	0.0	0.0	0.0	0.0	0.0	0.0	4.6	7.1	11.6	5.3	6.4	12.9
Total	**522.4**	**481.2**	**491.5**	**448.3**	**364.0**	**333.8**	**366.8**	**484.3**	**517.7**	**511.0**	**328.8**	**318.0**

Marine Distillates	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Navy – MGO	27.1	63.7	56.2	38.0	33.0	31.6	40.9	39.9	32.9	25.5	36.5	32.3
Navy – F76	305.6	347.8	434.4	413.1	355.9	404.1	376.9	311.4	402.2	346.6	337.9	273.1
Navy – IFO	15.4	47.5	39.4	19.7	25.4	8.8	19.0	23.1	12.9	9.5	6.1	3.0
Total	**348.2**	**459.0**	**530.0**	**470.7**	**414.3**	**444.4**	**436.7**	**374.4**	**448.0**	**381.5**	**380.6**	**308.5**

Note: Totals may not sum due to independent rounding.
+ indicates value does not exceed 0.05 million gallons.

Table A-166: Aviation and Marine Carbon Contents (MMT 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-167: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
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	19.70	19.70	19.70

Source: EPA (2010)

Table A-168: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Aviation	8.1	5.5	5.2	4.8	4.9	4.7	4.7	5.1	4.7	4.6	4.8	4.5	3.9	4.0	3.8	3.6	3.6	3.1	3.1	2.9
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	3.8	4.6	3.9	3.9	3.2
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**	**8.1**	**8.5**	**8.2**	**7.4**	**8.2**	**7.0**	**7.0**	**6.0**

Note: Totals may not sum due to independent rounding.

3.9. 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: refrigeration and air-conditioning, 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- 169, 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- 169: 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%

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment	Tertiary Substitute: Maximum Market Penetration	Growth Rate
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	25%	None								0.8%
	R-404A	1993	1995	75%									
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%	HFO-1234yf	2012	2015	1%	None				0.5%
					HFO-1234yf	2016	2021	99%	None				
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	HFO-1234yf	2012	2015	1%	None				1.2%
					HFO-1234yf	2016	2021	99%	None				
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								

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	
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				
									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; Technology Transition)													
DX[1]	DX	2000	2010	85%	DX	2010	2010	66%	None				0.8%
					DR[2]	2010	2010	30%	None				
					SLS[3]	2010	2010	4%	None				
	DR	2000	2010	13.5%	None								
	SLS	2000	2010	1.5%	None								
Retail Food (Large; Refrigerant Transition)													
CFC-12 and R-502[4]	R-404A	1995	2000	17.5%	R-404A	2000	2009	17.9%	None				0.8%
					R-507	2000	2009	1.7%	None				
					R-407A	2000	2009	0.4%	None				
	R-507	1995	2000	7.5%	R-404A	2000	2009	17.9%	None				
					R-507	2000	2009	1.7%	None				
					R-407A	2000	2009	0.4%	None				
	HCFC-22	1995	2000	75%	R-404A	2001	2010	17.9%	None				
					R-507	2001	2010	1.7%	None				
					R-407A	2001	2010	0.4%	None				
					R-404A	2009	2010	68%	R-404A	2010	2010	35.8%	
									R-507	2010	2010	3.6%	
									R-407A	2010	2010	0.7%	
					R-507	2009	2010	8.0%	R-404A	2010	2010	35.8%	

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-507	2010	2010	3.6%	
									R-407A	2010	2010	0.7%	
					R-407A	2009	2010	4.0%	R-404A	2010	2010	35.8%	
									R-507	2010	2010	3.6%	
									R-407A	2010	2010	0.7%	
Retail Food (Large Condensing Units)													
HCFC-22	R-402A	1995	2005	5%	R-404A	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-401A	1995	2005	6%	HFC-134a	2006	2006	100%	None				0.9%
	R-402A	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	91%	HFC-134a	1993	1995	91%	CO_2	2012	2015	1%	1.3%
									Non-ODP/GWP	2012	2015	3.7%	
									CO_2	2016	2016	11%	
									Non-ODP/GWP	2016	2016	17.3%	
					HFC-134a	2000	2009	9%					
	R-404A	1990	1993	9%	Non-ODP/GWP	2016	2016	30%					
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				
	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				

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	
Window Units													
HCFC-22	R-410A R-410A	2008 2009	2009 2010	10% 90%	None None								4.0%

[1] DX refers to direct expansion systems where the compressors are mounted together in a rack and share suction and discharge refrigeration lines that run throughout the store, feeding refrigerant to the display cases in the sales area.

[2] DR refers to distributed refrigeration systems that consist of multiple smaller units that are located close to the display cases that they serve such as on the roof above the cases, behind a nearby wall, or on top of or next to the case in the sales area.

[3] SLS refers to secondary loop systems wherein a secondary fluid such as glycol or carbon dioxide is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment.

[4] The CFC-12 large retail food market for new systems transitioned to R-502 from 1998 to 1990, and subsequently transitioned to HCFC-22 from 1990 to 1993. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

[5] HCFC-22 for new equipment after 2010 is assumed to be reclaimed material.

Table A- 170 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- 170: 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	8	3.0
Industrial Process Refrigeration	25	3.6 – 12.3
Mobile Air Conditioners	5 –16	2.3 – 18.0
Positive Displacement Chillers	20	0.5 – 1.5
PTAC/PTHP	12	3.9
Retail Food	10 – 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- 171.

Table A- 171: 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- 172.

Table A- 172: 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-43-10mee	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-43-10mee	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.

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

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- 173.

Table A- 173: 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	1995	0.1%					
	Halotron	1996	2000	5.4%	Non-ODP/GWP	2020	2020	56%	
	Non-ODP/GWP	1993	1994	56%	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.

$$Ep_j = lp \times \sum Qc_{j-m} \quad for\ m=k \rightarrow k+26$$

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- 174. The emission profiles of these 13 foam types are shown in Table A- 175.

Table A- 174: Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
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- 175: 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- 175

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Table A- 176. 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 million metric tons of CO_2 equivalents (MMT CO_2 Eq.). The conversion of metric tons of chemical to MMT 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- 177 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990-2013.

Table A- 177. Banks of ODS and ODS Substitutes, 1990-2013 (MT)

Year	CFC	HCFC	HFC
1990	708,618	283,317	872
1995	803,500	497,691	53,826
2000	670,184	923,318	197,846
2001	641,382	992,259	227,645
2002	616,613	1,045,111	257,403
2003	592,032	1,081,443	292,906
2004	566,997	1,118,711	329,927
2005	543,843	1,160,743	367,947
2006	520,570	1,199,456	411,176
2007	500,341	1,229,811	454,821
2008	485,402	1,249,466	494,914
2009	478,479	1,244,055	540,688
2010	464,946	1,208,739	606,692
2011	451,334	1,163,938	671,994
2012	437,294	1,118,609	744,542
2013	423,535	1,069,144	819,195

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.

3.10. 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 equines (mules and asses). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, a 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, and mules and asses.

Estimate Methane Emissions from Cattle

This section describes the process used to estimate CH_4 emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM). The CEFM was developed based on recommendations provided in and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). IPCC (2006), and uses information on population, energy requirements, digestible energy, and CH_4 conversion rates to estimate CH_4 emissions.[1] 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 are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2014). A summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-178. Cattle populations used in the Enteric Fermentation source category 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-178: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2013 (1,000 head)

Livestock Type	1990	1995	2000	2005	2009	2010	2011	2012	2013
Dairy									
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,791	4,666	4,706	4,772	4,743
Dairy Cows	10,015	9,482	9,183	9,004	9,333	9,086	9,150	9,230	9,218
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,327	1,347	1,362	1,350	1,338
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,101	3,179	3,210	3,236	3,184
Beef									
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	16,051	16,043	15,795	15,186	14,961
Bulls	2,160	2,385	2,293	2,214	2,184	2,190	2,155	2,096	2,056
Beef Cows	32,455	35,190	33,575	32,674	31,712	31,371	30,850	30,158	29,297
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,290	1,239	1,230	1,253	1,276
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	3,098	3,055	2,890	2,957	3,009
Steer Stockers	10,321	11,716	8,724	8,185	8,515	8,223	7,628	7,234	7,517
Heifer Stockers	5,946	6,699	5,371	5,015	5,059	5,054	4,759	4,483	4,503
Feedlot Cattle	9,549	11,064	13,006	12,652	12,953	13,191	13,546	13,172	13,086

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.[2] 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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[1] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

[2] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2014).

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, stockers, 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., calves are usually weaned between 4 and 6 months of age), each is modeled on a per-month basis. The type of cattle also influences 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. The transition matrix estimates total monthly populations for all cattle subtypes. These populations are then reallocated to the state level based on the percent of the cattle type reported in each state in the January 1 USDA data. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-179.

Table A-179: 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 & Steer)
	Cows
	Bulls[a]

[a] 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. Although enteric emissions are only calculated for 4- to 6-month old calves, it is necessary to calculate populations from birth as emissions from manure management require total calf populations and the estimates of populations for older cattle rely on the available supply of calves from birth. 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 per month. Annual birth information for each year was taken from USDA (2014). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month) while beef births are distributed according to Table A-180, based on approximations 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 6 months of age). An example of a transition matrix for calves is shown in Table A-181. Note that 1- to 6-month old calves in January of each year have been tracked through the model based on births and death loss from the previous year.

Table A-180: 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-181: 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	1,187	1,178	1,381	1,621	1,561	1,547	2,391	4,476	7,771	6,291	2,934	1,459
5	1,179	1,382	1,622	1,561	1,547	2,392	4,478	7,774	6,294	2,935	1,460	1,089
4	1,450	1,683	1,620	1,603	2,451	4,535	7,843	6,368	3,000	1,533	1,159	1,150

3	1,684	1,622	1,604	2,452	4,536	7,846	6,371	3,001	1,533	1,160	1,151	1,411
2	1,623	1,605	2,453	4,538	7,849	6,373	3,002	1,534	1,160	1,152	1,412	1,637
1	1,607	2,454	4,540	7,852	6,375	3,003	1,534	1,161	1,152	1,413	1,638	1,577
0	2,457	4,543	7,856	6,378	3,004	1,535	1,161	1,152	1,413	1,639	1,579	1,561

Note: The cohort starting at age 0 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss, and between months 4 and 5, a more significant loss is seen than in other months due to estimated veal slaughter.

Replacements and Stockers. At 7 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. Based on the USDA estimates for "replacement beef heifers" and "replacement dairy heifers," the transition matrix for the replacements is back-calculated from the known animal totals from USDA, and the number of calves needed to fill that requirement for each month is subtracted from the known supply of female calves. All female calves remaining after those needed for beef and dairy replacements are removed and become "stockers" that can be placed in feedlots (along with all male calves). During the stocker phase animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2014).

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 (added in month 7, bottom row of Table A-182) 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-182.

Table A-182: 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	177	187	106	36	15	9	7	7	5	2	0	0
22	306	152	50	19	11	9	9	8	5	2	3	188
21	248	71	26	14	11	11	11	8	5	54	195	326
20	117	37	19	14	14	13	10	8	110	305	339	264
19	60	28	19	17	16	13	10	177	424	562	276	125
18	45	27	23	20	15	12	222	569	804	465	130	64
17	45	34	27	19	15	272	666	1,096	671	216	78	48
16	55	39	26	19	334	774	1,294	920	309	304	48	48
15	64	38	26	413	907	1,513	1,088	422	550	48	48	59
14	61	37	568	1,078	1,782	1,275	499	847	48	48	59	68
13	61	813	1,396	2,125	1,506	585	1,118	48	48	59	68	65
12	946	1,543	2,412	1,707	707	1,540	226	48	59	68	65	65
11	1,750	2,665	1,938	802	1,930	297	148	79	88	84	86	1,014
10	3,026	2,158	903	2,306	419	210	188	236	205	207	1,153	2,368
9	2,456	1,023	2,601	521	387	384	421	417	385	1,308	2,856	5,180
8	1,157	3,091	704	534	647	787	710	737	1,509	3,326	6,107	4,910
7	3,520	853	846	1,018	1,232	1,179	1,168	1,920	3,764	6,676	5,368	2,401

Note: The cohort starting at age 7 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss and loss due to placement in feedlots (the latter resulting in the majority of the loss from the matrix).

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 (2014). 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 pounds. 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.[3] 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 pounds for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010).[4] Dairy replacement weight at 15 months was assumed to be 875 pounds and 1,300 pounds at 24 months. Live slaughter weights were estimated from dressed slaughter weight (USDA 2014) 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-183.

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. Interim years were calculated linearly, as shown in Table A-184, and weight gain was held constant starting in 2000. Table A-184 provides weight gains that vary by year in the CEFM.

Table A-183: Typical Animal Mass (lbs)

Year/Cattle Type	Calves	Dairy Cows[a]	Dairy Replacements[b]	Beef Cows[a]	Bulls[a]	Beef Replacements[b]	Steer Stockers[b]	Heifer Stockers[b]	Steer Feedlot[b]	Heifer Feedlot[b]
1990	269	1,500	900	1,221	1,832	820	692	652	923	846
1991	270	1,500	898	1,225	1,838	822	695	656	934	856
1992	269	1,500	897	1,263	1,895	841	714	673	984	878
1993	270	1,500	899	1,280	1,920	852	721	683	930	864
1994	270	1,500	898	1,280	1,920	854	721	689	944	876
1995	270	1,500	898	1,282	1,923	858	735	701	947	880
1996	269	1,500	898	1,285	1,928	859	739	707	940	878
1997	270	1,500	900	1,286	1,929	861	737	708	939	877
1998	270	1,500	897	1,296	1,944	866	736	710	957	892
1999	270	1,500	899	1,292	1,938	862	731	709	960	895
2000	270	1,500	897	1,272	1,908	849	720	702	961	899
2001	270	1,500	898	1,272	1,908	850	726	707	963	901
2002	270	1,500	897	1,276	1,914	852	726	708	982	915
2003	270	1,500	900	1,308	1,962	872	719	702	973	905
2004	270	1,500	897	1,323	1,985	878	719	702	967	905
2005	270	1,500	895	1,327	1,991	880	718	706	975	917
2006	270	1,500	898	1,341	2,012	890	725	713	984	925
2007	270	1,500	897	1,348	2,022	895	721	707	992	928
2008	270	1,500	898	1,348	2,022	895	721	705	1,000	939
2009	270	1,500	897	1,348	2,022	894	731	715	1,007	948
2010	270	1,500	898	1,348	2,022	897	727	714	997	937
2011	270	1,500	897	1,348	2,022	892	723	714	991	933
2012	270	1,500	899	1,348	2,022	893	715	708	1,005	947
2013	270	1,500	899	1,348	2,022	893	721	711	1,017	959

[a] Input into the model.

[b] Annual average calculated in model based on age distribution.

[3] Mature beef weight is held constant after 2007 but future inventory submissions will incorporate known trends through 2007 and extrapolate to future years, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

[4] Mature dairy weight is based solely on Holstein weight, so could be higher than the national average. Future Inventory submissions will consider other dairy breeds, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

Table A-184: 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 (e.g., more grain than forage, along with new dietary supplements), during this time weight gain is estimated to be 2.7 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet (concentrated, high energy) for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 2.9 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-185) 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-185 provides a summary of the reported feedlot placement statistics for 2013.

Table A-185: Feedlot Placements in the United States for 2013 (Number of animals placed/1,000 Head)

Weight Placed	When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs		460	400	380	445	415	460	620	715	685	840	750	550
600 – 700 lbs		475	365	360	310	355	380	400	365	415	590	500	385
700 – 800 lbs		544	492	589	485	480	420	495	476	504	487	377	360
> 800 lbs		410	410	585	545	560	435	620	690	865	575	410	378
Total		**1,889**	**1,667**	**1,914**	**1,785**	**1,810**	**1,695**	**2,135**	**2,246**	**2,469**	**2,492**	**2,037**	**1,673**

Source: USDA (2014).
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 pounds per animal per month. The monthly estimates for daily milk production by beef cows are shown in Table A-186. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2013 are shown in Table A-187. 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-186: Estimates of Monthly Milk Production by Beef Cows (lbs/cow)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beef Cow Milk Production (lbs/ head)	3.3	5.1	8.7	12.0	13.6	13.3	11.7	9.3	6.9	4.4	3.0	2.8

Table A-187: Dairy Lactation Rates by State (lbs/ year/cow)

State/Year	1990	1995	2000	2005	2009	2010	2011	2012	2013
Alabama	12,214	14,176	13,920	14,000	14,909	14,455	13,182	13,200	13,333
Alaska	13,300	17,000	14,500	12,273	10,000	11,833	13,800	14,250	10,667
Arizona	17,500	19,735	21,820	22,679	23,028	23,441	23,468	23,979	23,626
Arkansas	11,841	12,150	12,436	13,545	12,692	12,750	11,833	13,300	11,667
California	18,456	19,573	21,130	21,404	22,000	23,025	23,438	23,457	23,178
Colorado	17,182	18,687	21,618	22,577	23,081	23,664	23,430	23,978	24,248
Connecticut	15,606	16,438	17,778	19,200	18,579	19,158	19,000	19,889	20,611
Delaware	13,667	14,500	14,747	16,622	17,000	16,981	18,300	19,143	19,521
Florida	14,033	14,698	15,688	16,591	18,070	18,658	19,067	19,024	19,374
Georgia	12,973	15,550	16,284	17,259	18,182	17,671	18,354	19,125	19,500
Hawaii	13,604	13,654	14,358	12,889	14,200	13,316	14,421	14,200	13,409
Idaho	16,475	18,147	20,816	22,332	22,091	22,658	22,934	23,376	23,440
Illinois	14,707	15,887	17,450	18,827	18,873	19,170	19,357	19,541	19,371
Indiana	14,590	15,375	16,568	20,295	20,137	20,094	20,657	21,406	21,761
Iowa	15,118	16,124	18,298	20,641	20,367	20,724	21,309	22,010	22,144
Kansas	12,576	14,390	16,923	20,505	21,085	20,975	21,016	21,683	21,881
Kentucky	10,947	12,469	12,841	12,896	14,190	14,769	14,342	15,135	15,155
Louisiana	11,605	11,908	12,034	12,400	11,870	11,750	12,889	13,059	12,875
Maine	14,619	16,025	17,128	18,030	18,061	18,344	18,688	18,576	19,548
Maryland	13,461	14,725	16,083	16,099	18,255	18,537	18,654	19,196	19,440
Massachusetts	14,871	16,000	17,091	17,059	17,571	17,286	16,923	18,250	17,692
Michigan	15,394	17,071	19,017	21,635	22,445	23,277	23,164	23,976	24,116
Minnesota	14,127	15,894	17,777	18,091	19,230	19,366	18,996	19,512	19,698
Mississippi	12,081	12,909	15,028	15,280	13,889	13,118	14,571	14,214	13,214
Missouri	13,632	14,158	14,662	16,026	14,654	14,596	14,611	14,957	14,663
Montana	13,542	15,000	17,789	19,579	19,933	20,643	20,571	21,357	21,286
Nebraska	13,866	14,797	16,513	17,950	19,672	19,797	20,579	21,179	21,574
Nevada	16,400	18,128	19,000	21,680	21,821	23,500	23,138	22,966	22,207
New Hampshire	15,100	16,300	17,333	18,875	19,533	19,600	20,429	19,643	20,846
New Jersey	13,538	13,913	15,250	16,000	17,889	17,500	16,875	18,571	18,143
New Mexico	18,815	18,969	20,944	21,192	24,320	24,551	24,854	24,694	24,944
New York	14,658	16,501	17,378	18,639	20,071	20,807	21,046	21,623	22,080
North Carolina	15,220	16,314	16,746	18,741	19,644	19,636	20,089	20,435	20,326
North Dakota	12,624	13,094	14,292	14,182	16,739	18,286	18,158	19,278	19,000
Ohio	13,767	15,917	17,027	17,567	18,744	19,446	19,194	19,833	20,178
Oklahoma	12,327	13,611	14,440	16,480	16,983	17,125	17,415	17,688	17,556
Oregon	16,273	17,289	18,222	18,876	19,719	20,331	20,488	20,431	20,439
Pennsylvania	14,726	16,492	18,081	18,722	19,360	19,847	19,495	19,549	19,822
Rhode Island	14,250	14,773	15,667	17,000	17,818	17,727	17,909	18,300	19,000
South Carolina	12,771	14,481	16,087	16,000	19,000	17,875	17,438	17,250	16,500
South Dakota	12,257	13,398	15,516	17,741	20,128	20,478	20,582	21,391	21,521
Tennessee	11,825	13,740	14,789	15,743	16,232	16,346	16,200	16,100	15,979
Texas	14,350	15,244	16,503	19,646	20,898	21,375	22,232	22,009	21,984
Utah	15,838	16,739	17,573	18,875	21,036	21,400	21,068	22,341	22,130
Vermont	14,528	16,210	17,199	18,469	18,289	18,537	18,940	19,316	19,448
Virginia	14,213	15,116	15,833	16,990	18,083	18,095	17,906	17,990	18,337
Washington	18,532	20,091	22,644	23,270	23,171	23,510	23,727	23,794	23,820
West Virginia	11,250	12,667	15,588	14,923	14,727	15,700	15,600	15,800	15,200
Wisconsin	13,973	15,397	17,306	18,500	20,079	20,630	20,599	21,436	21,693
Wyoming	12,337	13,197	13,571	14,878	19,036	20,067	20,517	20,650	21,367

Source: USDA (2014).

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 USDA, 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-188. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007–2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in and Table A-189. 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-188: Regions used for Characterizing the Diets of 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-189: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2013

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:APHIS:VS (2010).
Note: States in **bold** represent a change in region from the 1990–2006 assessment.

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0$\pm$1.0 percent for feedlot cattle and 6.5$\pm$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, DE and Y_m values unique to the United States were developed for dairy and beef 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), which represents physiological processes in the ruminant animals, as well as diet characteristics from USDA (1996). The Donovan and Baldwin model is able to account 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—the review indicated highly variable diets, both temporally and spatially. 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. The statistical analysis of the COWPOLL model showed a trend in predicting Ym, and inventory team experts determined that the most comprehensive approach was to use the 1990 baseline from Donovan and Baldwin and then scale Y_m values for each of the diets beyond 1990 with the COWPOLL model.

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 (incorporating both Donovan and Baldwin (1999) and COWPOLL) 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, 1999–2003, 2004–2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers and dairy calves. Therefore, for dairy heifers assumptions were based on the relationship of the collected data in the 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 an estimated 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the United States. 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 "West" region of the United States versus all other regions in Table A-188 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-189 (Central, Northeast, and Southeast). 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 64.2 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 61.3 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-190. In addition, beef cattle are assumed to be fed a supplemental diet, consequently, two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Preston 2010, Archibeque 2011, USDA:APHIS:VS 2010) as shown in Table A-191 and Table A-192 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.[5] 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-193.

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.

For calves aged 4 through 6 months, a gradual weaning from milk is simulated, with calf diets at 4 months assumed to be 25 percent forage, increasing to 50 percent forage at age 5 months, and 75 percent forage at age 6 months. The portion of the diet allocated to milk results in zero emissions, as recommended by the IPCC (2006). For calves, the DE for the remainder of the diet is assumed to be similar to that of slightly older replacement heifers (both beef and dairy are calculated separately). The Y_m for beef calves is also assumed to be similar to that of beef replacement heifers (6.5 percent), as literature does not provide an alternative Y_m for use in beef calves. For dairy calves, the Y_m is assumed to be 7.8 percent at 4 months,

[5] For example, the West has a forage DE of 61.3 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-193.

8.03 percent at 5 months, and 8.27 percent at 6 months based on estimates provided by Soliva (2006) for Y_m at 4 and 7 months of age and a linear interpolation for 5 and 6 months.

Table A-194 shows the regional DE and Y_m for U.S. cattle in each region for 2013.

Table A-190: Feed Components and Digestible Energy Values Incorporated into Forage Diet Composition Estimates

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									
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								

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
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	**61.3**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**
Forage Diet for All Other Regions	**64.2**	**33.3%**	**33.3%**	**33.3%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Sources: Preston (2010) and Archibeque (2011).
Note that forages marked with an x indicate that the DE from that specific forage type is included in the general forage type for that column (e.g., grass pasture, range, meadow or meadow by month or season).

Table A-191: 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*	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 Supplement 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).

[*] 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-192: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2013

Feed	Source of DE (NRC1984)	Unweighted DE (% of GE)	West[a]	Central[a]	Northeast[a]	Southeast[a]
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 Supplement DE			**67.4**	**73.1**	**68.9**	**66.6**
Percent of Diet that is Supplement			**10%**	**15%**	**5%**	**15%**

Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (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-193: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2013

Animal Type	Data	West[a]	Central	Northeast	Southeast
Beef Repl. Heifers	DE[b]	61.9	65.6	64.5	64.6
	Y_m[c]	6.5%	6.5%	6.5%	6.5%
Beef Calves (4–6 mo)	DE	61.9	65.6	64.5	64.6
	Y_m	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] 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-189.

[b] DE is the digestible energy in units of percent of GE (MJ/Day).

[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Table A-194: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2013

Animal Type	Data	California[a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Repl. Heifers	DE[b]	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym[c]	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Dairy Calves (4–6 mo)	DE	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym	7.8% (4 mo), 8.03% (5 mo), 8.27% (6 mo)-all regions						
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] Note that emissions are currently calculated on a state-by-state basis, but diets are applied in Table A-188 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-188.
[b] DE is the digestible energy in units of percent of GE (MJ/Day).
[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

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)[6]
- Standard Reference Weight (kg)[7]
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- Y_m (the fraction of GE converted to CH_4)
- Population

Step 3a: Determine Gross Energy, GE

As shown in the following equation, 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).

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

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)

[6] 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).
[7] 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.

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 GE value and the methane conversion factor (Y_m) for each category. This relationship is shown in the following equation:

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

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 GE 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-195.

Table A-195: Calculated Annual National Emission Factors for Cattle by Animal Type (kg CH_4/head/year)

Cattle Type	1990	1995	2000	2005	2009	2010	2011	2012	2013
Dairy									
Calves	12	12	12	12	12	12	12	12	12
Cows	124	125	132	133	140	142	142	144	144
Replacements 7–11 months	48	46	46	45	46	46	46	46	46
Replacements 12–23 months	73	69	70	67	70	69	69	69	69
Beef									
Calves	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98
Cows	89	92	91	94	95	95	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	59	60	59	60	60
Feedlot Cattle	39	38	39	39	43	42	42	42	43

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

For quality assurance purposes, U.S. emission factors for each animal type were compared to estimates provided by the other Annex I member countries of the United Nations Framework Convention on Climate Change (UNFCCC) (the most recently available summarized results for Annex I countries are through 2012 only). Results, presented in Table A-196 indicate that U.S. emission factors are comparable to those of other Annex I countries. Results are presented in Table A-196 (along with Tier I emission factors provided by IPCC (2006)). Throughout the time series, beef cattle in the United States generally emit more enteric CH_4 per head than other Annex I member countries, while dairy cattle in the United States generally emit comparable enteric CH_4 per head.

Table A-196: Annex I Countries' Implied Emission Factors for Cattle by Year (kg CH_4/head/year)[8]

	Dairy Cattle		Beef Cattle	
Year	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)
1990	107	96	71	53
1991	107	97	71	53
1992	107	96	72	54
1993	106	97	72	54
1994	106	98	73	54
1995	106	98	72	54
1996	105	99	73	54
1997	106	100	73	54
1998	107	101	73	55
1999	110	102	72	55
2000	111	103	72	55
2001	110	104	73	55
2002	111	105	73	55
2003	111	106	73	55
2004	109	107	74	55
2005	110	109	74	55
2006	110	110	74	55
2007	114	111	75	55
2008	115	112	75	55
2009	115	112	75	56
2010	115	113	75	55
2011	116	113	75	55
2012	117	112	75	51
2013	117	NA	75	NA
Tier I EFs For North America, from IPCC (2006)		121		53

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:

$$Emissions_{state} = DayEmit_{state} \times Days/Month \times SubPop_{state}$$

where,

$Emissions_{state}$	=	Emissions for state during the month (kg CH_4)
$DayEmit_{state}$	=	Emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month	=	Number of days in the month
$SubPop_{state}$	=	Number of animals in the subcategory and state during the month

This process was repeated for each month, and the monthly 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-197. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

[8] Excluding calves.

Table A-197: CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2009	2010	2011	2012	2013
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,639**	**1,626**	**1,643**	**1,669**	**1,664**
Calves (4–6 months)	62	59	59	54	58	57	57	58	58
Cows	1,242	1,183	1,209	1,197	1,304	1,287	1,301	1,325	1,325
Replacements 7–11 months	58	56	55	56	61	62	63	62	61
Replacements 12–23 Months	212	201	196	196	216	221	222	224	220
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**5,022**	**4,976**	**4,867**	**4,747**	**4,684**
Calves (4–6 months)	182	193	186	179	169	169	166	160	158
Bulls	196	225	215	214	214	215	211	205	202
Cows	2,884	3,222	3,058	3,056	3,002	2,970	2,921	2,855	2,774
Replacements 7–11 months	69	85	74	80	78	75	74	76	77
Replacements 12–23 months	188	241	204	217	216	213	202	207	210
Steer Stockers	563	662	509	473	491	475	439	417	434
Heifer Stockers	306	375	323	299	300	301	283	268	269
Feedlot Cattle	375	416	502	488	552	559	570	559	560
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,661**	**6,602**	**6,510**	**6,416**	**6,348**

Notes: Totals may not sum due to independent rounding.

Emission Estimates from Other Livestock

"Other livestock" include horses, sheep, swine, goats, American bison, and mules and asses. All livestock population data, except for 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 2014) or earlier census data (USDA 1992, 1997). The Manure Management Annex discusses the methods for obtaining annual average populations and disaggregating into state data where needed and provides the resulting population data for the other livestock that were used for estimating all livestock-related emissions (see Table A-199). For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. American bison estimates prior to 2002 were estimated using data from the National Bison Association (1999).

Methane emissions from sheep, goats, swine, horses, mules and asses were estimated by multiplying 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-198 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-199 and Table A-200. Enteric fermentation emissions from most livestock types, broken down by state, for 2013 are shown in Table A-201 and Table A-202. Livestock populations are shown in Table A- 203.

Table A-198: Emission Factors for Other Livestock (kg CH_4/head/year)

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

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

Table A-199: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2009	2010	2011	2012	2013
Beef Cattle	119.1	135.5	126.7	125.2	125.5	124.4	121.7	118.7	117.1
Dairy Cattle	39.4	37.5	38.0	37.6	41.0	40.7	41.1	41.7	41.6
Swine	2.0	2.2	2.2	2.3	2.5	2.4	2.5	2.5	2.5
Horses	1.0	1.2	1.5	1.7	1.7	1.7	1.7	1.6	1.6
Sheep	2.3	1.8	1.4	1.2	1.1	1.1	1.1	1.1	1.1
Goats	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.4	0.4	0.3	0.3	0.3
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**178.7**	**170.6**	**168.9**	**172.7**	**171.1**	**168.7**	**166.3**	**164.5**

Notes: Totals may not sum due to independent rounding.
+ indicates emissions are less than 0.05 MMT CO_2 Eq.

Table A-200: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2009	2010	2011	2012	2013
Beef Cattle	4,763	5,419	5,070	5,007	5,022	4,976	4,867	4,747	4,684
Dairy Cattle	1,574	1,498	1,519	1,503	1,639	1,626	1,643	1,669	1,664
Swine	81	88	88	92	99	97	98	100	99
Horses	40	47	61	70	70	68	67	65	64
Sheep	91	72	56	49	46	45	44	43	43
Goats	13	12	12	14	15	14	14	13	13
American Bison	4	9	16	17	15	15	14	13	13
Mules and Asses	1	1	1	2	3	3	3	3	3
Total	**6,566**	**7,146**	**6,824**	**6,755**	**6,908**	**6,844**	**6,750**	**6,653**	**6,581**

Note: Totals may not sum due to independent rounding.

Table A-201: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2013

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 0 -12	Dairy Repl. Heif. 12-24	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 0-12	Beef Repl. Heif. 12-24	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	56	1,185	62	224	4,866	3,475	61,267	1,487	4,065	1,371	906	357	79,321
Alaska	3	40	3	10	301	28	492	20	54	15	3	2	971
Arizona	1,192	28,636	982	3,529	2,078	1,008	17,582	336	914	8,556	787	11,336	76,937
Arkansas	56	1,005	101	363	5,352	4,543	80,089	1,827	4,994	3,427	1,579	0	103,336
California	11,168	263,358	10,490	37,712	7,272	3,515	61,286	1,681	4,569	18,292	6,928	19,980	446,250
Colorado	847	19,561	1,083	3,892	4,675	4,120	71,835	1,986	5,400	24,783	16,375	43,840	198,396
Conn.	113	2,647	128	460	49	32	566	28	78	55	15	11	4,182
Delaware	28	641	43	153	29	21	377	10	27	52	18	11	1,412
Florida	765	19,429	546	1,964	5,352	4,847	85,454	1,629	4,452	548	731	196	125,914
Georgia	502	12,787	437	1,571	2,530	2,616	46,115	1,048	2,865	1,069	819	283	72,641
Hawaii	13	232	27	97	416	403	7,023	153	415	207	126	48	9,158
Idaho	3,639	86,991	4,169	14,988	4,155	2,939	51,239	1,833	4,985	8,113	6,613	9,786	199,450
Illinois	615	12,422	611	2,198	2,378	1,883	33,306	828	2,267	6,416	2,337	6,635	71,896
Indiana	1,092	23,603	713	2,564	1,808	993	17,573	566	1,549	2,433	1,368	4,203	58,465
Iowa	1,286	28,100	1,528	5,494	5,708	4,811	85,105	2,070	5,668	33,417	19,379	52,908	245,474
Kansas	828	17,964	1,274	4,579	8,086	6,906	122,183	3,174	8,690	52,666	39,042	93,938	359,331
Kentucky	452	10,077	780	2,806	7,298	5,488	96,747	2,124	5,807	6,168	4,677	582	143,006
Louisiana	100	1,868	72	259	2,919	2,424	42,727	1,090	2,981	493	614	174	55,722
Maine	201	4,564	221	793	146	59	1,038	36	97	137	59	31	7,382
Maryland	320	7,251	413	1,483	390	220	3,869	128	349	412	264	415	15,515
Mass.	78	1,686	85	307	98	35	613	28	78	55	29	13	3,106
Michigan	2,365	54,441	2,000	7,188	1,332	588	10,397	386	1,058	4,652	1,339	6,388	92,133
Minn.	2,917	59,508	3,566	12,820	3,330	1,950	34,502	1,380	3,778	12,565	5,130	12,856	154,302
Miss.	88	1,835	109	393	3,795	2,594	45,738	1,105	3,019	1,124	1,023	344	61,168
Missouri	583	10,160	509	1,831	9,513	9,138	161,653	4,002	10,958	9,357	5,700	2,114	225,518
Montana	88	1,874	102	366	10,389	8,678	151,306	6,646	18,069	6,786	5,889	1,528	211,719
Nebraska	345	7,422	255	916	9,513	9,387	166,070	4,830	13,225	60,151	39,327	106,553	417,994
Nevada	182	4,209	121	435	1,351	1,331	23,208	550	1,495	1,357	945	357	35,541
N. Hamp.	85	1,999	92	332	49	19	330	17	47	27	23	8	3,028
N. Jersey	44	957	57	205	98	48	849	28	78	55	29	13	2,462
N. Mexico	2,008	49,888	1,681	6,044	3,636	2,247	39,183	1,146	3,115	2,360	3,149	784	115,241
New York	3,827	93,438	4,553	16,368	1,854	482	8,494	583	1,592	990	1,290	1,037	134,507
N. Car.	289	7,526	359	1,291	3,211	1,943	34,257	1,020	2,787	877	731	250	54,541
N. Dakota	113	2,257	166	595	5,708	4,795	84,829	2,857	7,821	6,817	5,842	1,987	123,787
Ohio	1,694	35,035	1,592	5,723	1,903	1,508	26,682	759	2,078	4,946	1,852	6,796	90,568
Oklahoma	289	6,280	289	1,037	11,677	9,363	165,073	3,965	10,839	23,851	11,693	14,589	258,944
Oregon	772	16,997	914	3,288	3,740	3,037	52,947	1,864	5,068	4,632	2,677	2,736	98,670
Penn	3,357	76,918	4,411	15,857	2,440	830	14,628	781	2,135	4,675	1,906	3,110	131,048
R.Island	6	126	7	26	10	8	142	6	16	8	3	2	358

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 0 -12	Dairy Repl. Heif. 12-24	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 0-12	Beef Repl. Heif. 12-24	Steer Stockers	Heifer Stockers	Feedlot	Total
S. Car.	100	2,338	109	393	1,460	929	16,376	496	1,355	274	351	97	24,277
S. Dakota	577	12,397	700	2,518	8,562	8,779	155,305	4,347	11,902	19,248	15,531	13,270	253,139
Tenn.	301	6,899	390	1,403	6,325	4,868	85,830	2,054	5,613	3,427	2,046	173	119,329
Texas	2,729	67,535	2,886	10,374	29,194	21,433	377,860	8,497	23,226	68,536	45,310	114,982	772,562
Utah	565	13,035	672	2,417	2,285	1,815	31,648	932	2,534	2,213	1,952	1,145	61,214
Vermont	841	19,057	839	3,018	293	64	1,132	64	175	110	191	43	25,827
Virginia	590	14,524	546	1,964	3,892	3,662	64,561	1,756	4,800	5,346	2,368	954	104,963
Wash.	1,656	39,990	1,466	5,270	1,766	1,273	22,204	703	1,911	5,606	4,251	10,147	96,242
W. Virg.	63	1,245	71	256	1,366	1,071	18,875	511	1,398	1,320	733	174	27,083
Wisconsin	7,968	171,951	8,915	32,050	2,854	1,352	23,921	1,035	2,834	9,357	1,567	9,953	273,758
Wyoming	38	805	51	183	4,155	3,999	69,725	2,612	7,103	4,720	3,779	2,943	100,114

Table A-202: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2013

State	Swine	Horses	Sheep	Goats	American bison	Mules and Asses	Total
Alabama	128	1,062	97	236	19	115	1,657
Alaska	2	26	97	3	137	1	265
Arizona	263	1,748	1,120	388	2	33	3,553
Arkansas	173	1,035	97	199	20	83	1,607
California	143	2,429	4,560	709	104	66	8,011
Colorado	1,058	1,955	3,480	160	804	61	7,517
Connecticut	5	335	59	22	10	9	440
Delaware	9	119	97	9	8	1	242
Florida	23	2,180	97	255	19	91	2,664
Georgia	212	1,233	97	346	20	88	1,995
Hawaii	17	87	97	69	7	4	280
Idaho	57	1,061	1,880	91	319	39	3,447
Illinois	6,938	1,068	424	156	47	37	8,669
Indiana	5,438	1,811	440	185	99	52	8,025
Iowa	30,563	1,084	1,400	281	134	43	33,506
Kansas	2,719	1,294	520	204	489	38	5,264
Kentucky	473	2,432	344	287	111	128	3,774
Louisiana	12	1,074	97	91	5	69	1,348
Maine	7	215	59	33	20	4	337
Maryland	33	508	97	48	31	12	728
Massachusetts	13	365	59	43	7	6	493
Michigan	1,568	1,537	656	135	128	42	4,064
Minnesota	11,681	1,109	1,080	166	202	31	14,269
Mississippi	750	1,033	97	117	2	86	2,084
Missouri	4,200	1,997	600	526	140	100	7,562
Montana	249	1,736	1,880	50	1,208	47	5,169
Nebraska	4,556	1,153	640	120	1,990	37	8,497
Nevada	3	419	584	116	6	6	1,134
New Hampshire	6	161	59	25	25	3	279
New Jersey	14	489	97	39	17	9	664
New Mexico	2	903	800	150	430	19	2,303
New York	99	1,641	560	179	68	36	2,583
North Carolina	13,350	1,162	208	300	20	92	15,132
North Dakota	203	817	592	24	682	12	2,329
Ohio	3,210	2,036	968	240	61	70	6,585
Oklahoma	3,281	2,837	600	409	785	136	8,048
Oregon	13	1,199	1,680	161	118	35	3,207
Pennsylvania	1,691	2,171	688	242	85	95	4,972
Rhode Island	3	40	59	5	0	1	107
South Carolina	368	976	97	189	10	56	1,695

State	Swine	Horses	Sheep	Goats	American bison	Mules and Asses	Total
South Dakota	1,744	1,236	2,200	89	2,681	16	7,966
Tennessee	263	1,574	264	419	19	149	2,688
Texas	949	6,970	5,600	4,134	335	629	18,616
Utah	1,095	1,059	2,360	71	89	30	4,703
Vermont	5	204	59	57	8	12	345
Virginia	383	1,550	696	242	84	70	3,024
Washington	57	1,073	432	130	70	36	1,797
Wisconsin	458	1,803	672	311	318	58	3,619
West Virginia	8	436	240	85	1	29	798
Wyoming	135	1,275	3,000	47	737	26	5,221

3.11. 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 Annex 3.12).

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2013 for all livestock types, except American bison, goats, horses, mules and asses 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 2014b). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009a, 2009b, 2009c, 2009d, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014c and 2014d). Goat population data for 1992, 1997, 2002, 2007, and 2012 were obtained from the *Census of Agriculture* (USDA 2014a), as were horse, mule and ass population data for 1987, 1992, 1997, 2002, 2007, and 2012, and American bison population for 2002, 2007, and 2012. American bison population data for 1990-1999 were obtained from the National Bison Association (1999). 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—see section 5.1 Enteric Fermentation). 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: The USDA provides total state-level data annually for lambs and sheep. Population distribution 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 2013 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, 2007, and 2012 (USDA 2014a). The data for 1992 were used for 1990 through 1992. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 were extrapolated based on the 1992, 1997, 2002, 2007, and 2012 Census data.

Horses: Annual horse population data by state were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 2014a). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 were extrapolated based on the 1987, 1992, 1997, 2002, 2007, and 2012 Census data.

Mules and Asses: Annual mule and ass (burro and donkey) population data by state were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 2014a). The data for 2012 were used for 2013. Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 were extrapolated based on the 1987, 1992, 1997, 2002, 2007, and 2012 Census data.

American Bison: Annual American bison population data by state were available for 2002, 2007, and 2012 (USDA 2014a). The data for 2012 were used for 2013. Data for 1990 through 1999 were obtained from the Bison Association (1999). Data for 2000, 2001, 2003 through 2006, 2008 through 2011, and 2013 were extrapolated based on the Bison Association and 2002 2007, and 2012 Census data.

Poultry: The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), other chickens, and production (slaughter) data for broilers and turkeys (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014c, and 2014d). 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.

Because only production data are available for boilers and turkeys, population data are calculated by dividing the number of animals produced by the number of production cycles per year, or the turnover rate. Based on personal communications with John Lange, an agricultural statistician with USDA NASS, the broiler turnover rate ranges from 3.4 to 5.5 over the course of the inventory. For turkeys, the turnover rate ranges from 2.4 to 3.0. A summary of the livestock population characterization data used to calculate CH_4 and N_2O emissions is presented in Table A- 203.

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- 204 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 1996, 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- 205 (ERG 2010b and 2010c). The 1996 AWMFH data were based on measured values from U.S. farms; the 2008 AWMFH data were developed using the calculation method created by the American Society of Agricultural and Biological Engineers, which is based on U.S. animal dietary intake and performance measures. Since the values from each of the two AWMFHs result from different estimation methods and reflect changes in animal genetics and nutrition over time, both data sources were used to create a time series across the Inventory as neither value would be appropriate to use across the entire span of Inventory years. Although the AWMFH values are lower than the IPCC values, these values are more appropriate for U.S. systems because they have been calculated using U.S.-specific data. Animal-specific notes about VS and Nex are presented below:

- *Swine:* 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).
- *Poultry:* 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.
- *Goats, Sheep, Horses, Mules and Asses:* In cases where data were not available in the USDA documents, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* were used as a supplement.

The method for calculating VS excretion and Nex from American bison, beef and dairy cows, bulls, 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 *2006 IPCC Guidelines* Tier II methodology, and is modeled using the CEFM described in the enteric fermentation portion of the inventory (documented in Moffroid and Pape 2013) in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle. For American bison, VS and Nex were assumed to be the same as beef NOF bulls.

The VS 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 CEFM uses the input of digestible energy (DE) and the energy requirements of cattle to estimate gross energy (GE) intake and enteric CH_4 emissions. GE and DE are used to calculate the indigestible energy per animal as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal (2 or 4 percent). This value is then converted to VS production per animal 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:

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

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.

Total nitrogen ingestion in cattle is determined by dietary protein intake. 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 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.

$$N_{excreted} = N_{consumed} - (N_{growth} + N_{milk})$$

where,

$N_{excreted}$	= Daily N excreted per animal, kg per animal per day.
$N_{consumed}$	= Daily N intake per animal, kg per animal per day
N_{growth}	= Nitrogen retained by the animal for growth, kg per animal per day
N_{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,

$N_{consumed}$	= 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:

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

where,

N_{growth}	= Nitrogen retained by the animal for growth, kg per animal per day
WG	= Daily weight gain of the animal, as input into the CEFM transition matrix, kg per day
268	= Constant from *2006 IPCC Guidelines*
7.03	= Constant from *2006 IPCC Guidelines*
NEg	= Net energy required for growth, as calculated in the CEFM, 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*, and is calculated using milk production and percent protein, along with conversion factors. Milk N retained as product is calculated using the following equation:

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

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 (Fat assumed to be 4%)
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, animal type (heifers and steer on feed, heifers and steer not on feed, bulls and American bison), and year. Table A- 206 presents the state-specific VS and Nex production rates used for cattle in 2013.

Step 3: Waste Management System Usage Data

Table A- 207 summarizes 2013 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, American bison, goats, horses, mules and asses and sheep) 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- 208.

Beef Cattle, Dairy Heifers and American Bison: 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 personal communication 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. Using the expert opinions and EPA and USDA data, the runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* (ERG 2000a) 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. American bison WMS data were assumed to be the same as beef cattle not on feed.

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 2014a). It was assumed that the Census 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 2013. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006, and 2008 through 2013 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 the expert opinion of 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's Animal and Plant Health Inspection Service (APHIS)'s National Animal Health Monitoring System (Ott 2000). These data are based on a statistical sample of farms in the 20 U.S. states with the most dairy cows. Small 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, 2002, and 2007 (USDA 2014a) 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 2013, which were obtained from the USDA NASS (USDA 2014b).

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 APHIS collects 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).

Finally, the percentage of manure managed with anaerobic digestion (AD) systems with methane capture and combustion was added to the WMS distributions. AD system data were obtained from EPA's AgSTAR Program's project database (EPA 2012). This database includes basic information for AD systems in the United States, based on publically available data and data submitted by farm operators, project developers, financiers, and others involved in the development of farm AD projects.

Swine: The distribution of manure managed in each WMS was estimated using data from a USDA APHIS report and EPA's Office of Water site visits (Bush 1998, ERG 2000a). The USDA APHIS data are based on a statistical sample of farms in the 16 U.S. states with the most hogs. For operations with less than 200 head, manure management system data were obtained from USDA APHIS (Bush 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 2014a) 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 2013. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated using the 1992, 1997, 2002, and 2007 data. The manure management systems reported in the census 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. As with dairy, AD WMS were added to the WMS distribution based on data from EPA's AgSTAR database (EPA 2012).

Sheep: WMS 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's national sheep report (USDA, APHIS 2003). The USDA APHIS data are based on a statistical sampled of farms in the 22 U.S. states with the most sheep. 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. Based on expert opinion, it was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

Goats, Horses, and Mules and Asses: WMS data for 1990 to 2013 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). This report presents state WMS usage in percentages for the major animal types in the U.S., based on information obtained from extension service personnel in each state. It was assumed that all manure not deposited in pasture, range, or paddock lands was managed in dry systems. For mules and asses, the WMS was assumed to be the same as horses.

Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens: WMS 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, APHIS 2000). It was assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. It was also assumed that system usage in 2000 through 2013 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. As with dairy and swine, using information about AD WMS from EPA's AgSTAR database (EPA 2012), AD was added to the WMS distribution for poultry operations.

Poultry—Broilers and Turkeys: The percentage of turkeys and broilers on pasture was obtained from the Office of Air and Radiation's *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. As with dairy, swine, and other poultry, AD systems were added to the WMS distributions based on information from EPA's AgSTAR database (EPA 2012).

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- 209. 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 2014) 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 United States 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,

f	= van't Hoff-Arrhenius f factor, the proportion of VS that are biologically available for conversion to CH_4 based on the temperature of the system
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)

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 2014a). 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 2013 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 animal type, number of animals present, and the volatile solids excretion rate of the animals.
- 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 management and design factors which cause a system to operate at a less than optimal level.
- For all systems other than anaerobic lagoons, the amount of VS available for conversion to CH_4 each month 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 in the month of October.
- 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:

$$MCF_{annual} = \frac{CH_4\text{ generated }_{annual}}{\text{VS produced }_{annual} \times B_o}$$

where,

MCF_{annual}	= Methane conversion factor
VS $produced_{annual}$	= 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- 210 by state, WMS, and animal group for 2013.

Nitrous Oxide Emission Factors

Direct N_2O EFs 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- 211.

Indirect N_2O EFs 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 EFs 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 and there are a lack of data to quantify these losses. Therefore, leaching losses were assumed to be zero and $Frac_{runoff/leach}$ was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A- 212.

Step 5: CH_4 Emission Calculations

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

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

where,

VS excreted $_{\text{State, Animal, WMS}}$	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
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 in manure that is managed in each WMS was estimated using the following equation:

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

where,

VS excreted $_{\text{State, Animal, WMS}}$	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
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 excreted into a WMS was used to calculate CH_4 emissions using the following equation:

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

where,

CH_4	=	CH_4 emissions (kg CH_4/yr)
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)
MCF $_{\text{animal, state, WMS}}$	=	MCF for the animal group, state and WMS (percent)
0.662	=	Density of methane at 25º C (kg CH_4/m^3 CH_4)

A calculation was developed to estimate the amount of CH_4 emitted from 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:

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

where,

CH_4 Production $AD_{\text{AD system}}$	=	CH_4 production from a particular AD system, (kg/yr)
Population AD $_{\text{state}}$	=	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 25º C (kg CH_4/m^3 CH_4)
365.25	=	Days/year
0.90	=	CH_4 production factor for AD systems

The total amount of CH_4 produced by AD is calculated only as a means to estimate the emissions from AD; i.e., only the estimated amount of CH_4 actually entering the atmosphere from AD is reported in the inventory. The emissions to the atmosphere from AD are a result of leakage and incomplete combustion and are calculated using the collection efficiency (CE) and destruction efficiency (DE) of the AD system. The three primary types of AD systems in the U.S. are covered lagoons, complete mix and plug flow systems. 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 AD was calculated with the following equation:

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

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

Step 6: N_2O Emission Calculations

In addition to CH_4 emissions, total N_2O emissions were also 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 calves and animals other than cattle the following equation was used:

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

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 other than calves, 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:

$$\text{Direct } N_2O = \sum_{\text{State, Animal, WMS}} \left(\text{N excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

where,

Direct N_2O	=	Direct N_2O emissions (kg N_2O/yr)
N excreted $_{\text{State, Animal, WMS}}$	=	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:

$$\text{Indirect } N_2O = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times EF_{\text{volatilization}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times EF_{\text{runoff/leach}} \times \frac{44}{28} \right] \right)$$

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- 213 and Table A- 214 respectively. Emission estimates for 2013 are presented by animal type and state in Table A- 215 and Table A- 216 respectively.

Table A- 203: Livestock Population (1,000 Head)

Animal Type	1990	1995	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Dairy Cattle	19,512	18,681	17,927	17,833	17,919	17,642	17,793	18,078	18,190	18,423	18,552	18,278	18,427	18,588	18,482
Dairy Cows	10,015	9,482	9,172	9,106	9,142	8,988	9,004	9,104	9,145	9,257	9,333	9,086	9,150	9,230	9,218
Dairy Heifer	4,129	4,108	4,045	4,060	4,073	4,033	4,162	4,294	4,343	4,401	4,429	4,526	4,572	4,586	4,521
Dairy Calves	5,369	5,091	4,710	4,668	4,704	4,621	4,628	4,680	4,703	4,765	4,791	4,666	4,706	4,772	4,743
Swine[a]	53,941	58,899	58,913	60,028	59,827	60,735	61,073	61,887	65,417	67,408	65,990	64,768	65,589	66,473	65,747
Market <50 lb.	18,359	19,656	19,659	19,863	19,929	20,222	20,228	20,514	21,812	19,964	19,444	19,124	19,385	19,479	19,175
Market 50-119 lb.	11,734	12,836	12,900	13,284	13,138	13,400	13,519	13,727	14,557	17,219	16,995	16,699	16,966	17,192	16,995
Market 120-179 lb.	9,440	10,545	10,708	11,013	11,050	11,227	11,336	11,443	12,185	12,931	12,567	12,313	12,438	12,727	12,649
Market >180 lb.	7,510	8,937	9,465	9,738	9,701	9,922	9,997	10,113	10,673	11,193	11,079	10,854	11,009	11,236	11,116
Breeding	6,899	6,926	6,181	6,129	6,011	5,963	5,993	6,090	6,190	6,102	5,905	5,778	5,791	5,839	5,812
Beef Cattle[b]	81,576	90,361	84,237	84,260	83,361	81,672	82,193	83,263	82,801	81,524	80,862	80,365	78,851	76,540	75,700
Feedlot Steers	6,357	7,233	7,932	8,116	8,416	8,018	8,116	8,724	8,674	8,481	8,446	8,563	8,743	8,493	8,499
Feedlot Heifers	3,192	3,831	4,569	4,557	4,676	4,521	4,536	4,801	4,730	4,589	4,508	4,628	4,803	4,681	4,582
NOF Bulls	2,160	2,385	2,274	2,244	2,248	2,201	2,214	2,258	2,214	2,207	2,184	2,190	2,155	2,096	2,056
Beef Calves	16,909	18,177	17,508	17,483	17,126	17,013	16,918	16,814	16,644	16,229	16,051	16,043	15,795	15,186	14,961
NOF Heifers	10,182	11,829	9,832	9,843	9,564	9,321	9,550	9,716	9,592	9,350	9,448	9,348	8,878	8,693	8,788
NOF Steers	10,321	11,716	8,724	8,883	8,347	8,067	8,185	8,248	8,302	8,233	8,515	8,223	7,628	7,234	7,517
NOF Cows	32,455	35,190	33,398	33,134	32,983	32,531	32,674	32,703	32,644	32,435	31,712	31,371	30,850	30,158	29,297
Sheep	11,358	8,989	6,908	6,623	6,321	6,065	6,135	6,200	6,120	5,950	5,747	5,620	5,480	5,365	5,335
Sheep On Feed	1,180	1,771	3,256	3,143	3,049	2,923	2,971	3,026	3,000	2,911	2,806	2,778	2,692	2,661	2,626
Sheep NOF	10,178	7,218	3,652	3,480	3,272	3,142	3,164	3,174	3,120	3,039	2,941	2,842	2,788	2,704	2,709
Goats	2,516	2,357	2,475	2,530	2,652	2,774	2,897	3,019	3,141	3,037	2,933	2,829	2,725	2,622	2,518
Poultry[c]	1,537,074	1,826,977	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	2,104,335	2,095,951	2,168,697	2,177,310
Hens >1 yr.	273,467	299,071	340,317	340,209	340,979	343,922	348,203	349,888	346,613	339,859	341,005	341,884	338,944	346,965	352,638
Pullets	73,167	81,369	95,656	95,289	100,346	101,429	96,809	96,596	103,816	99,458	102,301	105,738	102,233	104,460	104,895
Chickens	6,545	7,637	8,126	8,353	8,439	8,248	8,289	7,938	8,164	7,589	8,487	7,390	6,922	6,827	6,795
Broilers	1,066,209	1,331,940	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	1,567,927	1,565,018	1,625,945	1,632,982
Turkeys	117,685	106,960	90,887	91,826	91,349	88,069	84,018	87,487	88,943	91,029	82,453	81,396	82,833	84,500	80,000
Horses	2,212	2,632	3,519	3,644	3,721	3,798	3,875	3,952	4,029	3,947	3,866	3,784	3,703	3,621	3,540
Mules and Asses	63	101	109	105	141	177	212	248	284	286	287	289	291	293	294
American Bison	47	104	213	232	225	218	212	205	198	191	184	177	169	162	155

Note: Totals may not sum due to independent rounding.

[a] 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.

[b] NOF = Not on Feed

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

Table A- 204: Waste Characteristics Data

Animal Group	Typical Animal Mass, TAM		Total Kjeldahl Nitrogen Excreted, Nex[a]		Maximum Methane Generation Potential, B_0		Volatile Solids Excreted, VS[a]	
	Value (kg)	Source	Value	Source	Value (m^3 CH_4/kg VS added)	Source	Value	Source
Dairy Cows	680	CEFM	Table A- 206	CEFM	0.24	Morris 1976	Table A- 206	CEFM
Dairy Heifers	406-408	CEFM	Table A- 206	CEFM	0.17	Bryant et al. 1976	Table A- 206	CEFM
Feedlot Steers	419-457	CEFM	Table A- 206	CEFM	0.33	Hashimoto 1981	Table A- 206	CEFM
Feedlot Heifers	384-430	CEFM	Table A- 206	CEFM	0.33	Hashimoto 1981	Table A- 206	CEFM
NOF Bulls	831-917	CEFM	Table A- 206	CEFM	0.17	Hashimoto 1981	Table A- 206	CEFM
NOF Calves	118	ERG 2003b	Table A- 205	USDA 1996, 2008	0.17	Hashimoto 1981	Table A- 205	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A- 206	CEFM	0.17	Hashimoto 1981	Table A- 206	CEFM
NOF Steers	314-335	CEFM	Table A- 206	CEFM	0.17	Hashimoto 1981	Table A- 206	CEFM
NOF Cows	554-611	CEFM	Table A- 206	CEFM	0.17	Hashimoto 1981	Table A- 206	CEFM
American Bison	578.5	Meagher 1986	Table A- 206	CEFM	0.17	Hashimoto 1981	Table A- 206	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A- 205	USDA 1996, 2008	0.48	Hashimoto 1984	Table A- 205	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A- 205	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A- 205	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A- 205	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A- 205	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A- 205	ASAE 1998	0.17	EPA 1992	Table A- 205	ASAE 1998
Horses	450	ASAE 1998	Table A- 205	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A- 205	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A- 205	IPCC 2006	0.33	EPA 1992	Table A- 205	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A- 205	USDA 1996, 2008	0.39	Hill 1982	Table A- 205	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A- 205	USDA 1996, 2008	0.39	Hill 1982	Table A- 205	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A- 205	USDA 1996, 2008	0.39	Hill 1982	Table A- 205	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A- 205	USDA 1996, 2008	0.36	Hill 1984	Table A- 205	USDA 1996, 2008
Turkeys	6.8	ASAE 1998	Table A- 205	USDA 1996, 2008	0.36	Hill 1984	Table A- 205	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A- 206 shows state-level values for 2013 only.

Table A- 205: Estimated Volatile Solids (VS) and Total Kjeldahl Nitrogen Excreted (Nex) Production Rates by year for Swine, Poultry, Sheep, Goats, Horses, Mules and Asses, and Cattle Calves (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	2011	2012	2013
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	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	5.4	5.4	5.4
Swine, Market 120-179 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	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	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	2.7	2.7	2.7
NOF Cattle 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	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	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	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	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	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	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	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	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	6.1	6.1	6.1
Mules and Asses	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Nex																								
Swine, Market <50 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	0.54	0.54	0.54
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	0.54	0.54	0.54
Swine, Market 120-179 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	0.54	0.54	0.54
Swine, Market >180 lbs.	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	0.20	0.20	0.20
Swine, Breeding	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	0.45	0.45	0.45
NOF Cattle Calves	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	0.45	0.45	0.45
Sheep	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	0.45	0.45	0.45
Goats	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	0.79	0.79	0.79
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	0.79	0.79	0.79
Pullets	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	1.10	1.10	1.10
Chickens	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	0.96	0.96	0.96
Broilers	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	0.63	0.63	0.63
Turkeys	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	0.25	0.25	0.25
Horses	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Mules and Asses	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	0.54	0.54	0.54

Table A- 206: Estimated Volatile Solids (VS) and Total Kjeldahl Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2013 (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	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Alabama	2,150	1,254	1,664	1,100	971	682	663	1,721	2,150	131	69	73	51	42	55	57	83	131
Alaska	1,896	1,254	1,891	1,276	1,115	682	662	1,956	1,896	118	69	59	42	33	55	56	69	118
Arizona	2,864	1,254	1,891	1,231	1,115	682	662	1,956	2,864	160	69	59	40	33	55	56	69	160
Arkansas	1,975	1,254	1,664	1,095	971	NA	NA	1,721	1,975	122	69	73	50	42	NA	NA	83	122
California	2,812	1,254	1,891	1,213	1,115	682	662	1,956	2,812	157	69	59	39	33	55	56	69	157
Colorado	2,911	1,254	1,891	1,193	1,115	682	662	1,956	2,911	162	69	59	38	33	55	56	69	162
Connecticut	2,639	1,254	1,674	1,109	977	682	663	1,731	2,639	150	69	74	52	42	55	57	84	150
Delaware	2,557	1,254	1,674	1,085	977	682	663	1,731	2,557	146	69	74	50	42	55	57	84	146
Florida	2,601	1,254	1,664	1,104	971	682	663	1,721	2,601	150	69	73	51	42	55	57	83	150
Georgia	2,610	1,254	1,664	1,096	971	682	663	1,721	2,610	151	69	73	50	42	55	56	83	151
Hawaii	2,101	1,254	1,891	1,257	1,115	682	663	1,956	2,101	127	69	59	41	33	55	56	69	127
Idaho	2,850	1,254	1,891	1,217	1,115	682	662	1,956	2,850	159	69	59	39	33	55	56	69	159
Illinois	2,546	1,254	1,589	1,014	923	682	662	1,643	2,546	146	69	75	50	43	55	56	85	146
Indiana	2,725	1,254	1,589	1,018	923	682	662	1,643	2,725	154	69	75	50	43	55	56	85	154
Iowa	2,753	1,254	1,589	984	923	682	662	1,643	2,753	155	69	75	48	43	55	56	85	155
Kansas	2,734	1,254	1,589	979	923	682	662	1,643	2,734	154	69	75	47	43	55	56	85	154
Kentucky	2,286	1,254	1,664	1,073	971	682	661	1,721	2,286	137	69	73	49	42	54	55	83	137
Louisiana	2,065	1,254	1,664	1,101	971	682	663	1,721	2,065	125	69	73	51	42	55	57	83	125
Maine	2,560	1,254	1,674	1,087	977	682	663	1,731	2,560	147	69	74	50	42	55	57	84	147
Maryland	2,551	1,254	1,674	1,081	977	682	662	1,731	2,551	146	69	74	50	42	55	56	84	146
Massachusetts	2,421	1,254	1,674	1,098	977	682	663	1,731	2,421	141	69	74	51	42	55	56	84	141
Michigan	2,901	1,254	1,589	1,009	923	682	662	1,643	2,901	161	69	75	49	43	55	56	85	161
Minnesota	2,571	1,254	1,589	1,007	923	682	662	1,643	2,571	147	69	75	49	43	55	56	85	147
Mississippi	2,141	1,254	1,664	1,093	971	682	663	1,721	2,141	130	69	73	50	42	55	57	83	130
Missouri	2,194	1,254	1,589	1,031	923	682	662	1,643	2,194	131	69	75	51	43	55	56	85	131
Montana	2,689	1,254	1,891	1,256	1,115	682	661	1,956	2,689	152	69	59	41	33	54	56	69	152
Nebraska	2,711	1,254	1,589	987	923	682	662	1,643	2,711	153	69	75	48	43	55	56	85	153
Nevada	2,758	1,254	1,891	1,240	1,115	682	661	1,956	2,758	155	69	59	40	33	54	56	69	155
New Hampshire	2,656	1,254	1,674	1,091	977	682	663	1,731	2,656	151	69	74	50	42	55	57	84	151
New Jersey	2,454	1,254	1,674	1,098	977	682	663	1,731	2,454	142	69	74	51	42	55	57	84	142
New Mexico	2,963	1,254	1,891	1,226	1,115	682	663	1,956	2,963	164	69	59	39	33	55	57	69	164
New York	2,749	1,254	1,674	1,079	977	682	662	1,731	2,749	155	69	74	50	42	55	56	84	155
North Carolina	2,672	1,254	1,664	1,098	971	682	663	1,721	2,672	153	69	73	50	42	55	57	83	153
North Dakota	2,519	1,254	1,589	1,023	923	682	663	1,643	2,519	145	69	75	50	43	55	56	85	145
Ohio	2,607	1,254	1,589	1,018	923	682	662	1,643	2,607	149	69	75	50	43	55	56	85	149
Oklahoma	2,415	1,254	1,664	1,065	971	682	662	1,721	2,415	140	69	73	48	42	55	56	83	140
Oregon	2,626	1,254	1,891	1,244	1,115	682	662	1,956	2,626	149	69	59	40	33	55	56	69	149
Pennsylvania	2,580	1,254	1,674	1,077	977	682	662	1,731	2,580	147	69	74	49	42	55	56	84	147

State	Volatile Solids									Nitrogen Excreted								
	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Rhode Island	2,519	1,254	1,674	1,109	977	682	663	1,731	2,519	145	69	74	52	42	55	56	84	145
South Carolina	2,386	1,254	1,664	1,098	971	682	663	1,721	2,386	141	69	73	50	42	55	57	83	141
South Dakota	2,707	1,254	1,589	1,008	923	682	662	1,643	2,707	153	69	75	49	43	55	56	85	153
Tennessee	2,347	1,254	1,664	1,092	971	682	666	1,721	2,347	139	69	73	50	42	56	58	83	139
Texas	2,747	1,254	1,664	1,049	971	682	662	1,721	2,747	155	69	73	47	42	55	56	83	155
Utah	2,752	1,254	1,891	1,234	1,115	682	661	1,956	2,752	155	69	59	40	33	55	56	69	155
Vermont	2,552	1,254	1,674	1,071	977	682	662	1,731	2,552	146	69	74	49	42	55	56	84	146
Virginia	2,524	1,254	1,664	1,085	971	682	662	1,721	2,524	147	69	73	50	42	55	56	83	147
Washington	2,879	1,254	1,891	1,201	1,115	682	662	1,956	2,879	160	69	59	38	33	55	56	69	160
West Virginia	2,235	1,254	1,674	1,091	977	682	662	1,731	2,235	133	69	74	50	42	55	56	84	133
Wisconsin	2,720	1,254	1,589	1,030	923	682	662	1,643	2,720	153	69	75	51	43	55	56	85	153
Wyoming	2,695	1,254	1,891	1,244	1,115	682	662	1,956	2,695	152	69	59	40	33	55	56	69	152

Source: CEFM. NA: Not available; no population exists in this state.

[a] Beef NOF Bull values were used for American bison Nex and VS.

Table A- 207: 2013 Manure Distribution Among Waste Management Systems by Operation (Percent)

State	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]						Dairy Heifer Facilities				Swine Operations[a]					Layer Operations		Broiler and Turkey Operations	
	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Alabama	100	1	100	51	16	7	10	16	0	17	38	0	45	5	4	7	54	31	42	58	1	99
Alaska	100	1	100	5	9	34	19	24	9	6	90	1	4	64	2	10	7	17	25	75	1	99
Arizona	100	0	100	0	10	9	19	61	0	10	90	0	0	6	3	6	55	29	60	40	1	99
Arkansas	100	1	100	60	14	10	7	9	0	15	28	0	57	4	4	13	45	35	0	100	1	99
California	100	1	100	1	11	9	20	59	0	11	88	1	1	10	3	7	50	29	12	88	1	99
Colorado	100	0	100	1	1	11	23	64	0	1	98	0	1	1	6	26	17	50	60	40	1	99
Connecticut	100	1	100	6	43	16	20	13	2	43	51	0	6	78	1	6	5	11	5	95	1	99
Delaware	100	1	100	6	44	19	19	10	2	44	50	0	6	8	5	25	17	46	5	95	1	99
Florida	100	1	100	13	22	7	15	43	0	22	61	1	17	72	1	8	6	13	42	58	1	99
Georgia	100	1	100	37	18	9	12	23	0	18	42	0	40	4	4	8	53	31	42	58	1	99
Hawaii	100	1	100	10	0	9	23	57	0	0	99	1	1	31	3	19	14	32	25	75	1	99
Idaho	100	0	100	0	0	11	23	65	0	1	99	0	0	12	5	23	15	44	60	40	1	99
Illinois	100	1	100	4	6	39	31	16	5	8	87	0	5	1	5	29	14	52	2	98	1	99
Indiana	100	1	100	5	8	29	31	24	3	13	79	0	8	1	5	28	14	52	0	100	1	99
Iowa	100	1	100	4	8	34	30	20	4	10	83	0	6	1	4	9	54	33	0	100	1	99
Kansas	100	1	100	2	3	21	37	36	2	5	92	0	3	2	5	28	13	52	2	98	1	99

State	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]						Dairy Heifer Facilities				Swine Operations[a]					Layer Operations		Broiler and Turkey Operations	
	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Kentucky	100	1	100	60	14	14	7	3	2	14	24	0	61	5	4	10	48	33	5	95	1	99
Louisiana	100	1	100	59	15	10	7	9	1	14	26	0	60	88	1	3	3	6	60	40	1	99
Maine	100	1	100	7	45	20	17	10	2	45	48	0	7	65	2	10	7	16	5	95	1	99
Maryland	100	1	100	7	44	22	16	8	3	44	49	0	7	7	5	25	17	47	5	95	1	99
Massachusetts	100	1	100	7	44	22	16	8	3	45	47	0	7	56	2	12	9	20	5	95	1	99
Michigan	100	1	100	2	4	24	38	29	3	6	91	0	3	4	5	26	17	48	2	98	1	99
Minnesota	100	1	100	5	8	39	28	17	4	10	84	0	6	1	5	26	18	50	0	100	1	99
Mississippi	100	1	100	54	15	10	8	12	0	15	28	0	57	2	4	6	58	31	60	40	1	99
Missouri	100	1	100	7	12	42	22	11	5	14	77	0	8	2	5	28	13	52	0	100	1	99
Montana	100	0	100	2	4	19	28	42	4	4	93	0	3	3	5	25	17	49	60	40	1	99
Nebraska	100	1	100	2	4	26	35	29	3	6	90	0	4	1	5	28	14	51	2	98	1	99
Nevada	100	0	100	0	0	10	24	65	0	0	99	0	0	34	3	18	14	31	0	100	1	99
New Hampshire	100	1	100	7	44	19	18	10	2	44	49	0	7	64	2	10	8	17	5	95	1	99
New Jersey	100	1	100	7	45	25	13	6	3	45	47	0	8	36	3	18	14	30	5	95	1	99
New Mexico	100	0	100	0	10	9	19	61	0	10	90	0	0	100	0	0	0	0	60	40	1	99
New York	100	1	100	6	44	17	18	13	2	45	48	0	7	13	5	23	15	44	5	95	1	99
North Carolina	100	1	100	46	17	11	15	10	2	15	31	0	54	0	4	7	57	32	42	58	1	99
North Dakota	100	1	100	7	11	38	26	15	4	11	83	0	6	5	5	25	17	48	2	98	1	99
Ohio	100	1	100	6	11	38	26	15	4	14	78	0	8	3	5	28	14	51	0	100	1	99
Oklahoma	100	0	100	0	7	21	22	45	4	6	94	0	0	1	4	6	58	31	60	40	1	99
Oregon	100	1	100	16	0	11	22	50	1	0	80	1	20	48	2	14	11	24	25	75	1	99
Pennsylvania	100	1	100	8	46	24	12	6	2	47	44	0	9	4	5	26	18	48	0	100	1	99
Rhode Island	100	1	100	9	47	25	13	5	2	47	44	0	9	72	1	8	6	13	5	95	1	99
South Carolina	100	1	100	47	17	8	11	18	0	15	31	0	54	3	4	7	55	31	60	40	1	99
South Dakota	100	1	100	3	4	24	36	31	2	8	87	0	5	1	5	26	17	50	2	98	1	99
Tennessee	100	1	100	58	15	12	9	4	2	15	26	0	59	13	3	11	41	32	5	95	1	99
Texas	100	0	100	0	9	11	22	58	1	8	92	0	0	3	4	6	57	30	12	88	1	99
Utah	100	0	100	1	1	15	26	56	2	1	98	0	1	1	6	26	17	51	60	40	1	99
Vermont	100	1	100	6	44	17	19	13	2	44	49	0	7	63	2	10	8	18	5	95	1	99
Virginia	100	1	100	56	15	11	10	5	2	15	28	0	57	4	4	7	54	31	5	95	1	99
Washington	100	1	100	11	0	11	22	56	1	0	83	1	17	43	3	15	11	28	12	88	1	99
West Virginia	100	1	100	8	46	23	14	7	2	45	48	0	7	59	2	11	7	20	5	95	1	99
Wisconsin	100	1	100	5	9	38	28	17	4	12	82	0	7	13	4	23	17	42	2	98	1	99
Wyoming	100	0	100	4	6	19	23	43	4	12	81	0	7	4	5	25	16	49	60	40	1	99

[a] In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA's AgSTAR Program.
[b] 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- 208: Manure Management System Descriptions

Manure Management System	Description[a]
Pasture, Range, Paddock	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed. Methane emissions are accounted for under Manure Management, but the N_2O emissions from manure deposited on PRP are included under the Agricultural Soil Management category.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. Methane emissions are accounted for under Manure Management, but the N_2O emissions during storage and treatment are assumed to be zero. N_2O emissions from land application are covered under the Agricultural Soil Management 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 VS 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 (complete mix or plug flow digester) or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, 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.

[a] Manure management system descriptions are based on 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- 209: Methane Conversion Factors (percent) for Dry Systems

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Aerobic Treatment	0	0	0
Anaerobic Digester	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

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

Source: IPCC 2006

Table A- 210: Methane Conversion Factors by State for Liquid Systems for 2013 (percent)

	Dairy		Swine		Beef	Poultry
State	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
Alabama	0.75	0.37	0.75	0.36	0.38	0.75
Alaska	0.47	0.15	0.47	0.15	0.15	0.47
Arizona	0.78	0.57	0.77	0.47	0.52	0.74
Arkansas	0.75	0.34	0.76	0.37	0.35	0.75
California	0.73	0.32	0.72	0.31	0.41	0.74
Colorado	0.65	0.22	0.68	0.24	0.24	0.65
Connecticut	0.69	0.25	0.69	0.26	0.26	0.69
Delaware	0.73	0.31	0.73	0.31	0.31	0.73
Florida	0.79	0.55	0.79	0.53	0.53	0.79
Georgia	0.76	0.39	0.75	0.38	0.37	0.75
Hawaii	0.76	0.57	0.76	0.57	0.57	0.76
Idaho	0.69	0.25	0.66	0.22	0.22	0.68
Illinois	0.72	0.29	0.72	0.28	0.27	0.72
Indiana	0.70	0.27	0.71	0.27	0.27	0.71
Iowa	0.70	0.25	0.70	0.26	0.26	0.70
Kansas	0.74	0.32	0.74	0.32	0.32	0.74
Kentucky	0.73	0.31	0.73	0.31	0.30	0.73
Louisiana	0.77	0.45	0.77	0.46	0.46	0.77
Maine	0.63	0.21	0.63	0.21	0.21	0.64
Maryland	0.72	0.30	0.72	0.30	0.31	0.73
Massachusetts	0.67	0.24	0.68	0.25	0.25	0.68
Michigan	0.67	0.23	0.67	0.24	0.24	0.67
Minnesota	0.68	0.24	0.69	0.24	0.24	0.67
Mississippi	0.76	0.40	0.76	0.38	0.41	0.76
Missouri	0.73	0.30	0.73	0.30	0.30	0.74
Montana	0.61	0.19	0.64	0.21	0.21	0.64
Nebraska	0.72	0.27	0.72	0.27	0.27	0.72
Nevada	0.70	0.26	0.71	0.27	0.25	0.70
New Hampshire	0.64	0.22	0.65	0.22	0.22	0.65
New Jersey	0.71	0.28	0.71	0.29	0.28	0.71
New Mexico	0.73	0.31	0.71	0.28	0.30	0.70
New York	0.65	0.23	0.66	0.23	0.23	0.66
North Carolina	0.73	0.31	0.75	0.36	0.30	0.73
North Dakota	0.66	0.22	0.66	0.22	0.22	0.66
Ohio	0.69	0.26	0.70	0.27	0.27	0.70
Oklahoma	0.76	0.37	0.75	0.35	0.36	0.76
Oregon	0.64	0.21	0.63	0.21	0.22	0.63
Pennsylvania	0.69	0.26	0.70	0.27	0.27	0.70
Rhode Island	0.69	0.26	0.69	0.26	0.26	0.69
South Carolina	0.75	0.37	0.76	0.38	0.36	0.75
South Dakota	0.69	0.24	0.70	0.25	0.25	0.70
Tennessee	0.73	0.31	0.74	0.32	0.31	0.73
Texas	0.76	0.41	0.76	0.44	0.38	0.77
Utah	0.65	0.22	0.69	0.25	0.24	0.65
Vermont	0.63	0.21	0.63	0.21	0.21	0.63
Virginia	0.71	0.28	0.72	0.31	0.29	0.71
Washington	0.64	0.21	0.66	0.22	0.23	0.65

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
West Virginia	0.69	0.26	0.70	0.27	0.26	0.69
Wisconsin	0.66	0.23	0.68	0.24	0.23	0.67
Wyoming	0.63	0.20	0.64	0.21	0.22	0.64

Note: MCFs developed using Tier 2 methods described in IPCC 2006, Section 10.4.2.

Table A- 211: Direct Nitrous Oxide Emission Factors for 2013 (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

Source: IPCC 2006

Table A- 212: Indirect Nitrous Oxide Loss Factors (percent)

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[a]				
			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
American Bison	Pasture	0	0	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
Mules and Asses	Dry Lot	23	0	0	0	0	0
Mules and Asses	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

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[a]				
			Central	Pacific	Mid-Atlantic	Midwest	South
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

Source: EPA 2002b, 2005.

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

Table A- 213: Methane Emissions from Livestock Manure Management (kt)[a]

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Dairy Cattle	590	607	591	614	656	685	695	725	771	841	889	951	985	1036	988	1057	1091	1212	1230	1218	1217	1244	1304	1271
Dairy Cows	581	598	583	606	647	676	687	716	763	832	880	942	977	1027	980	1049	1083	1202	1220	1208	1207	1235	1294	1261
Dairy Heifer	7	7	7	7	7	7	7	7	6	7	7	7	7	7	6	7	7	8	8	8	8	8	9	8
Dairy Calves	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Swine	622	674	637	678	740	763	729	782	891	849	835	854	877	859	858	916	902	984	940	898	945	941	974	922
Market Swine	483	522	499	533	584	608	581	625	720	693	681	697	719	705	707	755	742	816	782	750	790	787	816	773
Market <50 lbs.	102	110	103	108	119	121	116	125	140	133	131	134	137	135	135	142	141	155	110	104	110	110	113	106
Market 50-119 lbs.	101	110	104	110	119	123	117	127	144	138	136	138	144	140	141	150	148	163	175	168	177	176	183	174
Market 120-179 lbs.	136	147	139	150	164	170	163	175	201	193	189	192	199	196	196	210	206	228	229	219	230	228	238	228
Market >180 lbs.	144	156	152	164	182	193	184	198	234	229	225	232	240	234	235	252	247	270	268	260	272	272	282	265
Breeding Swine	139	151	138	146	156	155	148	157	171	157	155	158	158	154	151	161	160	168	157	148	155	154	158	150
Beef Cattle	126	126	129	130	135	139	136	134	137	137	131	134	131	131	129	133	137	134	130	130	132	131	127	120
Feedlot Steers	14	14	14	13	14	14	14	13	13	14	15	15	15	16	15	15	16	16	16	16	16	17	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	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	5	5	5
Beef Calves	6	6	6	6	7	7	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6
NOF Heifers	12	12	13	14	14	15	15	14	15	14	13	13	13	13	12	13	13	13	13	13	13	12	12	12
NOF Steers	12	12	13	14	13	14	14	13	13	12	11	11	11	10	10	10	11	10	10	10	10	10	9	9
NOF Cows	69	69	70	71	74	76	75	74	76	76	71	73	71	71	71	73	75	73	70	70	71	71	69	63
Sheep	7	7	7	6	6	5	5	5	5	4	4	4	4	4	3	3	3	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	1	1	1
Poultry	131	131	127	131	131	128	125	128	130	126	127	131	129	130	129	129	131	134	129	128	129	127	128	129
Hens >1 yr.	73	72	70	73	72	69	68	67	70	66	66	70	67	68	66	66	66	67	64	64	64	64	63	64
Total Pullets	25	26	23	23	23	22	21	23	23	21	22	22	22	22	23	22	23	25	23	23	24	23	23	23
Chickens	4	4	4	4	4	4	3	3	4	4	3	3	4	4	3	3	3	3	3	4	3	3	3	3
Broilers	19	20	20	21	22	23	24	25	26	27	28	28	29	29	30	31	32	32	33	31	31	31	32	33
Turkeys	10	10	10	10	9	9	9	9	8	7	7	7	7	7	7	7	7	7	7	6	6	6	6	6
Horses	9	9	9	9	10	11	11	12	13	13	13	13	13	13	12	12	12	11	10	10	10	10	10	9
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.
+ Emission estimate is less than 0.5 kt.

Table A- 214: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Dairy Cattle	17.1	17.0	17.0	17.3	17.4	17.7	17.7	17.9	18.0	17.6	17.9	18.2	18.5	18.7	17.8	18.3	18.9	18.9	18.6	18.8	18.9	19.1	19.4	19.3
Dairy Cows	10.0	10.1	10.0	10.0	10.1	10.3	10.3	10.4	10.5	10.2	10.5	10.5	10.6	10.8	10.3	10.5	10.8	10.8	10.6	10.8	10.6	10.8	11.0	11.0
Dairy Heifer	7.0	6.9	7.1	7.2	7.3	7.4	7.4	7.4	7.5	7.4	7.5	7.7	7.8	7.9	7.5	7.8	8.1	8.1	8.0	8.0	8.2	8.3	8.4	8.3
Dairy Calves	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine	4.0	4.2	4.3	4.4	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	6.3	6.4	6.3
Market Swine	3.0	3.1	3.3	3.3	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	5.5	5.6	5.5
Market <50 lbs.	0.6	0.6	0.6	0.6	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	0.0	0.8	0.8	0.8	0.8	0.8
Market 50-119 lbs.	0.6	0.7	0.7	0.7	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	0.0	1.2	1.2	1.2	1.3	1.2
Market 120-179 lbs.	0.9	0.9	0.9	1.0	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	1.6	1.6	1.6
Market >180 lbs.	0.9	1.0	1.0	1.0	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	1.9	1.9	1.9
Breeding Swine	1.0	1.1	1.1	1.1	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	0.8	0.8	0.8
Beef Cattle	19.8	20.3	20.1	19.1	20.9	21.8	21.4	21.5	21.6	24.0	25.0	24.1	24.8	25.0	23.6	24.0	25.7	25.6	25.2	25.1	25.3	25.8	25.5	25.7
Feedlot Steers	13.4	13.6	13.5	12.8	13.9	14.4	14.0	13.9	14.1	15.5	16.1	15.4	16.0	16.3	15.3	15.5	16.7	16.7	16.5	16.5	16.6	16.8	16.6	16.8
Feedlot Heifers	6.4	6.6	6.6	6.3	7.0	7.4	7.4	7.6	7.6	8.5	8.9	8.6	8.7	8.8	8.4	8.5	9.0	8.9	8.7	8.6	8.7	9.0	8.9	8.9
Sheep	0.4	0.4	0.4	0.4	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	1.1	1.1	1.0
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	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	4.8	4.9	5.0	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	5.2	5.3	5.3
Hens >1 yr.	1.0	1.0	1.0	1.0	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	1.3	1.3	1.3
Total Pullets	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	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Chickens	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Broilers	2.9	2.9	2.9	3.0	2.9	2.9	3.0	2.9	2.9	2.9	2.7	2.8	2.8	2.9	2.9	2.9	2.9	2.9	3.0	2.9	2.9	3.0	2.9	2.9
Turkeys	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8
Horses	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	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	0.5
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

+ Emission estimate is less than 0.1 kt.

Note: American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

Table A- 215: Methane Emissions by State from Livestock Manure Management for 2013 (kt)[a]

State	Beef on Feedlots	Beef Not on Feed[b]	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison
Alabama	0.0243	2.3856	0.5180	0.0105	1.3643	0.4741	8.7402	3.8087	0.0237	0.0085	0.0177	0.1939	0.0130	0.0007
Alaska	0.0001	0.0197	0.0197	0.0003	0.0017	0.0010	0.1999	+	0.0236	0.0057	0.0002	0.0032	+	0.0037
Arizona	0.6612	1.0510	51.2765	0.1709	2.7048	0.7272	0.7000	+	0.0237	0.0987	0.0291	0.3191	0.0037	0.0001
Arkansas	+	2.0885	0.2785	0.0131	0.7058	1.9556	0.5357	3.6191	0.7002	0.0085	0.0149	0.1890	0.0093	0.0005
California	1.3901	3.8210	395.6799	1.9942	1.4776	0.1200	3.6420	0.2005	0.3251	0.4017	0.0532	0.4433	0.0074	0.0042
Colorado	1.6394	2.7651	29.4555	0.1270	4.5767	2.6632	4.0926	+	0.0236	0.2044	0.0080	0.2379	0.0046	0.0215
Connecticut	0.0005	0.0202	0.9929	0.0152	0.0070	0.0036	0.2494	+	0.0236	0.0034	0.0011	0.0408	0.0007	0.0002
Delaware	0.0005	0.0118	0.2623	0.0053	0.0316	0.0437	0.0783	0.7805	0.0236	0.0057	0.0004	0.0144	0.0001	0.0002
Florida	0.0147	3.2149	21.3685	0.1006	0.0573	0.0371	6.0480	0.2339	0.0237	0.0085	0.0191	0.3979	0.0102	0.0007
Georgia	0.0191	1.7803	7.4110	0.0744	1.7958	0.6485	15.1594	4.8475	0.0237	0.0085	0.0260	0.2250	0.0100	0.0007
Hawaii	0.0036	0.2843	0.4044	0.0058	0.1078	0.0767	0.3127	+	0.0237	0.0085	0.0052	0.0159	0.0004	0.0003
Idaho	0.3640	1.8181	126.0590	0.4671	0.2657	0.0987	0.6391	+	0.0236	0.1104	0.0046	0.1291	0.0029	0.0085
Illinois	0.2636	1.0002	8.3679	0.0769	41.1263	10.3266	0.2517	0.1998	0.0236	0.0249	0.0078	0.1300	0.0027	0.0011
Indiana	0.1670	0.5558	13.9941	0.0891	33.1353	5.4527	0.9212	0.1998	0.4362	0.0258	0.0092	0.2204	0.0039	0.0022
Iowa	2.0840	3.0988	20.7681	0.1895	298.0906	30.7928	1.7034	0.1998	0.0236	0.0822	0.0141	0.1320	0.0033	0.0030
Kansas	3.8249	4.7235	22.5678	0.1627	20.1731	3.7562	0.0457	+	0.0236	0.0305	0.0102	0.1574	0.0029	0.0110
Kentucky	0.0259	2.6363	1.4648	0.0872	4.3226	1.1631	0.5986	1.1186	0.0236	0.0202	0.0143	0.2959	0.0096	0.0026
Louisiana	0.0124	1.6443	0.6174	0.0137	0.0130	0.0093	2.2482	0.2005	0.0237	0.0085	0.0068	0.1960	0.0078	0.0002
Maine	0.0013	0.0381	1.4047	0.0254	0.0101	0.0068	0.2859	+	0.0236	0.0034	0.0016	0.0262	0.0003	0.0005
Maryland	0.0185	0.1246	2.4774	0.0503	0.1681	0.0853	0.3083	1.1049	0.0236	0.0057	0.0024	0.0619	0.0009	0.0007
Massachusetts	0.0005	0.0215	0.5017	0.0100	0.0301	0.0140	0.0105	+	0.0236	0.0034	0.0022	0.0444	0.0005	0.0002
Michigan	0.2489	0.4593	47.0747	0.2460	8.6842	1.9544	0.7865	0.1998	0.0236	0.0385	0.0067	0.1870	0.0031	0.0029
Minnesota	0.5016	1.3182	31.8024	0.4388	63.9535	10.7909	0.3760	0.1741	1.0967	0.0634	0.0083	0.1350	0.0023	0.0045
Mississippi	0.0238	1.8000	0.5635	0.0187	7.4536	1.6819	7.5766	2.6660	0.0237	0.0085	0.0087	0.1885	0.0096	0.0001
Missouri	0.0851	4.2338	5.6655	0.0646	21.8290	7.0077	0.2995	2.6572	0.4237	0.0352	0.0263	0.2430	0.0075	0.0031
Montana	0.0566	4.4718	1.7636	0.0119	1.1301	0.3959	0.3876	+	0.0236	0.1104	0.0025	0.2113	0.0035	0.0323
Nebraska	4.2232	5.9382	7.5168	0.0318	25.4610	7.9160	0.5731	0.1998	0.0236	0.0376	0.0060	0.1403	0.0028	0.0448
Nevada	0.0134	0.6579	6.5983	0.0136	0.0123	0.0073	0.0232	+	0.0236	0.0343	0.0058	0.0510	0.0004	0.0001
New Hampshire	0.0003	0.0130	0.6330	0.0107	0.0129	0.0043	0.0720	+	0.0236	0.0034	0.0013	0.0196	0.0002	0.0006
New Jersey	0.0006	0.0256	0.2564	0.0069	0.0690	0.0105	0.0772	+	0.0236	0.0057	0.0019	0.0595	0.0007	0.0004
New Mexico	0.0299	1.2406	76.5352	0.1917	0.0002	0.0003	0.6559	+	0.0236	0.0470	0.0075	0.1098	0.0014	0.0115
New York	0.0435	0.4255	30.8241	0.5295	0.4566	0.1467	0.4753	0.1998	0.0236	0.0329	0.0089	0.1997	0.0027	0.0016
North Carolina	0.0110	0.9265	2.5096	0.0402	134.4188	30.8042	11.5349	2.8436	0.8475	0.0122	0.0150	0.1414	0.0069	0.0005
North Dakota	0.0768	2.3699	1.2523	0.0203	0.7569	0.6034	0.0432	+	0.0236	0.0348	0.0012	0.0994	0.0009	0.0153
Ohio	0.2689	0.8407	19.9131	0.1982	18.1674	3.2143	0.9551	0.2538	0.1371	0.0569	0.0120	0.2478	0.0052	0.0014
Oklahoma	0.5688	4.8192	8.0124	0.0452	30.5183	14.9005	3.3736	0.7465	0.0236	0.0352	0.0204	0.3452	0.0102	0.0185
Oregon	0.1206	1.6131	17.6821	0.1157	0.0360	0.0146	0.7621	0.1998	0.0236	0.0987	0.0081	0.1459	0.0026	0.0032
Pennsylvania	0.1344	0.6535	16.7101	0.5251	10.4508	1.9444	0.7831	0.6111	0.1745	0.0404	0.0121	0.2642	0.0071	0.0020
Rhode Island	0.0001	0.0041	0.0290	0.0008	0.0040	0.0026	0.0757	+	0.0236	0.0034	0.0002	0.0048	0.0001	+
South Carolina	0.0066	0.6572	1.1172	0.0184	4.6445	0.3175	4.5219	0.8227	0.3001	0.0085	0.0142	0.1781	0.0063	0.0004

State	Beef on Feedlots	Beef Not on Feed[b]	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison
South Dakota	0.5202	4.4668	11.9170	0.0865	9.2266	3.3722	0.1559	+	0.1072	0.1292	0.0044	0.1504	0.0012	0.0603
Tennessee	0.0077	2.2662	1.3034	0.0437	2.3101	0.4656	0.2329	0.6256	0.0236	0.0155	0.0210	0.1915	0.0112	0.0004
Texas	6.4840	17.5622	98.4871	0.4551	10.0549	2.9279	4.5243	2.2160	0.0237	0.4934	0.3099	1.2722	0.0707	0.0118
Utah	0.0428	0.9506	16.8078	0.0748	5.8569	1.3432	3.2060	+	0.0997	0.1386	0.0036	0.1288	0.0022	0.0024
Vermont	0.0018	0.0667	5.8801	0.0966	0.0094	0.0036	0.0113	+	0.0236	0.0034	0.0028	0.0248	0.0009	0.0002
Virginia	0.0419	1.7816	2.8060	0.0600	4.4057	0.1265	0.3477	0.9036	0.3863	0.0409	0.0121	0.1887	0.0052	0.0020
Washington	0.4497	0.8529	46.3650	0.1846	0.1792	0.0651	1.2541	0.1998	0.0236	0.0254	0.0065	0.1305	0.0027	0.0019
West Virginia	0.0075	0.5193	0.3386	0.0085	0.0204	0.0088	0.1720	0.3504	0.0773	0.0141	0.0042	0.0530	0.0022	+
Wisconsin	0.3875	1.0872	93.5080	1.0928	2.2546	0.6779	0.3315	0.1922	0.0236	0.0395	0.0155	0.2194	0.0043	0.0072
Wyoming	0.1093	2.0672	0.8502	0.0059	0.2560	0.3672	0.0087	+	0.0236	0.1762	0.0024	0.1552	0.0020	0.0197

+ Emission estimate is less than 0.00005 kt.

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

[b] Beef Not on Feed includes calves.

Table A- 216: Nitrous Oxide Emissions by State from Livestock Manure Management for 2013 (kt)

State	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine-Market	Swine-Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses
Alabama	0.0058	0.0109	0.0037	0.0036	0.0071	0.0018	0.0632	0.3370	0.0027	0.0046	0.0014	0.0067	0.0005
Alaska	+	0.0001	0.0004	0.0004	+	+	0.0034	+	0.0027	0.0015	+	0.0002	+
Arizona	0.1786	0.3391	0.2310	0.1529	0.0127	0.0026	0.0037	+	0.0027	0.0154	0.0023	0.0110	0.0001
Arkansas	+	+	0.0029	0.0046	0.0041	0.0084	0.0756	0.3202	0.0811	0.0040	0.0012	0.0065	0.0003
California	0.3191	0.6053	2.1241	1.6119	0.0083	0.0005	0.0767	0.0177	0.0377	0.0710	0.0042	0.0152	0.0003
Colorado	0.6929	1.3122	0.1845	0.1940	0.0485	0.0208	0.0246	+	0.0027	0.0480	0.0009	0.0123	0.0002
Connecticut	0.0002	0.0003	0.0146	0.0108	0.0001	+	0.0108	+	0.0027	0.0028	0.0001	0.0021	+
Delaware	0.0002	0.0003	0.0035	0.0035	0.0003	0.0003	0.0033	0.0693	0.0027	0.0046	0.0001	0.0007	+
Florida	0.0032	0.0060	0.1025	0.0502	0.0003	0.0001	0.0409	0.0207	0.0027	0.0046	0.0015	0.0137	0.0004
Georgia	0.0046	0.0086	0.0502	0.0276	0.0094	0.0025	0.1095	0.4289	0.0027	0.0046	0.0021	0.0077	0.0004
Hawaii	0.0008	0.0014	0.0021	0.0046	0.0006	0.0003	0.0034	+	0.0027	0.0015	0.0004	0.0005	+
Idaho	0.1541	0.2927	0.7845	0.7130	0.0029	0.0008	0.0037	+	0.0027	0.0259	0.0005	0.0067	0.0002
Illinois	0.1048	0.1991	0.1400	0.0973	0.3885	0.0713	0.0181	0.0177	0.0027	0.0174	0.0009	0.0067	0.0001
Indiana	0.0665	0.1262	0.2432	0.1026	0.3226	0.0389	0.1280	0.0177	0.0507	0.0180	0.0011	0.0114	0.0002
Iowa	0.8361	1.5880	0.2968	0.2328	1.8169	0.1376	0.2365	0.0177	0.0027	0.0574	0.0017	0.0068	0.0002
Kansas	1.4861	2.8200	0.1918	0.2139	0.1761	0.0242	0.0032	+	0.0027	0.0213	0.0012	0.0081	0.0002
Kentucky	0.0091	0.0175	0.0285	0.0286	0.0253	0.0050	0.0250	0.0993	0.0027	0.0164	0.0017	0.0153	0.0005
Louisiana	0.0028	0.0053	0.0055	0.0030	0.0001	+	0.0116	0.0177	0.0027	0.0040	0.0005	0.0067	0.0003
Maine	0.0005	0.0009	0.0245	0.0174	0.0001	0.0001	0.0131	+	0.0027	0.0028	0.0002	0.0013	+
Maryland	0.0066	0.0125	0.0397	0.0332	0.0015	0.0005	0.0129	0.0981	0.0027	0.0046	0.0003	0.0032	+
Massachusetts	0.0002	0.0004	0.0094	0.0067	0.0003	0.0001	0.0005	+	0.0027	0.0028	0.0003	0.0023	+
Michigan	0.1008	0.1917	0.5817	0.3312	0.0912	0.0153	0.0585	0.0177	0.0027	0.0269	0.0008	0.0096	0.0002
Minnesota	0.2030	0.3858	0.6478	0.5475	0.6501	0.0808	0.0522	0.0155	0.1275	0.0443	0.0010	0.0070	0.0001
Mississippi	0.0056	0.0105	0.0056	0.0046	0.0382	0.0062	0.0396	0.2359	0.0027	0.0046	0.0007	0.0065	0.0003
Missouri	0.0335	0.0635	0.1075	0.0719	0.2100	0.0492	0.0418	0.2359	0.0493	0.0246	0.0031	0.0125	0.0004
Montana	0.0239	0.0456	0.0189	0.0173	0.0130	0.0034	0.0024	+	0.0027	0.0259	0.0003	0.0109	0.0002
Nebraska	1.6847	3.1983	0.0807	0.0420	0.2467	0.0564	0.0412	0.0177	0.0027	0.0262	0.0007	0.0072	0.0001
Nevada	0.0056	0.0107	0.0385	0.0208	0.0001	+	0.0032	+	0.0027	0.0080	0.0007	0.0026	+
New Hampshire	0.0001	0.0002	0.0108	0.0075	0.0001	+	0.0033	+	0.0027	0.0028	0.0002	0.0010	+
New Jersey	0.0002	0.0004	0.0052	0.0044	0.0006	0.0001	0.0033	+	0.0027	0.0046	0.0002	0.0031	+
New Mexico	0.0125	0.0235	0.3988	0.2617	+	+	0.0037	+	0.0027	0.0110	0.0009	0.0057	0.0001
New York	0.0165	0.0313	0.4973	0.3601	0.0048	0.0011	0.0211	0.0177	0.0027	0.0267	0.0011	0.0103	0.0001
North Carolina	0.0040	0.0076	0.0272	0.0164	0.7077	0.1197	0.0849	0.2524	0.0985	0.0099	0.0018	0.0073	0.0004
North Dakota	0.0317	0.0597	0.0232	0.0250	0.0082	0.0048	0.0032	+	0.0027	0.0243	0.0001	0.0051	+
Ohio	0.1077	0.2041	0.3612	0.2280	0.1786	0.0232	0.1325	0.0225	0.0159	0.0459	0.0014	0.0128	0.0003
Oklahoma	0.2303	0.4366	0.0553	0.0435	0.1573	0.0560	0.0176	0.0663	0.0027	0.0245	0.0024	0.0178	0.0005
Oregon	0.0437	0.0829	0.1379	0.1271	0.0004	0.0001	0.0100	0.0177	0.0027	0.0261	0.0010	0.0075	0.0001
Pennsylvania	0.0495	0.0940	0.3966	0.3209	0.1003	0.0139	0.1088	0.0542	0.0203	0.0328	0.0014	0.0136	0.0004

Rhode Island	+	0.0001	0.0007	0.0005	+	+	0.0033	+	0.0027	0.0028	+	0.0002	+
South Carolina	0.0016	0.0030	0.0078	0.0050	0.0238	0.0012	0.0237	0.0728	0.0348	0.0046	0.0011	0.0061	0.0002
South Dakota	0.2096	0.3982	0.1333	0.1118	0.0916	0.0246	0.0114	+	0.0125	0.0902	0.0005	0.0078	0.0001
Tennessee	0.0029	0.0053	0.0200	0.0154	0.0138	0.0021	0.0099	0.0555	0.0027	0.0126	0.0025	0.0099	0.0006
Texas	1.8143	3.4406	0.5285	0.4277	0.0569	0.0122	0.0924	0.1961	0.0027	0.0772	0.0245	0.0437	0.0025
Utah	0.0180	0.0342	0.1227	0.1136	0.0594	0.0111	0.0192	+	0.0116	0.0325	0.0004	0.0066	0.0001
Vermont	0.0007	0.0013	0.1040	0.0675	0.0001	+	0.0005	+	0.0027	0.0028	0.0003	0.0013	+
Virginia	0.0152	0.0288	0.0427	0.0227	0.0247	0.0005	0.0149	0.0802	0.0449	0.0332	0.0014	0.0097	0.0003
Washington	0.1614	0.3072	0.3309	0.2128	0.0019	0.0005	0.0296	0.0177	0.0027	0.0067	0.0008	0.0067	0.0001
West Virginia	0.0028	0.0053	0.0068	0.0056	0.0002	0.0001	0.0076	0.0311	0.0090	0.0114	0.0005	0.0027	0.0001
Wisconsin	0.1572	0.2987	1.8133	1.3302	0.0226	0.0050	0.0246	0.0171	0.0027	0.0276	0.0018	0.0113	0.0002
Wyoming	0.0464	0.0881	0.0076	0.0075	0.0046	0.0048	0.0001	+	0.0027	0.0413	0.0003	0.0080	0.0001

+ Emission estimate is less than 0.00005 kt.

3.12. Methodology for Estimating N_2O Emissions and Soil Organic C Stock Changes from Agricultural Soil Management (Cropland and Grassland)

Nitrous oxide (N_2O) is produced in soils through the microbial processes of nitrification and denitrification[1] Management influences these processes by modifying the availability of mineral nitrogen (N), which is a key control on the N_2O emissions rates (Mosier et al. 1998). 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. Management practices influence soil organic C stocks in agricultural soils by modifying the natural processes of photosynthesis (i.e., crop and forage production) and microbial decomposition. This sub-annex describes the methodologies used to calculate N_2O emissions from agricultural soil management and annual carbon (C) stock changes from mineral and organic soils classified as *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*.[2] This annex provides the underlying methodologies for both N_2O emissions from agricultural soil management and soil organic C stock change from mineral and organic soils. There is considerable overlap in the methods and data sets used for these source categories, and the majority of emission are estimated with the same inventory analysis using the DAYCENT biogeochemical[3] simulation model.

A combination of Tier 1, 2 and 3 approaches is used to estimate direct and indirect N_2O emissions and C stock changes in agricultural soils.

More specifically, the methodologies used to estimate soil N_2O emissions include:

1) A Tier 3 method using the DAYCENT biogeochemical simulation model to estimate direct emissions from mineral soils that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, as well as non-federal grasslands and land use change between grassland and cropland (with the crops listed above and less than 35 percent coarse fragments);
2) A combination of the Tier 3 and 1 methods to estimate indirect N_2O emissions associated with management of cropland and grassland simulated with DAYCENT in Item 1;
3) A Tier 1 method to estimate direct and indirect N_2O emissions from mineral soils that are not simulated with DAYCENT, including very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume); mineral soils with less than 35 percent coarse fragments that are used to produce crops that are not simulated by DAYCENT; crops that are rotated with the crops that are not simulated with DAYCENT; and Pasture/Range/Paddock (PRP) manure N deposited on federal grasslands; and
4) A Tier 1 method to estimate direct N_2O emissions due to partial or complete drainage of organic soils in croplands and grasslands.

The methodologies used to estimate soil organic C stock changes include:

1) A Tier 3 method using the DAYCENT biogeochemical simulation model to estimate soil organic C stock changes in mineral soils as described in Item 1 for N_2O emissions;
2) Tier 2 methods with country-specific stock change factors for estimating mineral soil organic C stock changes for mineral soils that are very gravelly, cobbly, or shaley (greater than 35 percent coarse fragments by volume) and are used to produce crops or have land use changes to cropland and grassland (other than the conversions between cropland and grassland that are included in Item 1) that are not simulated with DAYCENT;
3) Tier 2 methods with country-specific emission factors for estimating losses of C from organic soils that are partly or completely drained for agricultural production; and
4) 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 2007.

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[1] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[2] Soil C stock change methods for forestland are described in the *Forestland Remaining Forestland* section.

[3] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

As described above, the Inventory uses a Tier 3 approach to estimate direct soil N_2O emissions and C stock changes for the majority of agricultural lands. This approach has the following advantages over the IPCC Tier 1 or 2 approaches:

1) It utilizes actual weather data at sub-county scales enabling quantification of inter-annual variability in N_2O emissions and C stock changes at finer spatial scales, as opposed to a single emission factor for the entire country for soil N_2O or broad climate region classification for soil C stock changes;
2) The model uses a more detailed characterization of spatially-mapped soil properties that influence soil C and N dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
3) 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
4) Soil N_2O emissions and C stock changes are estimated on a more continuous, daily basis as a function of the interaction of climate, soil, and land management, compared with the linear rate changes that are estimated with the Tier 1 and 2 methods.

The DAYCENT process-based simulation model (daily time-step version of the Century model) has been selected for the Tier 3 approach based on the following criteria:

1) The model has been developed in the United States and extensively tested and verified for U.S. conditions (e.g., Parton et al. 1987, 1993). 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), and soil N_2O emissions (e.g., Canada, China, Ireland, New Zealand) (Abdalla et al. 2010, Li et al. 2005, Smith et al. 2008, Stehfest and Muller 2004).
2) 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.
3) The model is designed to simulate management practices that influence soil C dynamics and direct N_2O emissions, with the exception of cultivated organic soils; cobbly, gravelly, or shaley soils; and crops that have not been parameterized for DAYCENT simulations (e.g., some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops). For these latter cases, an IPCC Tier 2 method has been used for soil C stock changes and IPCC Tier 1 method for N_2O emissions. The model can also be used estimate the amount of N leaching and runoff, as well as volatilization of N, which is subject to indirect N_2O emissions.
4) Much of the data needed for the model is available from existing national databases. The exceptions are CRP enrollment after 2007, management of federal grasslands, and sewage sludge amendments to soils, which are not known at a sufficient resolution to use the Tier 3 model. Soil N_2O emissions and C stock changes associated with these practices are addressed with a Tier 1 and 2 method, respectively.

Overall, the Tier 3 approach is used to estimate approximately 82 to 88 percent of direct soil N_2O emissions and 85 to 87 percent of the land area associated with estimation of soil organic C stock changes under agricultural management in the United States.

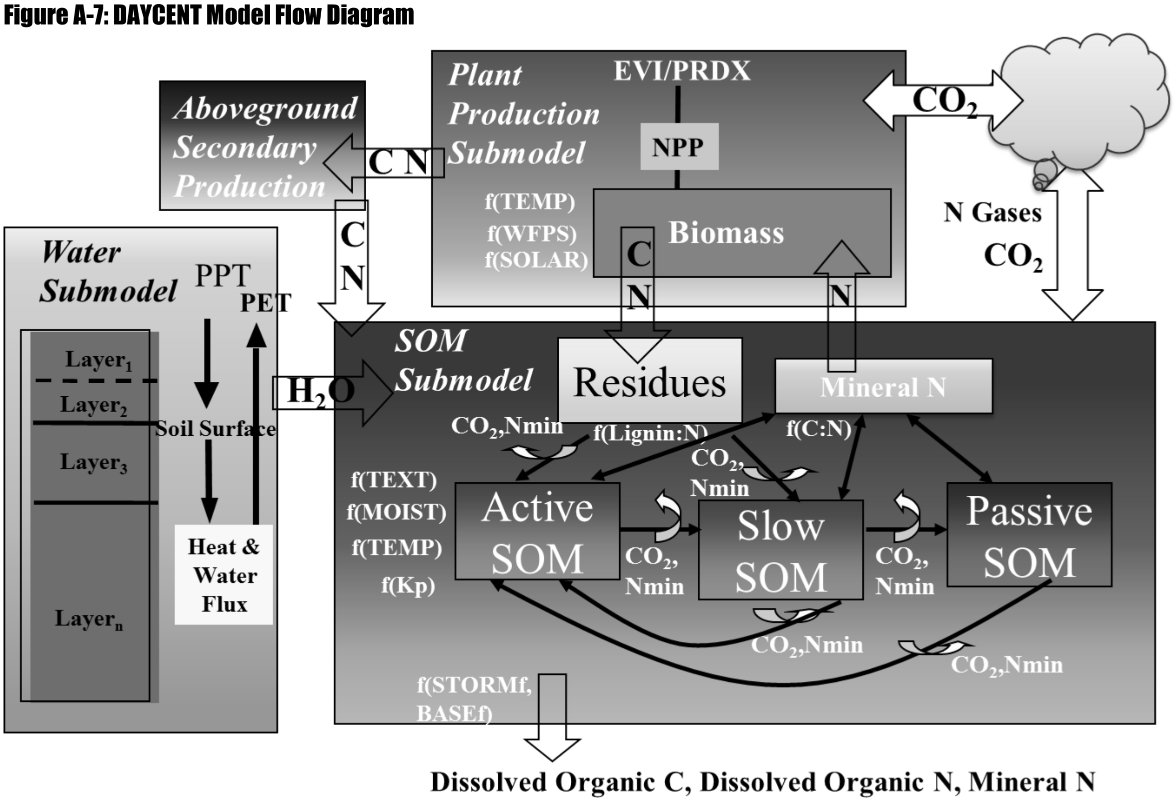
Tier 3 Method Description and Model Evaluation

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil; and provides a more complete estimation of soil C stock changes and N_2O emissions than IPCC Tier 1 or 2 methods by more thoroughly accounting for the influence of environmental conditions. These conditions include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth, along with residue management, determines C inputs to soils, which influence C stock changes, and removal of mineral N from the soil where plant growth influences the amount of N that can 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 a reduction in soil organic C stocks due to microbial respiration, and greater N_2O emissions by enhancing mineral N availability in soils.

Key processes simulated by DAYCENT include (1) plant growth; (2) organic matter formation and decomposition; (3) soil water and temperature regimes by layer, in addition to (4) nitrification and denitrification processes (Figure A-7). Each of these submodels will be described separately below.

1) 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). Maximum daily net primary production (NPP) is estimated using the NASA-CASA production algorithm (Potter et al.1993, 2007) and MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, or an approximation of EVI data derived from the MODIS products (Gurung et al. 2009). The NASA-CASA production algorithm is only used in the central United States for the major crops: corn, soybeans, sorghum, cotton and wheat.[4] Other regions and crops are simulated with a single value for the maximum daily NPP, instead of the more dynamic NASA-CASA algorithm. The maximum daily NPP rate is modified by air temperature and available water (to capture temperature and moisture stress). If the NASA-CASA algorithm is not used in the simulation, then production is further subject to nutrient limitations (i.e., nitrogen). Model evaluation has shown that the NASA-CASA algorithm improves the precision of NPP estimates using the EVI products to inform the production model. The r^2 is 83 percent for the NASA-CASA algorithm and 64 percent for the single parameter value approach. See Figure A-8.

Figure A-7: DAYCENT Model Flow Diagram



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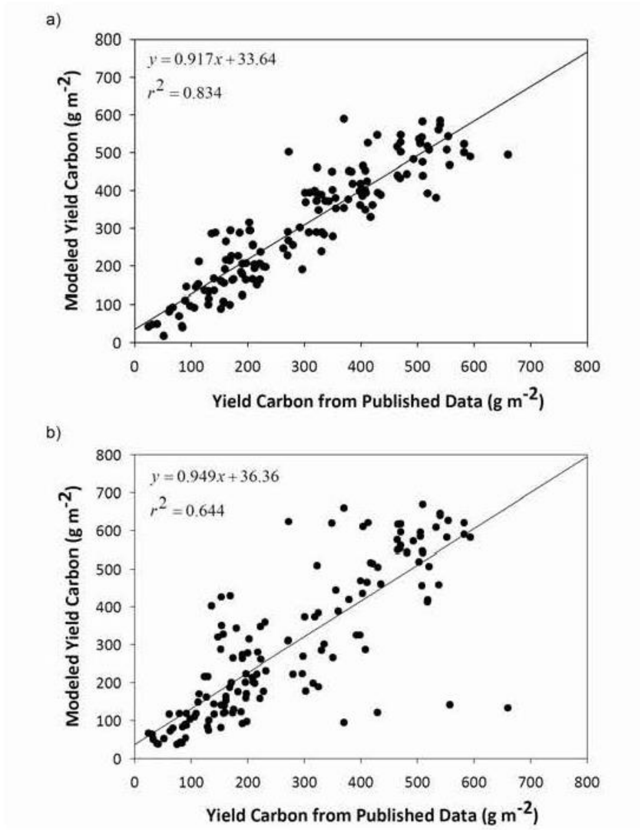
[4] It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

Figure A-8: Modeled versus measured net primary production (g C m^{-2})



Part a) presents results of the NASA-CASA algorithm (r^2 = 83%) and part b) presents the results of a single parameter value for maximum net primary production (r^2 = 64%).

2) Dynamics of soil organic C and N (Figure A-7) are simulated for the surface and belowground litter pools and soil organic matter in 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 (metabolic and structural) and three soil organic matter (SOM) pools (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 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 decomposition, leading to enhanced SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence decomposition and loss of C from the soil organic matter pools.

3) 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.

4) Soil mineral N dynamics are modeled based on N inputs from fertilizer inputs (synthetic and organic), residue N inputs, soil organic matter mineralization in addition to symbiotic and asymbiotic N fixation. Mineral N is available for plant

and microbial uptake, and is largely controlled by the specified stoichiometric limits for these organisms (i.e., C:N ratios). Mineral and organic N losses are simulated with leaching and runoff, and nitrogen can be volatilized and lost from the soil through ammonia volatilization, nitrification and denitrification. N_2O emissions occur through nitrification and denitrification. Denitrification is a function of soil NO_3^- concentration, water filled pore space (WFPS), heterotrophic (i.e., microbial) respiration, and texture. Nitrification is controlled by soil ammonium (NH_4^+) concentration, water filled pore space, temperature, and pH (See Box 2 for more information).

The model allows for a variety of management options to be simulated, including specifying different crop types, crop sequences (e.g., rotation), tillage practices, fertilization, organic matter addition (e.g., manure amendments), harvest events (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 day 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 with the model 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, 1998), Del Grosso et al. (2001, 2011) and Metherell et al. (1993), and archived copies of the model source code are available.

[BEGIN TEXT BOX]

Box 2. 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 (where nitrification mostly occurs) while denitrification is calculated for the entire soil profile (accounting for denitrification near the surface and subsurface as nitrate leaches through the 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, temperature (t), Water Filled Pore Space (WFPS) and pH according to the following equation:

$$Nit = NH_{4+} \times K_{max} \times F(t) \times F(WFPS) \times F(pH)$$

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-9a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A-9b)
F(pH)	=	the effect of soil pH on nitrification (Figure A-9c)

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

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. These rates vary for particular levels of electron acceptor and C substrate, and account for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

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

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-10a)
$F(NO_3)$	=	a function relating N gas flux to nitrate levels (Figure A-10b)
F(WFPS)	=	a dimensionless multiplier (Figure A-10c).

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

$$x\ inflection = 0.90 - M(CO_2)$$

where,

M	=	a multiplier that is a function of D_{FC}. In technical terms, the inflection point is the domain where either F(WFPS) is not differentiable or its derivative is 0. In this case, the inflection point can be interpreted as the WFPS value at which denitrification reaches half of its maximum rate.

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-10). 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-9: Effect of Soil Temperature (a) , Water-Filled Pore Space (b) , and pH (c) on Nitrification Rates

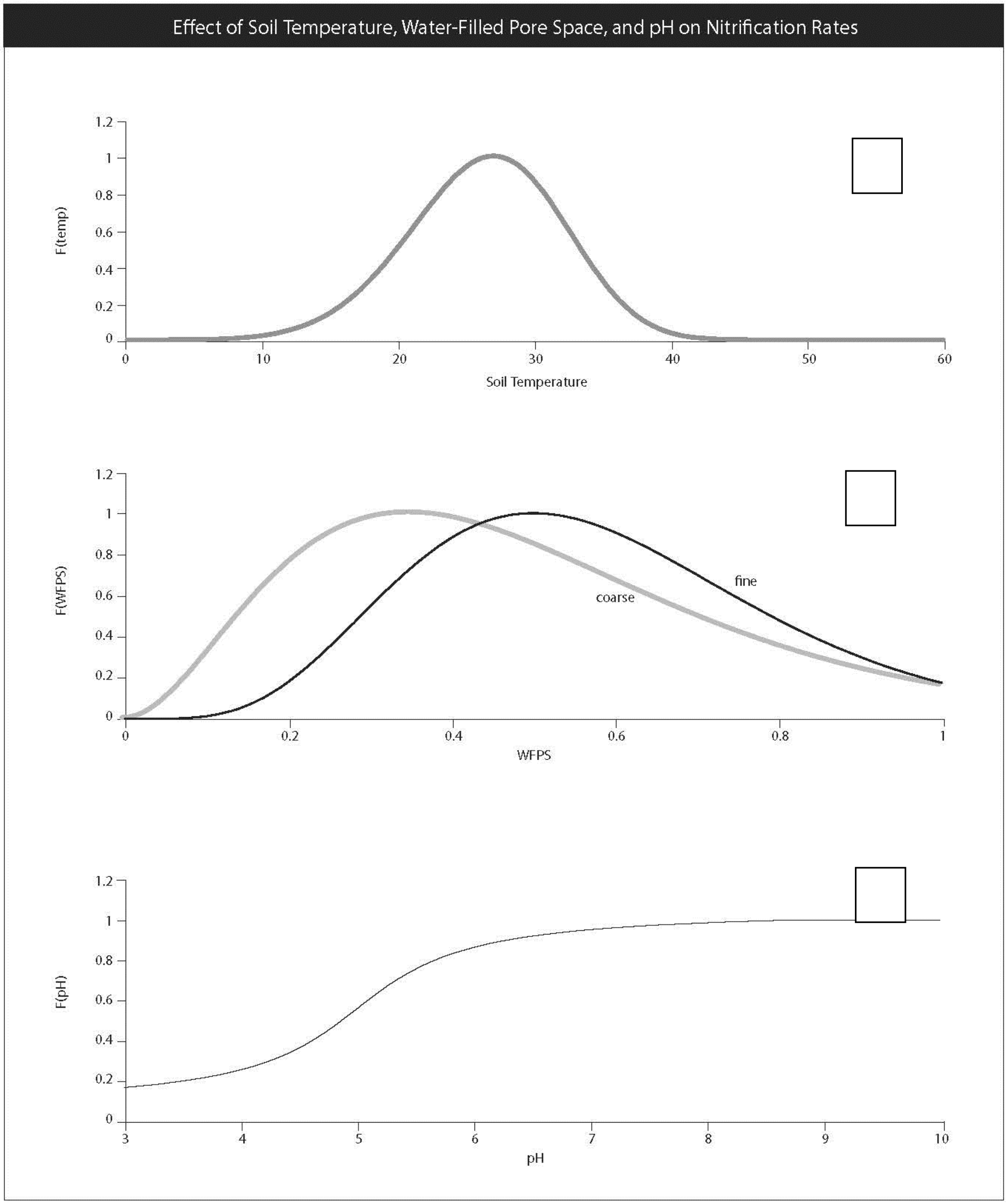
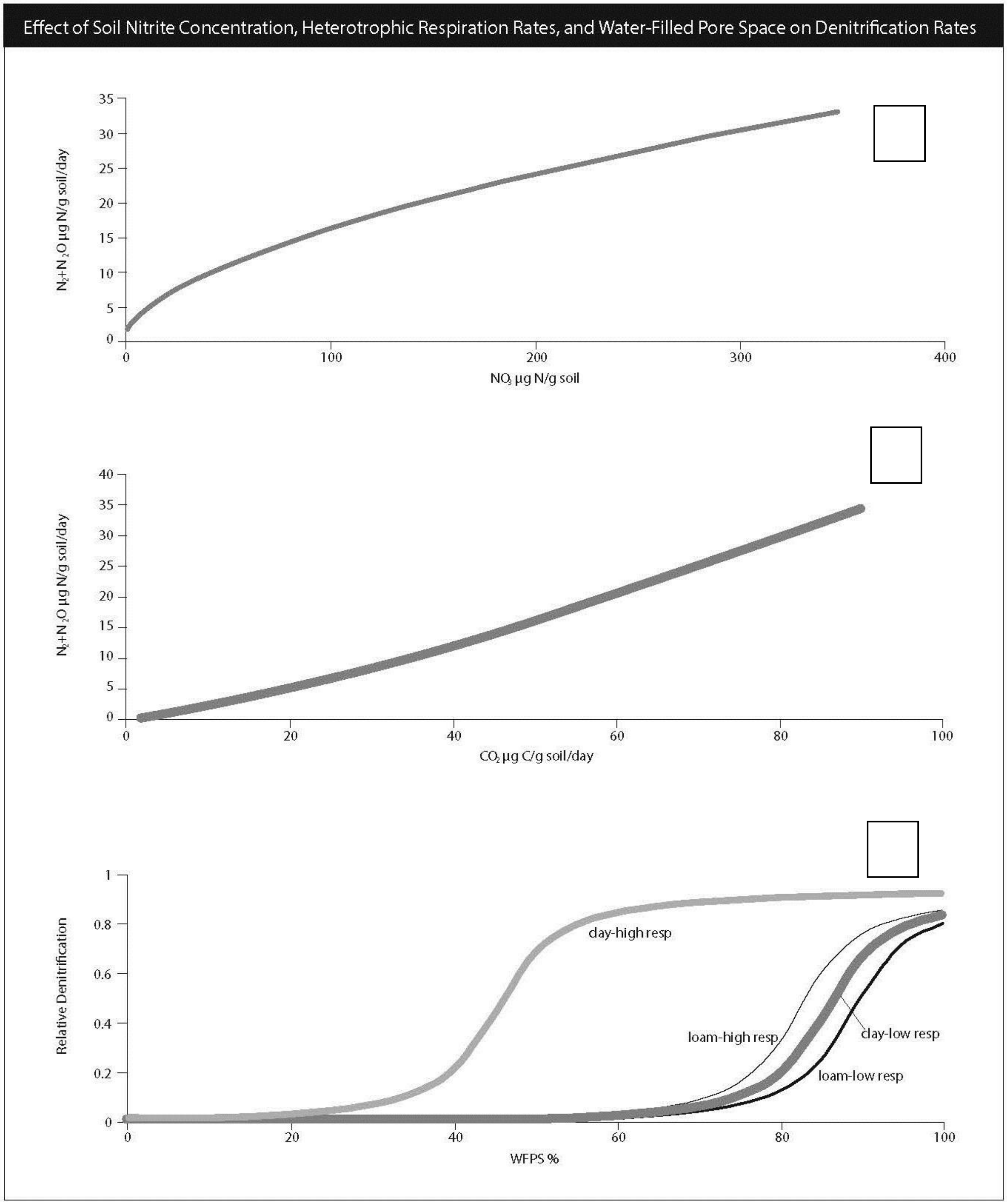


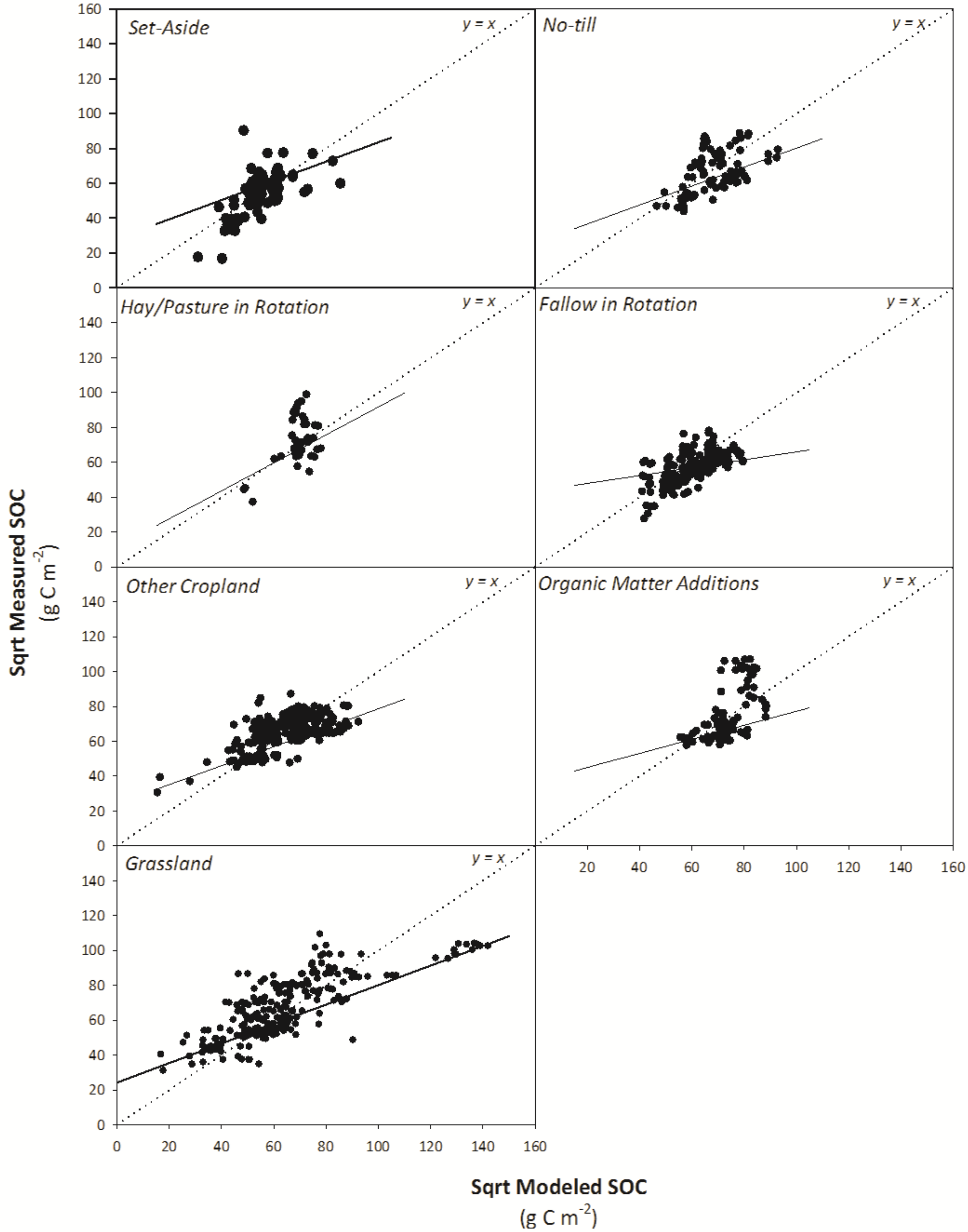
Figure A-10: Effect of Soil Nitrite Concentration (a) , Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



Comparison of model results and plot level data show that DAYCENT reliably simulates soil organic matter levels (Ogle et al. 2007). The model was tested and shown to capture the general trends in C storage across approximately 870 field plots from 47 experimental sites (Figure A-11). Some biases and imprecision occur in predictions of soil organic C, which is reflected in the uncertainty associated with DAYCENT model results. Regardless, the Tier 3 approach has considerably less uncertainty than Tier 1 and 2 methods (Del Grosso et al., 2010; Figure A-11).

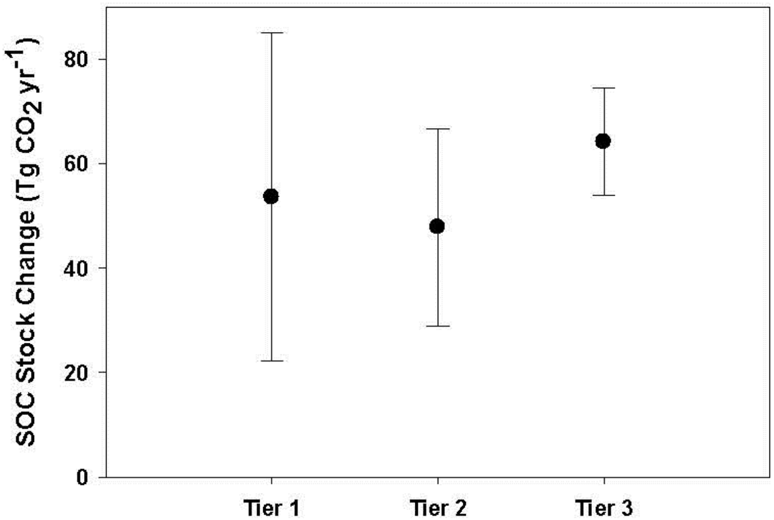
Similarly, DAYCENT model results have been compared to trace gas N_2O fluxes for a number of native and managed systems (Del Grosso et al. 2001, 2005, 2010) (Figure A-12). In general, the model simulates accurate emissions, but some bias and imprecision does occur in predictions, which is reflected in the uncertainty associated with DAYCENT model results. Comparisons with measured data showed that DAYCENT estimated N_2O emissions more accurately and precisely than the IPCC Tier 1 methodology (IPCC 2006) (See Figure 5-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach in the main chapter text). The linear regression of simulated vs. measured emissions for DAYCENT had higher r^2 values and a fitted line closer to a perfect 1:1 relationship between measured and modeled N_2O emissions compared to the IPCC Tier 1 approach (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). Volatilization of N gases that contribute to indirect soil N_2O emissions is the only component that has not been thoroughly tested, which is due to a lack of measurement data. Overall, the Tier 3 approach has reduced uncertainties in the agricultural soil C stock changes and N_2O emissions compared to using lower Tier methods.

Figure A-11: Comparisons of Results from DAYCENT Model and Measurements of Soil Organic C Stocks.



The points represent the model and measured SOC stocks from experimental sites, and the solid line is a best-fit regression line from the linear mixed-effect model.

Figure A-12: Comparison of Estimated Soil Organic C Stock Changes and Uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 Methods



Source: Tier 1 (IPCC 2007), Tier 2 (Ogle et al. 2003, 2006), Tier 3 (Ogle et al. 2010).

Inventory Compilation Steps

There are five steps involved in estimating soil organic C stock changes for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland*, direct N_2O emissions from cropland and grassland soils, and indirect N_2O emissions from volatilization, leaching, and runoff from croplands and grasslands. 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, soil organic C stock changes, direct and indirect N_2O emissions are estimated using DAYCENT and/or the Tier 1 and 2 methods. In the fifth step, total emissions are computed by summing all components separately for soil organic C stock changes and N_2O emissions. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

The following describes how the activity data are derived to estimate soil organic C stock changes and direct and indirect N_2O emissions. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates,[5] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) irrigation data, (7) Enhanced Vegetation Index (EVI), (8) daily weather data, and (9) edaphic characteristics.[6]

Step 1a: Activity Data for the Agricultural Land Base and Histories

The U.S. Department of Agriculture's 2007 *National Resources Inventory* (NRI) (USDA-NRCS 2009) provides 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*. In 1998, the NRI program began collecting annual data, and data are currently available through 2010 (USDA-NRCS, 2013) although this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory. Note that the Inventory does not include estimates of C stock changes and N_2O emissions for federal grasslands (with the exception of soil N_2O from PRP manure N, i.e., manure deposited directly onto pasture, range or paddock by grazing livestock) and a minor amount of croplands on federal lands, even though these areas are part of the managed land base for the United States. Methods are under development for estimating greenhouse gas emissions from soils on federal croplands and grasslands, and will be included in future inventories.

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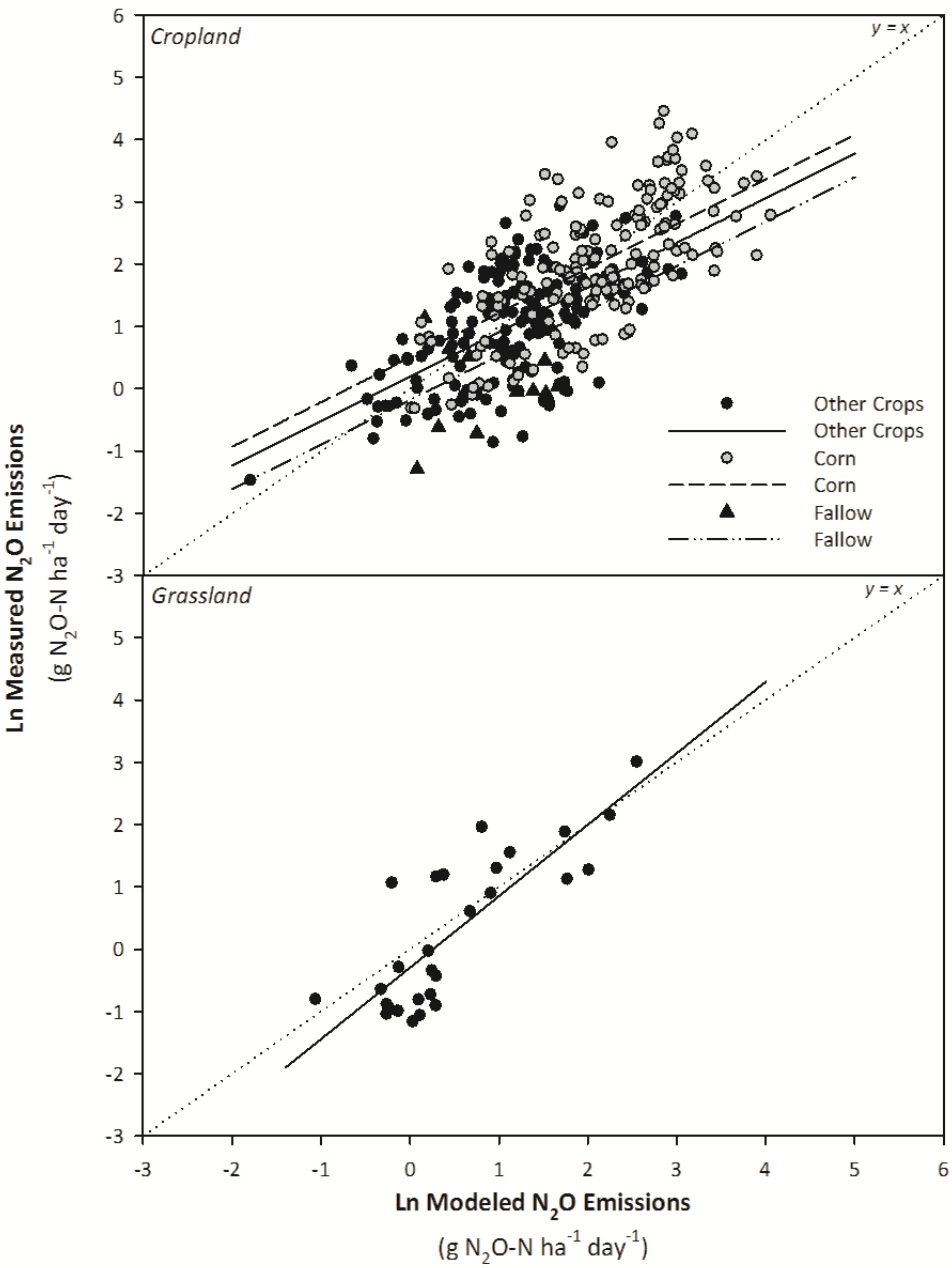
[5] No data are currently available at the national scale to distinguish the type of fertilizer applied or timing of applications rates. It is a planned improvement to address variation in these practices in future inventories.

[6] Edaphic characteristics include such factors as water content, acidity, aeration, and the availability of nutrients.

Figure A-13: Comparisons of Results from DAYCENT Model and Measurements of Soil Nitrous Oxide Emissions



The points represent the model and measured SOC stocks from experimental sites, and the solid line is a best-fit regression line from the linear mixed-effect model.

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 uses a sampling approach, 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 (Nusser et al. 1998).[7] 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 2007, with the exception of 1983, 1988, and 1993. These years are gap-filled using an automated set of rules so that cropping sequences are filled with the most likely crop type given the historical cropping pattern at each NRI point location. Grassland data are reported on 5-year increments prior to 1998, but it is assumed that the land use is also grassland between the years of data collection (see Easter et al. 2008 for more information).

NRI points are included in the land base for the agricultural soil C and N_2O emissions inventories if they are identified as cropland or grassland[8] between 1990 and 2007 (Table A-217).[9] The NRI data are reconciled with the Forest Inventory and Analysis Dataset, and in this process, the time series for *Grassland Remaining Grassland* and *Land Converted to Grassland* is modified to account for differences in forest land area between the two national surveys (See Section 6.1 for more information on the U.S. land representation). Overall, 529,687 NRI survey points are included in the inventory (USDA-NRCS 2009).

For each year, land parcels are 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 are classified as *Cropland Remaining Cropland* if the parcel has been used as cropland for at least 20 years[10]. Similarly land parcels under grassland management in a specific year of the inventory are classified as *Grassland Remaining Grassland* if they have been designated as grassland for at least 20 years. Otherwise, land parcels are 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). Lands converted into Cropland and Grassland are further subdivided into the specific land use conversions (e.g., *Forest Land Converted to Cropland)*.

Table A-217: Total Land Areas for the Agricultural Soil C and N_2O Inventory, Subdivided by Land Use Categories (Million Hectares)

	Land Areas (million ha)											
Category	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Mineral Soils	**357.26**	**357.24**	**356.94**	**352.00**	**351.86**	**352.01**	**352.19**	**352.36**	**346.83**	**347.10**	**347.29**	**347.35**
Croplands												
Cropland Remaining Cropland	152.72	152.52	152.27	147.96	146.81	146.48	146.12	145.73	141.48	141.52	141.53	141.53
Grassland Converted to Cropland	12.79	13.09	13.36	15.16	16.72	16.94	17.28	17.43	18.04	17.59	17.22	16.94
Forest Converted to Cropland	0.62	0.62	0.62	1.24	1.24	1.24	1.24	1.24	0.41	0.41	0.41	0.41
Other Lands Converted to Cropland	0.11	0.11	0.11	0.25	0.25	0.25	0.25	0.25	0.13	0.13	0.13	0.13
Settlements Converted to Croplands	0.24	0.24	0.24	0.66	0.66	0.66	0.66	0.66	0.33	0.33	0.33	0.33
Wetlands Converted to Croplands	0.08	0.08	0.08	0.22	0.22	0.22	0.22	0.22	0.10	0.10	0.10	0.10
Grasslands												
Grasslands Remaining Grasslands	181.58	181.40	180.98	175.02	173.86	173.85	173.86	173.87	170.98	171.17	171.24	171.16
Croplands Converted to Grasslands	7.41	7.48	7.59	8.99	9.59	9.86	10.06	10.44	12.59	13.06	13.55	13.98
Forest Converted to Grasslands	1.15	1.15	1.15	1.72	1.72	1.72	1.72	1.72	1.79	1.79	1.79	1.79
Other Lands Converted to Grasslands	0.25	0.25	0.25	0.40	0.40	0.40	0.40	0.40	0.55	0.55	0.55	0.55
Settlements Converted to Grasslands	0.08	0.08	0.08	0.14	0.14	0.14	0.14	0.14	0.18	0.18	0.18	0.18
Wetlands Converted to Grasslands	0.22	0.22	0.22	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Organic Soils	**1.20**	**1.19**	**1.18**	**1.16**	**1.17**	**1.16**	**1.15**	**1.14**	**1.13**	**1.12**	**1.11**	**1.10**

[7] In the current Inventory, NRI data only provide land-use and management statistics through 2007. More recent data will be incorporated in the future to extend the time series of land use and management data.

[8] Includes only non-federal lands because federal lands are not classified into land uses as part of the NRI survey (i.e., they are only designated as federal lands).

[9] Land use for 2008 to 2013 is assumed to be the same as 2007, but will be updated with newer NRI (i.e. USDA-NRCS 2013).

[10] NRI points are classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 2001.

Croplands												
Cropland Remaining Cropland	0.59	0.59	0.58	0.56	0.55	0.55	0.54	0.54	0.52	0.52	0.52	0.52
Grassland Converted to Cropland	0.06	0.07	0.06	0.07	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.11
Forest Converted to Cropland	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Other Lands Converted to Cropland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Croplands	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Wetlands Converted to Croplands	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Grasslands												
Grasslands Remaining Grasslands	0.44	0.43	0.43	0.42	0.41	0.40	0.39	0.38	0.37	0.36	0.36	0.32
Croplands Converted to Grasslands	0.05	0.05	0.05	0.05	0.06	0.07	0.06	0.07	0.08	0.08	0.08	0.09
Forest Converted to Grasslands	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Other Lands Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wetlands Converted to Grasslands	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Total	**358.46**	**358.43**	**358.11**	**353.16**	**353.04**	**353.17**	**353.34**	**353.49**	**347.97**	**348.22**	**348.40**	**348.45**

Category	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Mineral Soils	**347.48**	**347.70**	**347.44**	**347.05**	**346.72**	**346.46**	**346.37**	**346.32**	**346.30**	**346.28**	**346.26**	**346.24**
Croplands												
Cropland Remaining Cropland	142.01	144.11	143.14	143.54	143.82	144.43	144.43	144.43	144.43	144.43	144.43	144.43
Grassland Converted to Cropland	16.38	14.30	14.20	13.56	13.09	12.24	12.24	12.24	12.24	12.24	12.24	12.24
Forest Converted to Cropland	0.41	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Other Lands Converted to Cropland	0.13	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Settlements Converted to Croplands	0.33	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wetlands Converted to Croplands	0.10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Grasslands												
Grasslands Remaining Grasslands	171.79	174.27	174.21	174.05	174.12	174.63	174.59	174.57	174.58	174.60	174.61	174.63
Croplands Converted to Grasslands	13.54	12.86	13.71	13.72	13.52	12.99	12.95	12.91	12.88	12.84	12.81	12.78
Forest Converted to Grasslands	1.79	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Other Lands Converted to Grasslands	0.55	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Settlements Converted to Grasslands	0.18	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Wetlands Converted to Grasslands	0.25	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Organic Soils	**1.09**	**1.06**	**1.05**	**1.05**	**1.04**	**1.04**	**1.03**	**1.03**	**1.03**	**1.03**	**1.03**	**1.03**
Croplands												
Cropland Remaining Cropland	0.52	0.54	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Grassland Converted to Cropland	0.10	0.10	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Forest Converted to Cropland	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Lands Converted to Cropland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Croplands	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Wetlands Converted to Croplands	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grasslands												
Grasslands Remaining Grasslands	0.32	0.31	0.31	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Croplands Converted to Grasslands	0.10	0.09	0.10	0.10	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Forest Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Lands Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wetlands Converted to Grasslands	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	**348.57**	**348.76**	**348.49**	**348.10**	**347.76**	**347.50**	**347.40**	**347.35**	**347.33**	**347.31**	**347.29**	**347.27**

Note: The area estimates are not consistent with the land representation chapter because the current Inventory does not cover all managed lands. For example, grassland and cropland in Alaska and federal lands in the conterminous United States are not included in the Inventory.

The Tier 3 method using the DAYCENT model is applied to estimate soil C stock changes and N_2O emissions for most of the NRI points that occur on mineral soils. For the Tier 3 inventory, the actual crop and grassland histories are simulated with the DAYCENT model. Parcels of land that are not simulated with DAYCENT are allocated to the Tier 2 approach for estimating soil organic C stock change, and a Tier 1 method (IPCC 2006) to estimate soil N_2O emissions (Table A-242) (Note: the Tier 1 method for soil N_2O does not require land area data -- with the exception of emissions from drainage and cultivation of organic soils -- so in practice it is only the amount of N input to mineral soils that is addressed by the Tier 1 method and not the actual land area).

The land base that is not simulated with DAYCENT includes (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest and federal lands in one or more years of the inventory; (3) land parcels on mineral soils that are 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 are used to produce some of the vegetable crops, perennial/horticultural crops, and tobacco, which are either grown continuously or in rotation with other crops. DAYCENT has not been fully tested or developed to simulate biogeochemical processes in soils used to produce some annual (e.g., tobacco), horticultural (e.g., flowers), or perennial (e.g., vineyards, orchards) crops and agricultural use of organic soils. In addition, DAYCENT has not been adequately tested for soils with a high gravel, cobble, or shale content.

Table A-218: Total Land Area Estimated with Tier 2 and 3 Inventory Approaches (Million Hectares)

	Land Areas (million ha)				
	Mineral			Organic	
Year	Tier 1/2	Tier 3	Total	Tier 1/2	**Total**
1990	31.78	325.48	357.26	1.20	**358.46**
1991	31.78	325.46	357.24	1.19	**358.43**
1992	31.78	325.16	356.94	1.18	**358.11**
1993	26.90	325.10	352.00	1.16	**353.16**
1994	26.90	324.96	351.86	1.17	**353.04**
1995	26.90	325.11	352.01	1.16	**353.17**
1996	26.90	325.29	352.19	1.15	**353.34**
1997	26.90	325.46	352.36	1.14	**353.49**
1998	21.50	325.33	346.83	1.13	**347.97**
1999	21.50	325.59	347.10	1.12	**348.22**
2000	21.50	325.79	347.29	1.11	**348.40**
2001	21.50	325.85	347.35	1.10	**348.45**
2002	21.50	325.97	347.48	1.09	**348.57**
2003	21.63	326.07	347.70	1.06	**348.76**
2004	21.63	325.80	347.44	1.05	**348.49**
2005	21.63	325.41	347.05	1.05	**348.10**
2006	21.63	325.09	346.72	1.04	**347.76**
2007	21.63	324.83	346.46	1.04	**347.50**
2008	21.63	324.74	346.37	1.03	**347.40**
2009	21.63	324.69	346.32	1.03	**347.35**
2010	21.63	324.67	346.30	1.03	**347.33**
2011	21.63	324.65	346.28	1.03	**347.31**
2012	21.63	324.63	346.26	1.03	**347.29**
2013	21.63	324.61	346.24	1.03	**347.27**

NRI points on mineral soils are classified into specific crop rotations, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis (Table A-219). NRI points are 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, probability distribution functions (PDFs) for the NRI land-use data are 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 are taken into account resulting from the likelihood that current use is correlated with past use. These dependencies occur because as some land use/management categories increase in area, the area of other land use/management categories will decline. The covariance matrix addresses these relationships.

Table A-219: Total Land Areas by Land-Use and Management System for the Tier 2 Mineral Soil Organic C Approach (Million Hectares)

Land-Use/Management System	Land Areas (million ha) 1990-1992 (Tier 2)	1993-1997 (Tier 2)	1998-2002 (Tier 2)	2003-2013 (Tier 2)
Cropland Systems	**17.20**	**15.16**	**15.04**	**13.50**
Aquaculture	0.00	0.00	0.01	0.01
Conservation Reserve Program	0.86	0.80	0.40	0.45
Continuous Hay	1.20	1.16	1.32	1.36
Continuous Hay with Legumes or Irrigation	0.29	0.27	0.31	0.29
Continuous Perennial or Horticultural Crops	0.71	0.59	0.51	0.41
Continuous Rice	0.00	0.00	0.00	0.00
Continuous Row Crops	2.96	2.31	2.55	2.50
Continuous Row Crops and Small Grains	2.01	1.57	1.37	1.29
Continuous Small Grains	0.66	0.57	0.53	0.44
Irrigated Crops	5.61	5.41	5.76	5.04
Low Residue Annual Crops (e.g., Tobacco or Cotton)	0.79	0.90	0.72	0.57
Miscellaneous Crop Rotations	0.00	0.01	0.00	0.00
Rice in Rotation with other crops	0.01	0.00	0.01	0.03
Row Crops and Small Grains in with Hay and/or Pasture	0.47	0.35	0.41	0.22
Row Crops and Small Grains with Fallow	0.05	0.04	0.04	0.04
Row Crops in Rotation with Hay and/or Pasture	0.28	0.30	0.35	0.20
Row Crops with Fallow	0.03	0.01	0.03	0.00
Small Grains in Rotation with Hay and/or Pasture	0.19	0.11	0.10	0.06
Small Grains with Fallow	0.47	0.29	0.18	0.21
Vegetable Crops	0.61	0.47	0.44	0.38
Grassland Systems	**10.63**	**7.51**	**8.53**	**8.72**
Rangeland	3.71	2.88	3.27	3.43
Continuous Pasture	6.84	4.56	5.17	5.16
Continuous Pasture with Legumes or Irrigation	0.08	0.07	0.10	0.13
CRP	0.00	0.00	0.00	0.00
Total	**27.83**	**22.67**	**23.57**	**22.22**

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 or soil N_2O emissions. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and relatively large losses of C, and those used for managed pasture, which are assumed to have less drainage with smaller losses of C. N_2O emissions are assumed to be similar for both drained croplands and grasslands. Overall, the area of organic soils drained for cropland and grassland has remained relatively stable since 1990 (see Table A-220).

Table A-220: Total Land Areas for Drained Organic Soils By Land Management Category and Climate Region (Million Hectares)

IPCC Land-Use Category for Organic Soils	Land Areas (million ha) 1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Cold Temperate														
Cultivated Cropland (high drainage)	0.37	0.36	0.36	0.36	0.37	0.37	0.36	0.37	0.36	0.36	0.35	0.35	0.34	0.34
Managed Pasture (low drainage)	0.31	0.30	0.30	0.30	0.30	0.29	0.29	0.28	0.29	0.29	0.28	0.27	0.28	0.27
Undrained	0.05	0.05	0.05	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.02
Total	**0.72**	**0.72**	**0.71**	**0.70**	**0.70**	**0.69**	**0.69**	**0.68**	**0.68**	**0.67**	**0.67**	**0.65**	**0.64**	**0.63**
Warm Temperate														
Cultivated Cropland (high drainage)	0.09	0.09	0.09	0.08	0.09	0.09	0.09	0.08	0.09	0.09	0.09	0.08	0.09	0.09
Managed Pasture (low drainage)	0.07	0.07	0.07	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Undrained	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Total	**0.17**	**0.17**	**0.17**	**0.16**	**0.17**	**0.17**	**0.17**	**0.16**	**0.17**	**0.17**	**0.17**	**0.16**	**0.16**	**0.16**
Tropical														

Cultivated Cropland (high drainage)	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.17	0.17	0.19	0.19	0.19
Managed Pasture (low drainage)	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.08	0.08	0.07
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Total	**0.30**	**0.30**	**0.30**	**0.30**	**0.30**	**0.29**	**0.29**	**0.28**	**0.28**	**0.28**	**0.28**	**0.28**	**0.28**	**0.26**

	Land Areas (million ha)									
IPCC Land-Use Category for Organic Soils	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
	Cold Temperate									
Cultivated Cropland (high drainage)	0.33	0.33	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Managed Pasture (low drainage)	0.27	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Undrained	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	**0.63**	**0.63**	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**
	Warm Temperate									
Cultivated Cropland (high drainage)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Managed Pasture (low drainage)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**0.17**	**0.17**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**
	Tropical									
Cultivated Cropland (high drainage)	0.19	0.18	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Managed Pasture (low drainage)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Undrained	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**

Step 1b: Obtain Management Activity Data for the Tier 3 Method to estimate Soil C Stock Changes and N_2O Emissions from Mineral Soils

Synthetic N Fertilizer Application: Data on N fertilizer rates are based primarily on the USDA–Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011). In these surveys, data on inorganic N fertilization rates are collected for crops simulated by DAYCENT (barley, corn, cotton, dry beans, hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat) in the high production states and for a subset of low production states. These data are used to build a time series of fertilizer application rates for specific crops and states for the 1990 through 1999 time period and 2000 through 2013 time period. If only a single survey is available for a crop, as is the case with sorghum, the rates for the one survey are used for both time periods.

Mean fertilizer rates and standard deviations for irrigated and rainfed crops are produced for each state. If a state is not surveyed for a particular crop or if there are not enough data to produce a state-level estimate, then data are aggregated to USDA 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) (USDA-NASS 2014). If Farm Production Region data are not available, crop data are aggregated to the entire United States (all major states surveyed) to estimate a mean and standard deviation. Standard deviations for fertilizer rates are used to construct PDFs with log-normal densities in order to address uncertainties in application rates (see Step 2a for discussion of uncertainty methods). The survey summaries also present estimates for fraction of crop acres receiving fertilizer, and these fractions are used to determine if a crop is receiving fertilizer. Alfalfa hay and grass-clover hay are assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003). Total fertilizer application data are found in Table A- 221.

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

Managed Livestock Manure Amendments:[11] County-level manure addition estimates have been derived from manure N addition rates developed by the USDA Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, USDA-NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level rates of manure N application to cropland and pasture. Edmonds et al. (2003) defined a hierarchy that included 24 crops, permanent pasture, and cropland used as 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 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. The estimates were based on 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. In order to address uncertainty in these data, uniform probability distributions are 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 is 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 is 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 is divided by the manure N available in 1997. If the ratio is greater than 1, there is more manure N available in that county relative to the amount in 1997, and so it is assumed a larger area is amended with manure. In contrast, ratios less than one imply less area is amended with manure because there is a lower amount available in the year compared to 1997. The amendment area in each county for 1997 is 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 is calculated by determining the populations of livestock on feedlots or otherwise housed, requiring collection and management of the manure. The methods are described in the *Manure Management* section (Section 5.2) and annex (Annex 3.11). The total managed manure N applied to soils is found in Table A- 222.

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 are 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 are 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 is 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 are derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (USDA-ERS 1997). Mineral N fertilization rates are reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and whether it is irrigated or rainfed. The reduction factors are randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

[11] 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 drylots, 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.

PRP Manure N: Another key source of N for grasslands is PRP manure N deposition (i.e., manure deposited by grazing livestock). The total amount of PRP manure N was estimated using methods described in the *Manure Management* section (Section 5.2) and annex (Annex 3.11). Nitrogen from PRP animal waste deposited on non-federal grasslands in a county was generated by multiplying the total PRP N (based on animal type and population data in a county) by the fraction of non-federal grassland area in the county. PRP manure N input rates for the Tier 3 DAYCENT simulations were estimated by dividing the total PRP manure N amount by the land area associated with non-federal grasslands in the county from the NRI survey data. The total PRP manure N added to soils is found in Table A- 222.

Residue N Inputs: Crop residue N, fixation by legumes, and N residue inputs from senesced grass litter are included as sources of N to the soil, and are estimated in the DAYCENT simulations as a function of vegetation type, weather, and soil properties. 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" as it is not a model input. The simulated total N inputs of above- and below-ground residue N and fixed N that is not harvested and not burned (the DAYCENT simulations assumed that 3 percent of non-harvested above ground residues for crops are burned[12]) are provided in Table A-223.

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. Mineralization of soil organic matter will also include the effect of land use change on this process as recommended by the IPCC (2006). 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-223.

Tillage Practices: Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center[13] (CTIC 2004). 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 are provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices are grouped into 3 categories: full, reduced, and no-tillage. Full tillage is 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 (2004). No-till is 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 are derived from the 1995 Cropping Practices Survey by the Economic Research Service (USDA-ERS 1997).

Tillage data are further processed to construct PDFs. Transitions between tillage systems are 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 are modeled and applied to NRI points occurring within a county are full tillage to reduced and no-till, and reduced tillage to no-till. The remaining amount of cropland is assumed to have no change in tillage (e.g., full tillage remained in full tillage). Transition matrices are constructed from CTIC data to represent tillage changes for three time periods, 1980-1989, 1990-1999, 2000-2007. 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 are available) are used for the first time period, data from 1997 are used for the second time period, and data from 2004 are used for the last time period. Percentage areas of cropland in each county are 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. It is assumed that there are no transitions for NT→FT or NT→NT after accounting for NT systems that have intermittent tillage. Uniform probability distributions are established for each

[12] Another improvement is to reconcile the amount of crop residues burned with the *Field Burning of Agricultural Residues* source category (Section 5.5).

[13] National scale tillage data are no longer collected by CTIC, and a new data source will be needed, which is a planned improvement.

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 is 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 is greater than or equal to 0 and less than 80, a transition from full to reduced till if the random draw is equal to or greater than 80 and less than 95, or a transition from full to no-till if the draw is greater than or equal to 95. See step 2b for additional discussion of the uncertainty analysis.

Irrigation: NRI (USDA-NRCS 2009) differentiates between irrigated and non-irrigated land, but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation is modeled by assuming that applied water to field capacity with intervals between irrigation events where the soils drain to about 60 percent of field capacity.

Daily Weather Data: Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). It is necessary to use computer-generated weather data because weather station data do not exist near all NRI points, and moreover weather station data are for a point in space. The NARR product uses this information with interpolation algorithms to derive weather patterns for areas between these stations. NARR weather data are available for the U.S. from 1980 through 2007 at a 32 km resolution. Each NRI point is assigned the NARR weather data for the grid cell containing the point.

Enhanced Vegetation Index: The Enhanced Vegetation Index (EVI) from the MODIS vegetation products, (MOD13Q1 and MYD13Q1) is an input to DAYCENT for estimating net primary production using the NASA-CASA production algorithm (Potter et al. 1993, 2007). MODIS imagery is collected on a nominal 8 day-time frequency when combining the two products. A best approximation of the daily time series of EVI data is derived using a smoothing process based on the Savitzky-Golay Filter (Savitzky and Golay 1964) after pre-screening for outliers and for cloud-free, high quality data as identified in the MODIS data product quality layer. The NASA-CASA production algorithm is only used for the following crops: corn, soybeans, sorghum, cotton, wheat and other close-grown crops such as barley and oats.[14]

The MODIS EVI products have a 250 m spatial resolution, and some pixels in images have mixed land uses and crop types at this resolution, which is problematic for estimating NPP associated with a specific crop at a NRI point. Therefore, a threshold of 90 percent purity in an individual pixel is the cutoff for estimating NPP using the EVI data derived from the imagery (i.e., pixels with less than 90 percent purity for a crop are assumed to generate bias in the resulting NPP estimates). The USDA-NASS Crop Data Layer (CDL) (Johnson and Mueller 2010) is used to determine the purity levels of the EVI data. CDL data have a 30 to 58 m spatial resolution, depending on the year. The level of purity for individual pixels in the MODIS EVI products is determined by aggregating the crop cover data in CDL to the 250m resolution of the EVI data. In this step, the percent cover of individual crops is determined for the 250m EVI pixels. Pixels that did not meet a 90 percent purity level for any crop are eliminated from the dataset. CDL did not provide full coverage of crop maps for the conterminous United States until 2009 so it is not possible to evaluate purity for the entire cropland area prior to 2009.

The nearest pixel with at least 90 percent purity for a crop is assigned to the NRI point based on a 50 km buffer surrounding the survey location. EVI data are not assigned to a point if there are no pixels with at least 90 percent purity within the 50 km buffer. Furthermore, MODIS products do not provide any data on EVI prior to 2000, which preceded the launch of the MODIS sensor on the Aqua and Terra Satellites. It is good practice to apply a method consistently across a time series (IPCC 2006), and so a statistical model is used to estimate EVI for the inventory time series prior to 2000 and also to fill gaps if no pixel has at least 90 percent purity within the 50 km buffer due to purity limitations, lack of CDL data to evaluate purity, or low quality data (Gurung et al. 2009).

Soil Properties: Soil texture and natural drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as input to the DAYCENT model. Texture is one of the main controls on soil C turnover and stabilization in the DAYCENT model, which uses particle size fractions of sand (50-2,000 μm), silt (2-50 μm), and clay (< 2 μm) as inputs. Hydric condition are poorly-drained, and hence prone to have a high water table for part of the year in their native (pre-cultivation) condition , Non-hydric soils are moderately to well-drained .[15] 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

[14] Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

[15] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

anaerobic, varying over the year. Decomposition rates are modified according to a linear function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in DAYCENT).[16] Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, are estimated from soil texture data using a standardized hydraulic properties calculator (Saxton et al. 1986). Soil input data are derived from Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). The data are based on field measurements collected as part of soil survey and mapping. Each NRI point is assigned the dominant soil component in the polygon containing the point from the SSURGO data product.

Step 1c: Obtain Additional Management Activity Data for the Tier 1 Method to estimate Soil N_2O Emissions from Mineral Soils

Synthetic N Fertilizer: A process-of-elimination approach is used to estimate synthetic N fertilizer additions to crops in the Tier 1 method. 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 through 2013, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2014). Fertilizer application data are available for crops and grasslands simulated by DAYCENT (discussed in Step 1a section for Tier 3). Thus, the amount of N applied to crops in the Tier 1 method (i.e., not simulated by DAYCENT) is assumed to be the remainder of the fertilizer used on farms after subtracting the amount applied to crops and non-federal grasslands simulated by DAYCENT. The differences are aggregated to the state level, and PDFs are derived based on uncertainties in the amount of N applied to crops and non-federal grasslands for the Tier 3 method. Total fertilizer application to crops in the Tier 1 method is found in Table A- 224.

Managed Livestock Manure and Other Organic Amendments: Manure N that is not applied to crops and grassland simulated by DAYCENT is assumed to be applied to other crops that are included in the Tier 1 method. Estimates of total national annual N additions from other commercial organic fertilizers are derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2014). Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer are 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 content of 0.5 percent (AAPFCO 2000). The fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b). Values for July to December are not available for calendar year 2013 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value. PDFs are derived for the organic fertilizer applications assuming a default ±50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A- 225. The fate of manure N is summarized in Table A- 222.

PRP Manure N: Soil N_2O emissions from PRP manure N deposited on federal grasslands are estimated with a Tier 1 method. PRP manure N data are derived using methods described in the *Manure Management* section (Section 5.2) and Annex 3.11. PRP N deposited on federal grasslands is calculated using a process of elimination approach. The amount of PRP N generated by DAYCENT model simulations of non-federal grasslands was subtracted from total PRP N and this difference was assumed to be applied to federal grasslands. The total PRP manure N added to soils is found in Table A-222.

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 are derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1990-2012, in dry mass units, are obtained from AAPFCO (1995-2014). Values for 2013 were not available so a "least squares line" statistical extrapolation using the previous 5 years of data was used to arrive at an approximate value. The total sludge generation estimates are then converted to units of N by applying an average N content of 69 percent (AAPFCO 2000), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices are agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other

[16] 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 DAYCENT model.

disposal methods. The resulting estimates of sewage sludge N applied to agricultural land are used to estimate N_2O emissions from agricultural soil management; the estimates of sewage sludge N applied to other land and surface-disposed are used in estimating N_2O fluxes from soils in *Settlements Remaining Settlements* (see section 6.9 of the *Land Use, Land-Use Change, and Forestry* chapter). Sewage sludge disposal data are provided in Table A- 226.

Residue N Inputs: Soil N_2O emissions for residue N inputs from croplands that are not simulated by DAYCENT are estimated with a Tier 1 method. Annual crop production statistics for all major commodity and specialty crops are taken from U.S. Department of Agriculture crop production reports (USDA 2014). Total production for each crop was converted to tons of dry matter product using the residue dry matter fractions shown in Table A- 227. Dry matter yield is then converted to tons of above- and below-ground biomass N. Above-ground biomass is calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass is calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. N inputs are estimated by multiplying above- and below-ground biomass by respective N concentrations and by the portion of cropland that was not simulated by DAYCENT. All ratios and equations used to calculate residue N inputs are from IPCC (2006) and Williams (2006). PDFs are derived assuming a ±50 percent uncertainty in the yield estimates (USDA-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- 228.

Step 1d: Obtain Additional Management Activity Data for the Tier 2 Method to estimate Soil C Stock Changes in Mineral Soils

Tillage Practices: For the Tier 2 method that is used to estimate soil organic C stock changes, PDFs are constructed for the CTIC tillage data (CTIC 2004) as bivariate normal on a log-ratio scale to reflect negative dependence among tillage classes. This structure ensured that simulated tillage percentages are 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) are modified based on consultation with CTIC experts, as discussed in Step 1a (downward adjustment of total no-tillage area based on the amount of no-tillage that is rotated with more intensive tillage practices) (Towery 2001).

Managed Livestock Manure Amendments: 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 DAYCENT model discussion in Step1b, the amount of land receiving manure is 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 are used to re-classify a portion of crop and grassland into a new management category. Specifically, a portion of medium input cropping systems is re-classified as high input, and a portion of the high input systems is re-classified as high input with amendment. In grassland systems, the estimated proportions for land amended with manure are 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 2006). Uncertainties in the amount of land amended with manure are based on the sample variance at the climate region scale, assuming normal density PDFs (i.e., variance of the climate region estimates, which are derived from county-scale proportions).

Sewage Sludge Amendments: Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment facilities and is typically used as a soil amendment or is sent for waste disposal to landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. See section on sewage sludge in Step 1c for more information about the methods used to derive sewage sludge N estimates. The total amount of sewage sludge N is given in Table A- 226. Sewage sludge N is 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 is divided by the assimilative capacity to estimate the total land area over which sewage sludge had been applied. The resulting estimates are used for the estimation of soil C stock change.

CRP Enrollment after 2007: The change in enrollment for the Conservation Reserve Program after 2007 is based on the amount of land under active contracts from 2008 through 2013 relative to 2007 (USDA-FSA 2013).

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 (USFWS 2010). The area of restored wetlands is 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 is used to construct the PDFs for the uncertainty analysis.

Table A- 221: Synthetic Fertilizer N Added to Tier 3 Crops (kt N)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Fertilizer N	8,859	8,666	9,271	9,029	9,139	8,992	9,229	9,269	8,836	9,743	9,729	9,642	9,697	9,575	9,587	9,670

Table A- 222: Fate of Livestock Manure Nitrogen (kt N)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Managed Manure N Applied to Tier 3 Cropland and Non-federal Grasslands[a,b]	874	808	975	936	939	931	929	927	898	990	977	977	977	977	983	990
Managed Manure N Applied to Tier 1 Cropland[c]	1,533	1,716	1,647	1,678	1,713	1,735	1,659	1,701	1,807	1,742	1,732	1,714	1,704	1,732	1,755	1,742
Managed Manure N Applied to Grasslands	57	63	60	61	62	62	60	61	65	62	61	61	61	62	62	62
Pasture, Range, & Paddock Manure N	4,090	4,522	4,143	4,130	4,128	4,128	4,073	4,116	4,158	4,049	4,002	3,956	3,907	3,807	3,710	3,654
Total	**6,553**	**7,110**	**6,825**	**6,805**	**6,841**	**6,856**	**6,721**	**6,805**	**6,928**	**6,843**	**6,772**	**6,707**	**6,648**	**6,577**	**6,510**	**6,448**

[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-223: Crop Residue N and Other N Inputs to Tier 3 Crops as Simulated by DAYCENT (kt N)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Residue N[a]	576	618	625	630	594	641	661	662	633	630	630	630	630	630	630	630
Mineralization & Asymbiotic Fixation	10,141	10,991	10,019	10,952	10,840	10,858	11,526	11,008	11,176	10,810	10,797	10,797	10,797	10,797	10,806	10,810

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 224: Synthetic Fertilizer N Added to Tier 1 Crops (kt N)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Fertilizer N	1,719	1,832	1,875	1,750	1,922	2,208	2,251	1,962	2,309	2,163	1,883	1,709	2,020	2,422	2,523	2,118

Table A- 225: Other Organic Commercial Fertilizer Consumption on Agricultural Lands (kt N)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Other Commercial Organic Fertilizer N[a]	4	10	9	7	8	8	9	10	12	15	12	10	10	11	11	10

a Includes dried blood, tankage, compost, other. Excludes dried manure and sewage sludge used as commercial fertilizer to avoid double counting.

Table A- 226: Sewage Sludge Nitrogen by Disposal Practice (kt N)

Disposal Practice	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Applied to Agricultural Soils	52	68	84	86	89	91	94	98	101	104	107	110	113	116	119	122
Other Land Application	25	28	30	30	30	30	30	31	31	32	32	32	32	33	33	33
Surface Disposal	20	16	10	9	8	6	5	5	4	4	3	3	3	2	2	2
Total	**97**	**111**	**124**	**125**	**127**	**128**	**130**	**134**	**137**	**140**	**142**	**145**	**148**	**151**	**153**	**156**

Note: Totals may not sum due to independent rounding.

Table A- 227: Key Assumptions for Crop Production in the Tier 1 Method

	Dry Matter	Above-ground Residue			Residue N Fraction	
Crop	Fraction of Harvested Product	Slope	Intercept	Ratio of Below-ground	Above-ground	Below-ground

				Residue to Above-ground Biomass		
Barley	89%	0.98	0.59	0.22	0.007	0.014
Corn	87%	1.03	0.61	0.22	0.006	0.007
Cotton	93%	2.54	0	0.13	0.01	0.015
Hay	90%	0.29	0	0.4	0.027	0.019
Oats	89%	0.91	0.89	0.25	0.007	0.008
Peanuts for Nuts	94%	1.07	1.54	0.2	0.016	0.014
Rice	89%	0.95	2.46	0.16	0.007	0.009
Sorghum	89%	0.88	1.33	0.22	0.007	0.006
Soy	91%	0.93	1.35	0.19	0.008	0.008
Sugar Beat	22%	0.1	1.06	0.2	0.019	0.014
Sunflower	90%	1.94	0.46	0.154	0.007	0.009
Tobacco	87%	0.7	0	0.4	0.008	0.018
Wheat	89%	1.51	0.52	0.24	0.006	0.009

Table A- 228: Nitrogen in Crop Residues Retained on Soils Producing Crops not Simulated by DAYCENT (kt N)

Crop	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Barley	21	17	13	11	10	11	10	9	9	9	9	9	9	8	9	9
Corn	157	128	138	128	119	132	148	135	134	153	142	154	146	145	127	163
Cotton	13	17	15	19	15	16	19	22	17	14	10	9	14	12	13	10
Hay	280	277	244	247	229	239	239	226	208	218	217	219	216	195	178	202
Oats	13	10	10	9	9	10	10	10	10	9	9	9	9	9	9	9
Peanuts for Nuts	41	39	37	38	37	39	42	40	38	39	43	39	41	39	48	41
Rice	28	27	29	29	30	29	31	30	29	28	28	29	30	28	28	28
Sorghum	21	18	17	17	15	16	16	15	14	17	16	15	15	13	14	15
Soy	64	57	63	64	60	53	68	65	66	60	65	71	71	67	66	71
Sugar Beat	30	30	29	27	27	27	27	27	28	27	27	27	27	27	28	27
Sunflower	6	7	5	6	5	6	5	6	5	5	6	5	5	5	5	5
Tobacco	13	10	8	8	7	6	7	5	6	6	6	6	6	5	6	6
Wheat	63	48	47	39	33	46	43	42	30	39	46	42	41	38	42	40
Total	**748**	**684**	**655**	**643**	**597**	**630**	**663**	**631**	**594**	**625**	**625**	**636**	**630**	**590**	**573**	**626**

Step 1e: Additional Activity Data for Indirect N_2O Emissions

A portion of the N that is applied as synthetic fertilizer, livestock manure, sewage sludge, and other organic amendments volatilizes as NH_3 and NO_x. 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 is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation does 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- 221 through Table A- 226, and Table A- 228.

Using the DAYCENT model, volatilization and leaching/surface run-off of N from soils is computed internally for crops and non-federal grasslands in the Tier 3 method. 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 model 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 is also estimated by DAYCENT. Estimated leaching losses of N from DAYCENT are 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 are 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 are summed for the annual cycle. The implied emission factor for N volatilization ranges from 7 to 9 percent for cropland (Table A-15, Tier 1 default value is 10 percent). The implied emission factor for NO_3^- from leaching/runoff ranges from 25 to 31 percent for cropland (Table A-15, Tier 1 default value is 30 percent). The implied emission factor for N volatilization ranges from 21 to 57 percent for grassland (Table A-16, Tier 1 default value is 20 percent). The implied emission factor for NO_3^- from leaching/runoff ranges from 14 to 22 percent for grassland (Table A-16, Tier 1 default value is 30 percent). Uncertainty in the estimates is 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 is used to estimate N losses from mineral soils due to volatilization and leaching/runoff for crops, sewage sludge applications, and PRP manure on federal grasslands, which is simulated by DAYCENT. To estimate volatilized losses, synthetic fertilizers, manure, sewage sludge, and other organic N inputs are 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 ranges from 0.03-0.3 kg NH_3-N+NO_x-N/kg N for synthetic fertilizer and 0.05-0.5 kg NH_3-N+NO_x-N/kg N for organic amendments (IPCC 2006). Leaching/runoff losses of N are 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 is 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 are derived for each of the N inputs in the same manner as direct N_2O emissions, discussed in Steps 1a and 1c.

Volatilized N is summed for losses from croplands and grasslands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff are summed to obtain the total losses for this pathway.

Step 2: Estimate Soil Organic C Stock Changes and Direct N_2O Emissions from Mineral Soils

In this step, soil organic C stock changes and N_2O emissions are estimated for cropland, and non-federal grasslands. Three methods are used to estimate soil organic C stock changes and direct N_2O emissions from mineral soils. The DAYCENT process-based model is used for the croplands and non-federal grasslands included in the Tier 3 method. A Tier 2 method is used to estimate soil organic C stock changes for crop histories that included crops that were not simulated by DAYCENT and land use change other than conversions between cropland and grassland. A Tier 1 methodology is used to estimate N_2O emissions from crops that are not simulated by DAYCENT, as well as PRP manure N deposition on federal grasslands. Soil organic C stock changes and N_2O emissions are not estimated for federal grasslands (other than the effect of PRP manure N), but are under evaluation as a planned improvement and may be estimated in future inventories.

Step 2a: Estimate Soil Organic C Stock Changes and N_2O Emissions for Crops and Non-Federal Grassland with the Tier 3 DAYCENT Model

Crops that are simulated with DAYCENT include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, which combined represent approximately 85-87 percent of total cropland in the United States. The DAYCENT simulations also included all non-federal grasslands in the United States.

The methodology description is divided into two sub-steps. First, the model is used to establish the initial conditions and C stocks for 1979, which is the last year before the NRI survey is initiated. In the second sub-step, DAYCENT is used to estimate changes in soil organic C stocks and direct N_2O emissions based on the land-use and management histories recorded in the NRI from 1990 through 2007 (USDA-NRCS 2009).

Simulate Initial Conditions (Pre-NRI Conditions): DAYCENT 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, and 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 soil organic C algorithms 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, historical climate data based on the NARR product (1980-2007), 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 simulates 5,000 years in the pre-settlement era in order to achieve a steady-state condition.

The second step is to simulate the period of time from European settlement and expansion of agriculture 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 DAYCENT simulations has been 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).

NRI History Simulations: After model initialization, DAYCENT is used to simulate the NRI land use and management histories from 1979 through 2007.[17] The simulations address the influence of soil management on direct N_2O emissions, soil organic C stock changes and losses of N from the profile through leaching/runoff and volatilization. The NRI histories identify the land use and land use change histories for the NRI survey locations, as well as cropping patterns and irrigation history (see Step 1a for description of the NRI data). The input data for the model simulations also include the NARR weather dataset and SSURGO soils data, synthetic N fertilizer rates, managed manure amendments to cropland and grassland, manure deposition on grasslands (i.e., PRP), tillage histories and EVI data (See Step 1b for description of the inputs). The total number of DAYCENT simulations is over 18 million with a 100 repeated simulations (i.e., iterations) for each NRI point location in a Monte Carlo Analysis. The simulation system incorporates a dedicated MySQL database server and a 30-node parallel processing computer cluster. Input/output operations are managed by a set of run executive programs written in PERL.

The simulations for the NRI history are integrated with the uncertainty analysis. Evaluating uncertainty is an integral part of the analysis and includes three components: (1) uncertainty in the main activity data inputs affecting soil C and N_2O emissions (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, Del Grosso et al. 2010). For component 1, input uncertainty is evaluated for fertilization management, manure applications, and tillage, which are primary management activity data that are supplemental to the NRI observations and have significant influence on soil organic C dynamics and N_2O emissions. As described in Step 1b, PDFs are derived from surveys at the county scale for the inputs in most cases. In addition, uncertainty is included for predictions of EVI data that are needed to fill-data gaps and extend the time series (see Enhanced Vegetation Index in Step 1b). To represent uncertainty in all of these inputs, a Monte-Carlo Analysis is used with 100 iterations for each NRI point; random draws are made from PDFs for fertilizer, manure application, tillage, and EVI predictions. As described above, an adjustment factor is also selected from PDFs with normal densities to represent the dependence between manure amendments and N fertilizer application rates.

The second component deals with uncertainty inherent in model formulation and parameterization. This component is the largest source of uncertainty in the Tier 3 model-based inventory analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010, Del Grosso et al. 2010). An empirically-based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments (Ogle et al. 2007). For soil organic C, the DAYCENT model is evaluated with measurements from 84 long-term field experiments that have over 900 treatments, representing a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, and manure amendments). There are 24 experimental sites available to evaluate structural uncertainty in the N_2O emission predictions from DAYCENT (Del Grosso et al. 2010). The inputs to the model are essentially known in the simulations for the long-term experiments, and, therefore, the analysis is designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization). USDA is developing a national soil monitoring network to evaluate the Inventory in the future (Spencer et al. 2011).

[17] The estimated soil C stock change in 2007 is currently assumed to represent the changes between 2008 and 2013. More recent data will be incorporated in the future to extend the time series of land use and management data.

The relationship between modeled soil organic C stocks and field measurements are statistically analyzed using linear-mixed effect modeling techniques. Additional fixed effects are 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 are 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 cropland model includes variables for modeled soil organic C inclusion of hay/pasture in cropping rotations, use of no-till, set-aside lands, organic matter amendments, and inclusion of bare fallow in the rotation, which are significant at an alpha level of 0.05. The final grassland model only included the model soil organic C. These fixed effects are used to make an adjustment to modeled values due to biases that are creating significant mismatches between the modeled and measured stocks. For soil N_2O, simulated DAYCENT emissions are a highly significant predictor of the measurements, with a p-value of <0.01. Several other variables are considered in the statistical model to evaluate if DAYCENT exhibits bias under certain conditions related to climate, soil types, and management practices. Random effects are included in the model to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients.

A Monte Carlo approach is used to apply the uncertainty estimator (Ogle et al. 2010). Parameter values for the statistical equation (i.e., fixed effects) are 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 estimate and associated management information is then used as input into the equation, and adjusted values are computed for each C stock and N_2O emissions estimate. The variance of the adjusted estimates is computed from the 100 simulated values from the Monte Carlo analysis.

The third element is the uncertainty associated with scaling the DAYCENT results for each NRI point to the entire land base, using the expansion factors provided with the NRI survey dataset. The expansion factors represent the number of hectares associated with the land-use and management history for a particular point. This uncertainty is determined by computing the variances from a set of replicated weights for the expansion factor.

For the land base that is simulated with the DAYCENT model, soil organic C stock changes are provided in Table A-229, and soil N_2O emissions are provided in Table A-230.

Table A-229: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (MMT 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	(82.69)	(115.99) to (49.38)	17.62	6.29 to 28.95	(5.72)	(37.34) to 25.90	(4.64)	(9.78) to 0.49
1991	(83.48)	(120.71) to (46.25)	17.18	5.22 to 29.14	(4.52)	(41.33) to 32.29	(5.29)	(10.03) to (0.55)
1992	(80.27)	(116.28) to (44.27)	17.89	7.02 to 28.76	(6.01)	(39.89) to 27.88	(4.62)	(9.19) to (0.04)
1993	(57.97)	(88.89) to (27.05)	17.72	6.85 to 28.59	(5.23)	(45.57) to 35.11	(3.87)	(9.48) to 1.74
1994	(64.31)	(99.09) to (29.53)	12.14	(0.14) to 24.41	(17.37)	(53.36) to 18.61	(5.78)	(11.64) to 0.08
1995	(52.02)	(85.83) to (18.21)	16.42	4.25 to 28.58	4.80	(31.63) to 41.22	(5.20)	(10.97) to 0.57
1996	(57.52)	(91.20) to (23.84)	13.47	(0.01) to 26.96	(19.06)	(58.70) to 20.57	(5.62)	(11.21) to (0.04)
1997	(54.48)	(88.29) to (20.67)	15.43	3.41 to 27.45	(4.96)	(40.20) to 30.28	(6.11)	(11.52) to (0.70)
1998	(43.18)	(83.97) to (2.40)	10.38	(3.73) to 24.49	(9.67)	(45.83) to 26.49	(6.33)	(13.06) to 0.40
1999	(50.51)	(84.83) to (16.20)	11.95	(0.63) to 24.52	(2.36)	(43.30) to 38.58	(6.36)	(12.86) to 0.14
2000	(57.01)	(92.94) to (21.09)	10.77	(3.58) to 25.12	(32.81)	(73.76) to 8.13	(7.98)	(15.78) to (0.17)
2001	(51.58)	(85.83) to (17.33)	11.34	(0.76) to 23.43	(12.90)	(51.31) to 25.50	(8.43)	(16.50) to (0.35)
2002	(38.56)	(67.55) to (9.56)	13.28	1.75 to 24.81	(14.30)	(52.36) to 23.77	(7.29)	(15.0) to 0.41
2003	(36.79)	(68.80) to (4.78)	11.84	0.46 to 23.23	(12.64)	(50.97) to 25.69	(7.51)	(15.81) to 0.80
2004	(45.63)	(79.31) to (11.94)	11.58	(0.23) to 23.39	(0.06)	(36.60) to 36.47	(7.32)	(16.20) to 1.56
2005	(47.60)	(81.87) to (13.32)	13.21	0.61 to 25.81	2.19	(39.72) to 44.10	(7.74)	(16.10) to 0.63
2006	(48.92)	(85.18) to (12.66)	11.25	(1.55) to 24.04	(18.98)	(54.14) to 16.19	(8.86)	(18.19) to 0.46
2007	(49.33)	(83.74) to (14.93)	9.79	(1.33) to 20.91	10.20	(25.62) to 46.01	(7.48)	(16.97) to 2.0
2008	(48.81)	(82.39) to (15.23)	9.86	(1.71) to 21.42	9.81	(27.07) to 46.68	(7.52)	(16.76) to 1.72
2009	(48.81)	(82.39) to (15.23)	9.86	(1.71) to 21.42	9.83	(27.06) to 46.73	(7.50)	(16.71) to 1.72
2010	(48.81)	(82.39) to (15.23)	9.86	(1.71) to 21.42	9.86	(27.05) to 46.76	(7.47)	(16.66) to 1.72
2011	(48.81)	(82.39) to (15.23)	9.86	(1.71) to 21.42	9.88	(27.05) to 46.80	(7.45)	(16.62) to 1.72
2012	(49.11)	(82.13) to (16.09)	9.76	(1.51) to 21.03	9.76	(26.46) to 45.98	(7.36)	(16.86) to 2.13
2013	(49.33)	(83.74) to (14.93)	9.79	(1.33) to 20.91	10.34	(25.53) to 46.22	(7.34)	(16.68) to 2.01

Note: Estimates after 2007 are based on NRI data from 2007 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-230: Annual N_2O Emissions (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (MMT CO_2 Eq.)

	Tier 3 Cropland		Non-Federal Grasslands	
Year	Estimate	95% CI	Estimate	95% CI
1990	95.7	90.34 to 103.32	68.1	63.01 to 75.29
1991	103.3	97.48 to 111.66	84.2	78.53 to 92.15
1992	104.1	97.99 to 112.89	71.2	66.57 to 77.52
1993	108.5	102.2 to 117.33	77.4	72.73 to 83.94
1994	101.8	96.57 to 109.01	68.7	64.84 to 73.98
1995	104.8	99.22 to 112.52	77.5	72.87 to 83.87
1996	114.8	108.67 to 123.16	80.7	76.07 to 87.03
1997	111.9	105.8 to 120.31	80.3	75.59 to 86.64
1998	101.1	95.5 to 108.94	72.2	67.74 to 78.39
1999	100.9	95.68 to 107.98	62.2	58.77 to 67.01
2000	93.6	89.01 to 99.61	59.0	55.59 to 63.64
2001	107.1	101.88 to 113.89	69.9	65.26 to 76.43
2002	103.6	98.52 to 110.38	63.6	59.76 to 68.94
2003	97.5	92.65 to 103.96	61.3	57.78 to 66.05
2004	104.7	99.41 to 111.83	74.9	70.24 to 81.18
2005	107.8	102.45 to 114.96	72.3	68.21 to 77.96
2006	104.5	98.99 to 111.77	66.7	62.69 to 72.13
2007	110.4	104.59 to 118.27	84.4	78.79 to 92.18
2008	115.0	109.11 to 122.73	84.0	78.37 to 91.97
2009	114.4	108.54 to 122.15	83.9	78.24 to 91.83
2010	113.3	107.4 to 121.03	83.8	78.12 to 91.7
2011	112.4	106.55 to 120.18	83.7	78 to 91.57
2012	112.3	106.39 to 120.15	83.1	77.48 to 91.0
2013	112.1	106.22 to 119.88	83.6	78.01 to 91.33

In DAYCENT, the model cannot distinguish among the original sources of N after the mineral N enters the soil pools, and therefore it is not possible 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 NRI point, the N inputs in a simulation are 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 is divided by the total N input, and this proportion is used to determine the amount of N_2O emissions assigned to each of the practices.[18] For example, if 70 percent of the mineral N made available in the soil is due to mineral fertilization, then 70 percent of the N_2O emissions are 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 N fixation 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 cropland soils compared to application of synthetic fertilizers and manure amendments, along with symbiotic fixation. Mineralization of soil organic matter accounts for the majority of available N in grassland soils. Accounting for the influence of "other N inputs" is necessary in order to meet the recommendation for 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 results associated with subdividing the N_2O emissions based on N inputs are provided in Table A- 231 and Table A- 232.

[18] 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 currently 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). Further research and model development may allow for other approaches in the future.

Table A- 231: Direct N_2O Emissions from Cropland Soils (MMT CO_2 Eq.)

N Source	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Mineral Soils	**114.4**	**124.7**	**113.2**	**126.2**	**123.5**	**119.0**	**126.2**	**128.0**	**126.6**	**131.7**	**134.9**	**133.5**	**133.7**	**134.7**	**135.1**	**133.2**
Tier 3 Cropland	**95.7**	**104.8**	**93.6**	**107.1**	**103.6**	**97.5**	**104.7**	**107.8**	**104.5**	**110.4**	**115.0**	**114.4**	**113.3**	**112.4**	**112.3**	**112.1**
Synthetic Fertilizer	41.4	42.4	40.8	44.5	43.3	40.4	42.7	45.1	42.4	48.3	50.5	49.8	49.8	48.8	48.8	48.9
Managed Manure	4.0	4.1	4.3	4.6	4.5	4.2	4.4	4.5	4.4	4.8	5.0	5.0	5.0	5.0	5.0	5.0
Residue N[a]	2.7	3.1	2.8	3.2	2.8	2.9	3.1	3.3	3.1	3.2	3.3	3.3	3.3	3.3	3.3	3.2
Mineralization and Asymbiotic Fixation	47.7	55.2	45.7	54.8	52.9	50.1	54.6	54.9	54.7	54.1	56.2	56.3	55.3	55.3	55.2	54.9
Tier 1 Cropland	**18.8**	**19.9**	**19.6**	**19.1**	**19.9**	**21.5**	**21.5**	**20.2**	**22.1**	**21.3**	**19.9**	**19.1**	**20.4**	**22.3**	**22.8**	**21.1**
Synthetic Fertilizer	8.0	8.6	8.8	8.2	9.0	10.3	10.5	9.2	10.8	10.1	8.8	8.0	9.5	11.3	11.8	9.9
Managed Manure and Other Organic Commercial Fertilizer	7.2	8.1	7.8	7.9	8.1	8.2	7.8	8.0	8.5	8.2	8.2	8.1	8.0	8.2	8.3	8.2
Residue N	3.5	3.2	3.1	3.0	2.8	3.0	3.1	3.0	2.8	2.9	2.9	3.0	2.9	2.8	2.7	2.9
Organic Soils	**2.7**	**2.6**	**2.5**	**2.7**	**2.6**	**2.7**	**2.6**	**2.6**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total*	**117.1**	**127.3**	**115.7**	**128.9**	**126.1**	**121.6**	**128.8**	**130.6**	**129.1**	**134.2**	**137.4**	**136.0**	**136.2**	**137.2**	**137.6**	**135.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 232: Direct N_2O Emissions from Grasslands (MMT CO_2 Eq.)

N Source	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Mineral Soils	**71.4**	**81.2**	**62.7**	**73.5**	**67.2**	**64.8**	**78.3**	**75.8**	**70.2**	**87.8**	**87.4**	**87.2**	**87.1**	**86.9**	**86.4**	**86.9**
Tier 3	**68.1**	**77.5**	**59.0**	**69.9**	**63.6**	**61.3**	**74.9**	**72.3**	**66.7**	**84.4**	**84.0**	**83.9**	**83.8**	**83.7**	**83.1**	**83.6**
Synthetic Fertilizer	1.9	1.5	1.9	2.2	2.3	1.7	2.1	1.8	1.9	1.9	1.9	1.9	1.9	2.0	2.1	2.2
PRP Manure	13.4	16.6	13.0	15.5	14.4	13.2	14.3	14.4	14.0	15.7	15.5	15.4	15.2	14.9	14.5	14.4
Managed Manure	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Residue N[a]	1.8	2.2	1.4	1.9	1.7	1.7	2.0	2.1	1.9	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Mineralization and Asymbiotic Fixation	50.7	56.8	42.5	50.0	44.9	44.4	56.2	53.6	48.5	64.2	64.0	64.0	64.0	64.1	63.9	64.3
Tier 1	**3.3**	**3.8**	**3.6**	**3.6**	**3.6**	**3.5**	**3.5**	**3.5**	**3.5**	**3.4**	**3.4**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
PRP Manure	3.1	3.4	3.3	3.2	3.2	3.1	3.0	3.1	3.1	2.9	2.9	2.8	2.8	2.7	2.7	2.7
Sewage Sludge	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Organic Soils	**2.3**	**2.2**	**2.1**	**2.3**	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Total	**73.7**	**83.4**	**64.8**	**75.8**	**69.5**	**67.0**	**80.6**	**78.1**	**72.4**	**90.0**	**89.6**	**89.4**	**89.2**	**89.1**	**88.5**	**89.0**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.
[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Step 2b: Soil N_2O Emissions from Agricultural Lands on Mineral Soils Approximated with the Tier 1 Approach

To estimate direct N_2O emissions from N additions to crops in the Tier 1 method, the amount of N in applied synthetic fertilizer, manure and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) is added to N inputs from crop residues, and the resulting annual totals are multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006). The uncertainty is determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranges from 0.3–3.0 kg N_2O-N/kg N (IPCC 2006). For flooded rice soils, the IPCC default emission factor is 0.003 kg N_2O-N/kg N and the uncertainty range is 0.000–0.006 kg N_2O-N/kg N (IPCC 2006).[1] Uncertainties in the emission factor and fertilizer additions are 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.

The Tier 1 method is also used to estimate emissions from manure N deposited by livestock on federal lands (i.e., PRP manure N), and from sewage sludge application to grasslands. These two sources of N inputs to soils are multiplied by the IPCC (2006) default emission factors (0.01 kg N_2O-N/kg N for sludge and horse, sheep, and goat manure, and 0.02 kg N_2O-N/kg N for cattle, swine, and poultry manure) to estimate N_2O emissions (Table A- 232). The uncertainty is 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).

Step 2c: Soil Organic C Stock Changes in Agricultural Lands on Mineral Soils Approximated with the Tier 2 Approach

Mineral soil organic C stock values are derived for crop rotations that were not simulated by DAYCENT and land converted from non-agricultural land uses to cropland or grassland in 1982, 1992, 1997, 2002 and 2007, based on the land-use and management activity data in conjunction with appropriate reference C stocks, land-use change, management, input, and wetland restoration factors. Each input to the inventory calculations for the Tier 2 approach has some level of uncertainty that is quantified in PDFs, including the land-use and management activity data, reference C stocks, and management factors. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on uncertainty in the inputs. Input values are 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.

Derive Mineral Soil Organic C Stock Change Factors: Stock change factors representative of U.S. conditions are 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). Studies from the United States and Canada are used in this analysis under the assumption that they would best represent management impacts for the Inventory.

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-233). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

[1] 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.

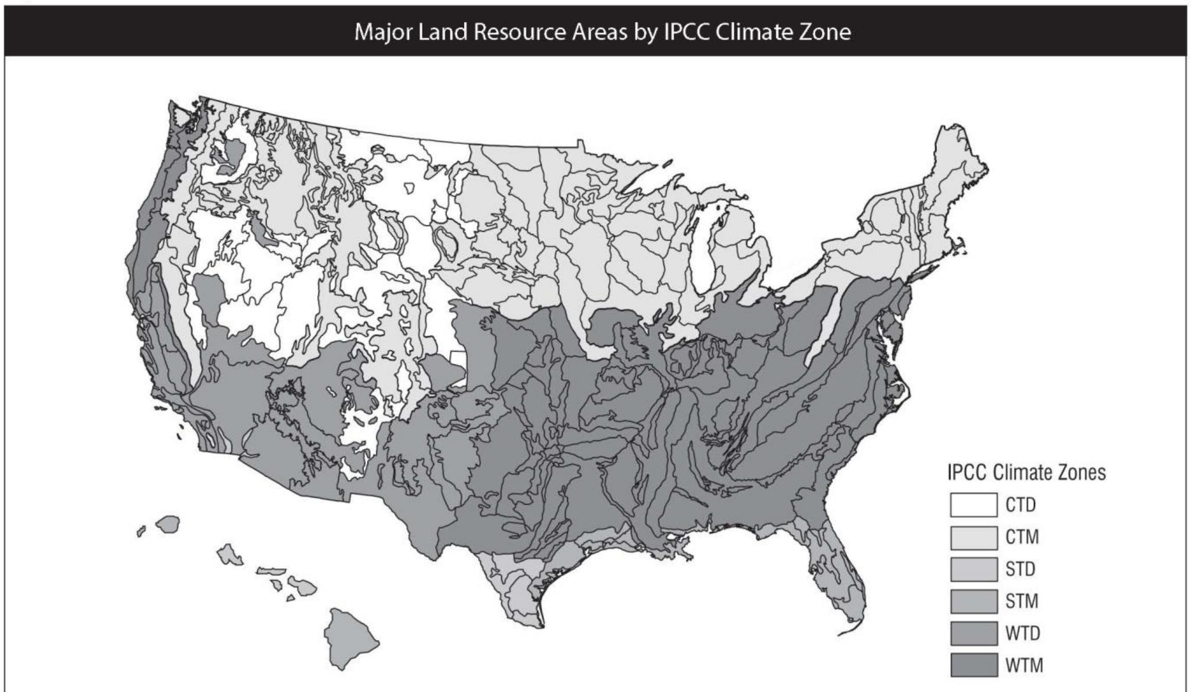
Table A-233: Characteristics of the IPCC Climate Zones that Occur in the United States

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[a]	> 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) are used to classify climate zones. Mean annual precipitation and annual temperature data are averaged (weighted by area) for each of the 4×4 km grid cells occurring within a MLRA region. These averages are used to assign a climate zone to each MLRA according to the IPCC climate classification (Figure A-14). 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-14: 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.

Soils are 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, are 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-234). These stocks are used in conjunction with management factors to estimate the change in SOC stocks that result from management and land-use activity. PDFs, which represent the variability in the stock estimates, are constructed as normal densities based on the mean and variance from the pedon data. Pedon locations are 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 are tested for spatial autocorrelation using the Moran's I test, and variance terms are inflated by 10 percent for all zones with significant p-values.

Table A-234: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

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

To estimate the land use, management and input factors, 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 are 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 are not aggregated for the C stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) is included as a separate point in the dataset. Similarly, time series data are not aggregated in these datasets. Linear regression models assume that the underlying data are independent observations, but this is not the case with data from the same experimental site, or plot in a time series. These data are more related to each other than data from other sites (i.e., not independent). Consequently, random effects are 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 are estimated for the effect of management practices at 20 years for the top 30 cm of the soil (Table A-235). Variance is 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 C stock changes in 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.[2] 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 are insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2006) are 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 is provided for these factors in IPCC (2006), which is used to construct PDFs.

[2] Improved grasslands are identified in the 2007 *National Resources Inventory* as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-235: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

	IPCC default	U.S. Factor 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-Asidea (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Grassland Factors					
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[b]	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[b]	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) are converted to represent changes in SOC storage from a cultivated condition rather than a native condition.
[b] U.S.-specific factors are 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 (2006) are 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 is 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-236). A PDF with a normal density is 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 is 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 are used to construct a PDF with a normal density (Table A-236).

Table A-236: Factor Estimate for the Initial Increase and Subsequent Annual Mass Accumulation Rate (Mg C/ha-yr) in Soil Organic 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

Note: Mass accumulation rate represents additional gains in C for mineral soils after the first 10 years (Euliss and Gleason 2002).

Estimate Annual Changes in Mineral Soil Organic C Stocks: In accordance with IPCC methodology, annual changes in mineral soil C are calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[3] 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 1997 is the difference between the 1997 and 1992 C stocks. The annual average change between 1998 and 2002 is the difference between the 1998 and 2002 C stocks. The annual average change between 2003 and 2013 is the difference between the 2003 and 2007. Using the Monte Carlo approach, SOC stock changes for mineral soils are estimated 50,000 times between 1982 and 1992, 1993 and 1997, 1998 and 2002, and 2003 and 2007. From the final distribution of 50,000 values, a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution (Ogle et al. 2003). Soil organic C stock changes are provided in Table A-237.

[3] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

Table A-237: 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 (MMT CO_2 Eq./yr)

Croplands:	Cropland Remaining Cropland		Grassland Converted to Cropland		Forest Converted to Cropland		Other Land Converted to Cropland		Settlements Converted to Cropland		Wetlands Converted to Cropland	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990-1992	-6.49	(9.24) to (4.07)	2.34	1.29 to 3.48	1.47	0.81 to 2.18	0.26	0.14 to 0.38	0.56	.31 to .83	0.18	.10 to .27
1993-1997	-7.64	(10.70) to (4.79)	2.02	1.06 to 3.06	1.39	0.73 to 2.12	0.28	0.15 to 0.43	0.74	.39 to 1.13	0.25	.13 to .38
1998-2002	-6.93	(9.67) to (4.44)	1.78	0.90 to 2.73	0.82	0.41 to 1.25	0.27	0.13 to 0.41	0.65	.33 to 1.0	0.21	.10 to .32
2003-2013	-2.82	(5.08) to (0.91)	0.78	0.40 to 1.20	0.26	0.13 to 0.40	0.11	0.06 to 0.17	0.32	.16 to .50	0.08	.04 to .12
Organic Soils												
1990	23.98	15.43 to 34.78	2.51	1.36 to 4.05	0.83	0.34 to 1.51	-	-	0.14	0.06 to 0.26	0.67	0.37 to 1.09
1991	23.72	15.21 to 34.31	2.59	1.40 to 4.12	0.83	0.35 to 1.51	-	-	0.09	0.03 to 0.16	0.67	0.36 to 1.09
1992	23.74	15.27 to 34.52	2.43	1.33 to 3.90	0.77	0.29 to 1.43	-	-	0.09	0.03 to 0.16	0.62	0.34 to .98
1993	23.01	14.68 to 33.58	2.75	1.56 to 4.32	0.81	0.32 to 1.50	-	-	0.19	0.09 to 0.33	0.68	0.39 to 1.06
1994	22.40	14.36 to 32.77	3.10	1.78 to 4.83	0.85	0.35 to 1.55	-	-	0.35	0.18 to 0.59	0.79	0.47 to 1.18
1995	22.19	14.12 to 32.46	3.11	1.77 to 4.90	0.81	0.32 to 1.52	-	-	0.35	0.18 to 0.58	0.80	0.49 to 1.20
1996	21.83	13.88 to 31.93	3.25	1.87 to 5.09	0.93	0.40 to 1.67	-	-	0.36	0.19 to 0.59	0.81	0.49 to 1.22
1997	21.69	13.75 to 31.76	3.33	1.92 to 5.20	0.93	0.40 to 1.67	-	-	0.36	0.19 to 0.59	0.81	0.49 to 1.21
1998	21.72	13.63 to 32.09	3.44	1.85 to 5.55	0.83	0.30 to 1.58	-	-	0.36	0.08 to 0.73	0.86	0.25 to 1.68
1999	21.64	13.63 to 31.77	3.34	1.77 to 5.44	0.76	0.31 to 1.39	-	-	0.36	0.08 to 0.72	0.67	0.28 to 1.26
2000	21.52	13.51 to 31.60	3.26	1.77 to 5.27	0.70	0.27 to 1.31	-	-	0.26	0.04 to 0.55	0.62	0.24 to 1.20
2001	21.96	13.84 to 32.17	4.68	1.91 to 9.31	0.42	0.14 to 0.80	-	-	0.29	0.06 to 0.59	0.62	0.24 to 1.19
2002	21.92	13.85 to 32.08	4.34	1.73 to 8.88	0.29	0.04 to 0.63	-	-	0.27	0.05 to 0.57	0.48	0.17 to 1.01
2003	22.92	14.50 to 33.46	4.04	1.70 to 7.89	0.26	0.02 to 0.60	-	-	0.27	0.04 to 0.56	0.30	0.15 to 0.50
2004	22.61	14.24 to 33.46	4.36	1.03 to 11.27	0.29	0.0 to 0.95	-	-	0.21	0.12 to 0.34	0.30	0.14 to 0.50
2005	22.39	14.06 to 33.01	4.29	0.95 to 11.22	0.27	0.0 to 0.91	-	-	0.21	0.12 to 0.34	0.30	0.14 to 0.50
2006	22.29	13.98 to 32.83	4.17	0.86 to 11.10	0.22	0.0 to 0.81	-	-	0.20	0.11 to 0.32	0.30	0.14 to 0.50
2007	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2008	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2009	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2010	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2011	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2012	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61
2013	22.14	14.05 to 32.46	4.02	0.69 to 10.93	0.23	0.0 to 0.81	-	-	0.18	0.10 to 0.29	0.36	0.17 to 0.61

Note: Estimates after 2007 are based on NRI data from 2007 and therefore do not fully reflect changes occurring in the latter part of the time series.

Grasslands:	Grassland Remaining Grassland		Cropland Converted to Grassland		Forest Converted to Grassland		Other Land Converted to Grassland		Settlements Converted to Grassland		Wetlands Converted to Grassland	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990-1992	-0.19	(0.38) to (0.03)	-1.73	(2.41) to (1.06)	-1.07	(1.51) to (0.67)	-0.19	(0.27) to (0.12)	-0.41	(0.58) to (0.26)	-0.13	(0.19) to (0.08)
1993-1997	-0.08	(0.18) to 0.0	-1.56	(2.18) to (0.94)	-1.06	(1.51) to (0.65)	-0.21	(0.31) to (0.13)	-0.56	(0.80) to (0.35)	-0.19	(0.27) to (0.12)
1998-2002	-0.01	(0.08) to 0.06	-1.74	(2.47) to (1.03)	-0.79	(1.14) to (0.47)	-0.26	(0.37) to (0.15)	-0.63	(0.91) to (0.38)	-0.20	(0.29) to (0.12)
2003-2013	0.10	0.01 to 0.21	-1.28	(1.86) to (0.71)	-0.42	(0.62) to (0.24)	-0.18	(0.27) to (0.10)	-0.52	(0.77) to (0.29)	-0.13	(0.19) to (0.07)
Organic Soils												
1990	4.60	2.54 to 7.33	0.54	0.24 to 0.98	0.11	0.03 to 0.23	-	-	0.01	0.0 to 0.05	0.10	0.02 to 0.22
1991	4.50	2.47 to 7.19	0.50	0.22 to 0.92	0.11	0.03 to 0.24	0.02	0.0 to 0.05	0.01	0.0 to 0.05	0.10	0.02 to 0.22
1992	4.47	2.45 to 7.14	0.55	0.24 to 0.99	0.11	0.03 to 0.23	-	-	0.01	0.0 to 0.05	0.10	0.01 to 0.24
1993	4.40	2.42 to 7.03	0.56	0.25 to 1.02	0.10	0.03 to 0.22	-	-	0.02	0.0 to 0.06	0.11	0.03 to 0.24
1994	4.29	2.37 to 6.87	0.69	0.31 to 1.23	0.11	0.02 to 0.23	-	-	0.02	0.0 to 0.06	0.16	0.07 to 0.31
1995	4.14	2.28 to 6.61	0.73	0.34 to 1.30	0.11	0.02 to 0.23	-	-	0.02	0.0 to 0.06	0.17	0.07 to 0.32
1996	4.04	2.22 to 6.47	0.71	0.33 to 1.25	0.10	0.02 to 0.23	-	-	0.02	0.0 to 0.06	0.17	0.07 to 0.32
1997	3.91	2.14 to 6.28	0.74	0.35 to 1.30	0.11	0.02 to 0.23	0.01	0.0 to 0.04	0.01	0.0 to 0.03	0.17	0.07 to 0.32
1998	3.80	1.96 to 6.32	0.89	0.40 to 1.63	0.10	0.0 to 0.27	-	-	0.02	0.0 to 0.06	0.18	0.05 to 0.38
1999	3.73	1.92 to 6.25	0.89	0.40 to 1.62	0.10	0.0 to 0.27	-	-	0.02	0.0 to 0.06	0.17	0.05 to 0.38
2000	3.69	1.91 to 6.14	0.88	0.40 to 1.62	0.09	0.0 to 0.23	-	-	0.03	0.01 to 0.07	0.17	0.05 to 0.38
2001	3.28	1.76 to 5.33	0.94	0.42 to 1.70	0.08	0.0 to 0.22	-	-	0.02	0.0 to 0.06	0.16	0.04 to 0.35
2002	3.24	1.72 to 5.24	1.05	0.45 to 1.96	0.05	0.0 to 0.16	-	-	0.02	0.0 to 0.06	0.16	0.04 to 0.34
2003	3.08	1.66 to 4.97	0.92	0.39 to 1.73	0.05	0.0 to 0.16	0.01	.0 to 0.05	0.02	0.0 to 0.06	0.09	0.05 to 0.16
2004	3.05	1.66 to 4.90	1.03	0.39 to 2.03	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.19
2005	3.06	1.67 to 4.91	1.05	0.40 to 2.05	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.12	0.06 to 0.22
2006	2.97	1.59 to 4.81	0.97	0.36 to 1.93	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.21
2007	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2008	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2009	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2010	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2011	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2012	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20
2013	3.03	1.62 to 4.93	0.90	0.33 to 1.78	0.07	0.0 to 0.24	-	-	0.03	0.0 to 0.07	0.11	0.05 to 0.20

Note: Estimates after 2007 are based on NRI data from 2007 and therefore do not fully reflect changes occurring in the latter part of the time series.

Step 2d: Estimate Additional Changes in Soil Organic C Stocks Due to CRP Enrollment after 2007 and Sewage Sludge Amendments

There are two additional land use and management activities in U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves 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 is assumed that sewage sludge for agricultural land application is 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 is 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-235), by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions are that reference C stock are 50 metric tonnes C/ha, which represents a mid-range value of reference C stocks for the cropland soils in the United States,[1] that the land use factor for grassland of 1.4 and 1.11 for high input improved grassland are representative of typical conditions, and that the change in stocks are occurring over a 20 year (default value) time period (i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). A nominal ±50 percent uncertainty is 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 influence of sewage sludge on soil organic C stocks are provided in Table A- 238.

The second activity is the change in enrollment for the Conservation Reserve Program after 2007 for mineral soils. Relative to the enrollment in 2007, the total area in the Conservation Reserve Program has decreased from 2008 to 2013 (USDA-FSA 2013). An average annual change in SOC of 0.5 metric tonnes C/ha-yr is 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-235) by estimating the impact of setting aside a medium input cropping system in the Conservation Reserve Program. The assumptions are that reference C stock are 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 is 1.2 for setting-aside cropland from production, with the change in stocks occurring over a 20 year (default value) time period equal to 0.5 (i.e., $[50 \times 1.2 - 50] / 20 = 0.5$). A nominal ±50 percent uncertainty is attached to these estimates due to limited information about the enrollment trends at subregional scales, which creates uncertainty in the rate of soil C stock change (stock change factors for set-aside lands vary by climate region). Estimates are provided in Table A- 243.

Step 3: Estimate Soil Organic C Stock Changes and Direct N_2O Emissions from Organic Soils

In this step, soil organic C losses and N_2O emissions are estimated for organic soils that are drained for agricultural production.

Step 3a: Direct N_2O Emissions Due to Drainage of Organic Soils in Cropland and Grassland

To estimate annual N_2O emissions from drainage of organic soils in cropland and grassland, the area of drained organic soils in croplands and grasslands for temperate regions is multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions is 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 is 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 3b: Soil Organic C Stock Changes Due to Drainage of Organic Soils in Cropland and Grassland

Change in soil organic C stocks due to drainage of cropland and grassland soils are estimated annually from 1990 through 2007, based on the land-use and management activity data in conjunction with appropriate loss rate emission factors. The activity data are based on annual data from 1990 through 2007 from the NRI. The results for 2007 are applied to the years 2007 through 2013. Organic Soil emission factors representative of U.S. conditions have been estimated from published studies (Ogle et al. 2003), based on subsidence studies in the United States and Canada (Table A-239). PDFs are constructed as normal densities based on the mean C loss rates and associated variances. Input values are randomly selected from PDFs in a Monte Carlo analysis to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results.. Losses of soil organic C from drainage of cropland and grassland soils are provided in Table A-237.

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[1] Reference C stocks are based on cropland soils for the Tier 2 method applied in this Inventory.

Step 4: Estimate Indirect N_2O Emissions for Croplands and Grasslands

In this step, N_2O emissions are estimated for the two indirect emission pathways (N_2O emissions due to volatilization, and N_2O emissions due to leaching and runoff of N), which are summed to yield total indirect N_2O emissions from croplands and grasslands.

Step 4a: Indirect Soil N_2O Emissions Due to Volatilization

Indirect emissions from volatilization of N inputs from synthetic and commercial organic fertilizers, and PRP manure, are calculated according to the amount of mineral N that is transported in gaseous forms from the soil profile and later emitted as soil N_2O following atmospheric deposition. See Step 1e for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized is multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) to estimate total N_2O emissions from volatilization. The uncertainty is estimated 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). The estimates and uncertainties are provided in Table A- 240.

Step 4b: Indirect Soil N_2O Emissions Due to Leaching and Runoff

The amount of mineral N from synthetic fertilizers, commercial organic fertilizers, PRP manure, crop residue, N mineralization, asymbiotic fixation that is transported from the soil profile in aqueous form is used to calculate indirect emissions from leaching of mineral N from soils and losses in runoff of water associated with overland flow. See Step 1e 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 is 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 emission estimates are provided in Table A-242. The uncertainty is estimated 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 Soil Organic C Stock Changes and N_2O Emissions for U.S. Soils

Step 5a: Estimate Total Soil N_2O Emissions

Total N_2O emissions are estimated by adding total direct emissions (from mineral cropland soils, drainage and cultivation of organic soils, and grassland management) to indirect emissions. Uncertainties in the final estimate are combined using simple error propagation methods (IPCC 2006), and expressed as a 95 percent confidence interval. Estimates and uncertainties are provided in Table A- 238.

Direct and indirect simulated emissions of soil N_2O vary regionally in croplands as a function of N input amount and timing of fertilization, tillage intensity, crop rotation sequence, weather, and soil type. Note that there are other management practices, such as fertilizer formulation (Halvorson et al. 2013), that influence emissions but are not represented in the model simulations. The highest total N_2O emissions occur in Iowa, Illinois, Kansas, Minnesota, Nebraska and Texas (Table A- 243). On a per area unit basis, direct N_2O emissions are high in the northeast and many of the Mississippi River Basin states where there are high N inputs to hay, corn and soybean crops, and in some western states where irrigated crops are grown that require high N inputs (Figure A-15). Note that although the total crop area in the northeast is relatively low, emissions are high on a per unit area basis because a large portion of the cropland area in these states is used for hay production that receives large N inputs from both fertilizer and symbiotic fixation. Indirect emissions also tend to be high on a per unit of area basis in some northeastern states and Florida. In Florida, the high emission rates are driven by relatively high rainfall and coarse textured soils that facilitate N losses from leaching and runoff. Some Great Plains states also have indirect emissions where irrigation can contribute to leaching and runoff (Figure A-16).

Direct and indirect emissions from non-federal grasslands are typically lower than those from croplands (Table A- 244, Figure A-17, and Figure A-18) because N inputs tend to be lower, particularly from synthetic fertilizer. Texas, Oklahoma, Kansas, Nebraska, Missouri, Colorado, South Dakota and Montana are the highest emitters for this category due to large land areas used for pastures and rangeland. On a per unit of area basis, emissions are higher in the Northeastern United States and some of the Great Lakes and Midwestern states because these grasslands 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, but N volatilization can be substantial.

Figure A-15: Tier 3 Cropland,2013 Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, (kg N/ha/year)

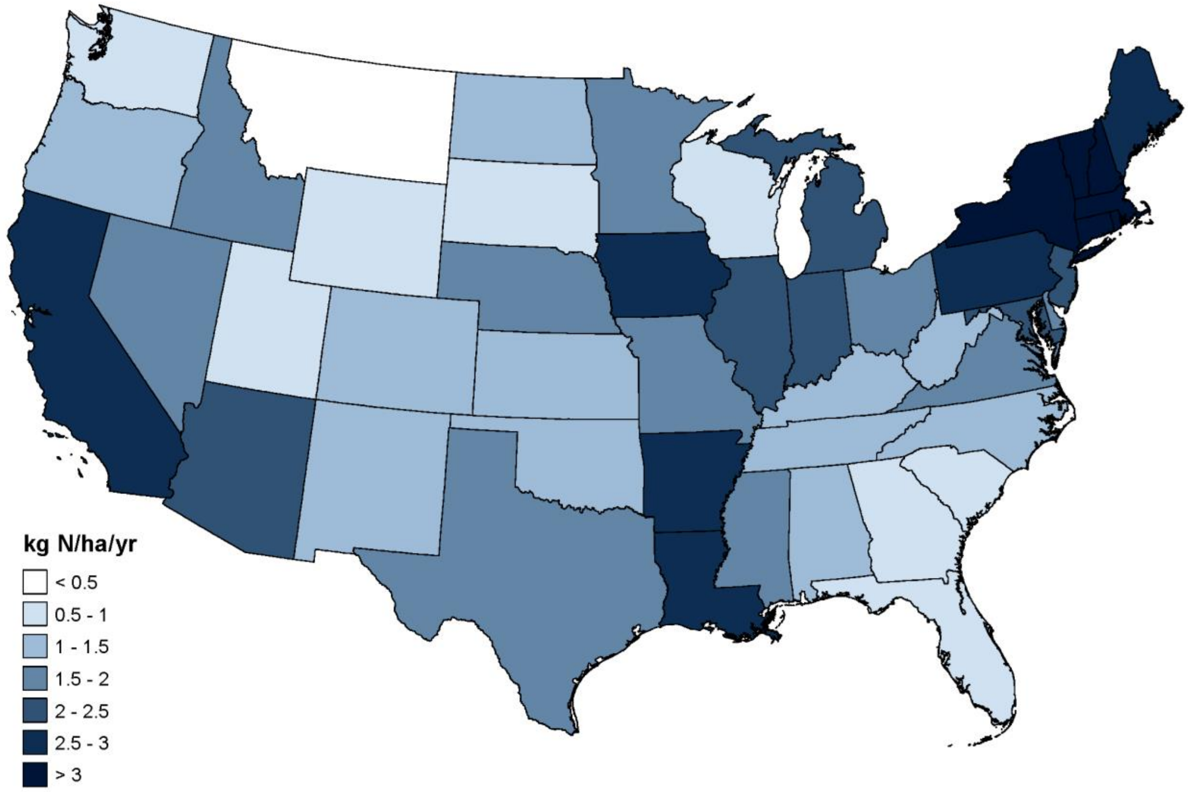


Figure A-16: Tier 3 Crops, 2013 Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, (kg N/ha/year)

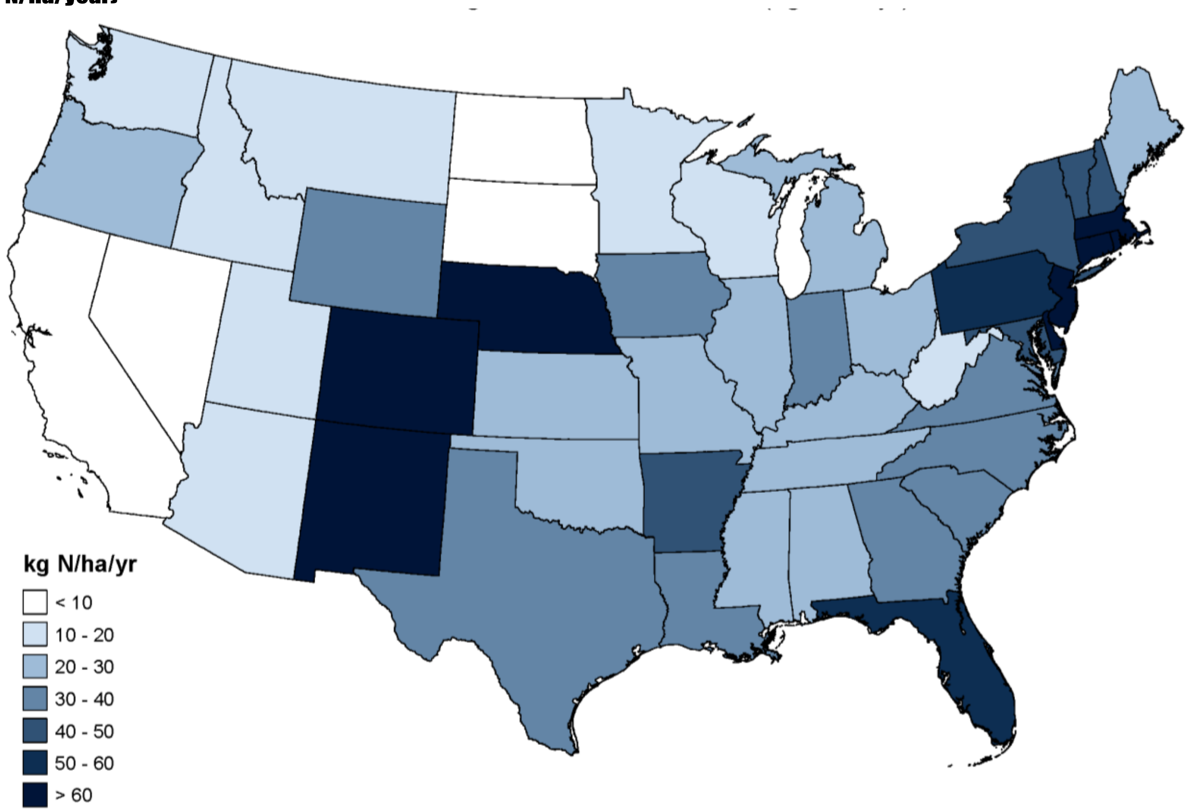


Figure A-17: Non-federal Grasslands, 2013 Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, (kg N/ha/year)

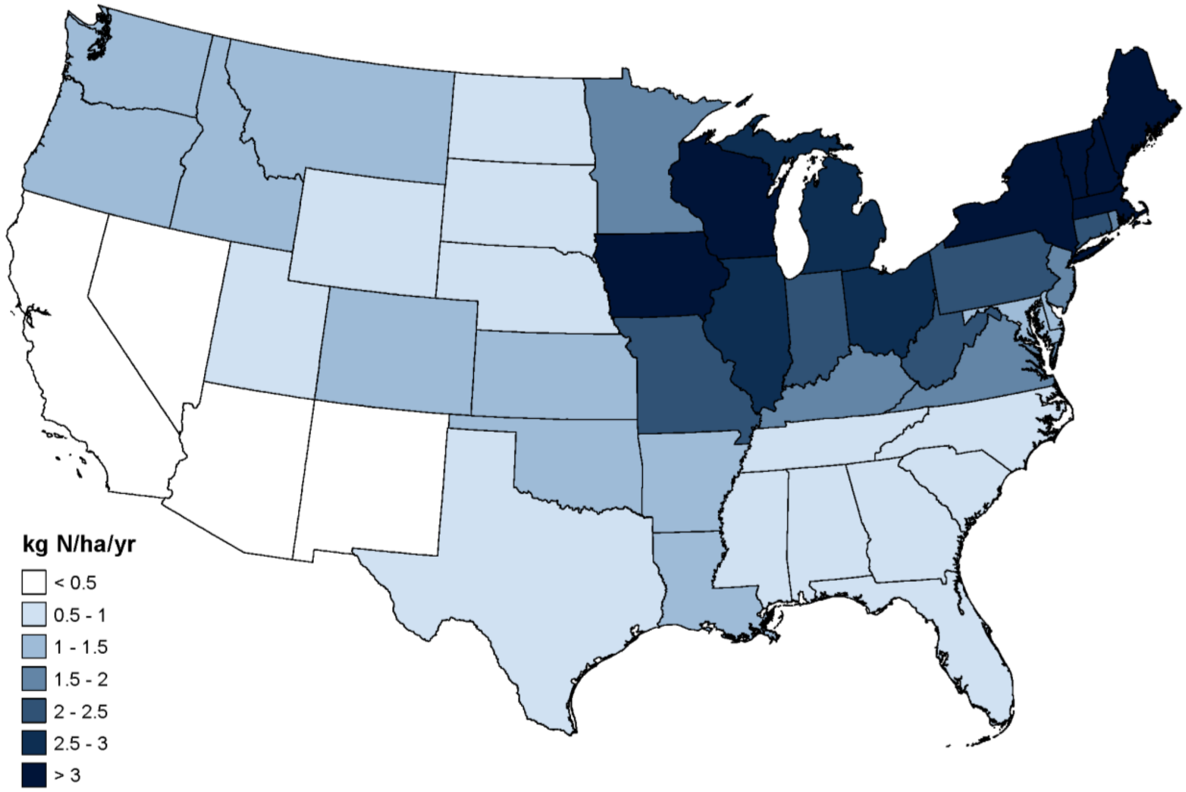
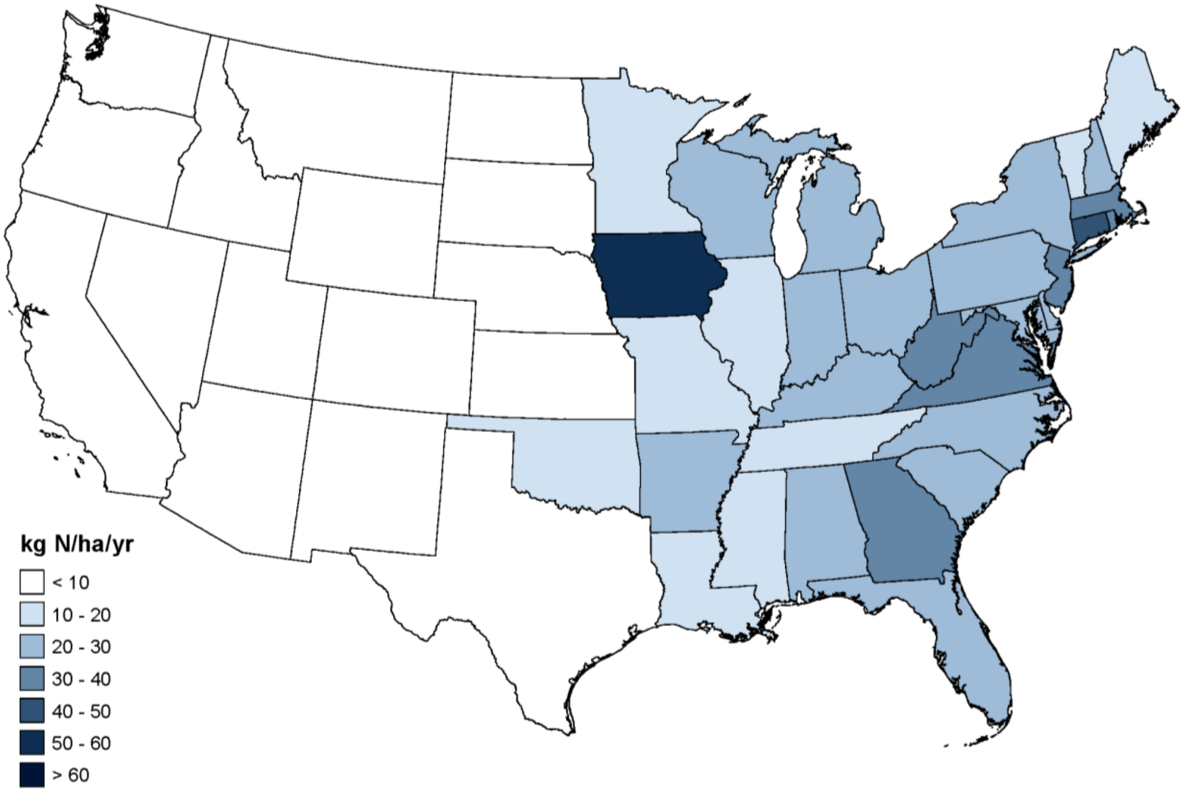


Figure A-18: Non-federal Grasslands, 2013 Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, (kg N/ha/year)



Step 5b: Estimate Total Soil Organic Stock Change

The sum of total CO_2 emissions and removals from the Tier 3 DAYCENT Model Approach, Tier 2 IPCC Methods and additional land-use and management considerations are provided in Table A- 243. The total change in soil organic C stocks (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-19 and Figure A-20). The states with highest total amounts of C sequestration are Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Ohio and Tennessee (Table A- 245). On a per hectare basis, the highest rates of C accumulation occur in states found in the Southeast, Northeast and Midwest. For organic soils, emission rates are highest in the regions that contain the majority of drained organic soils, including California, Florida, Indiana, Michigan, Minnesota, North Carolina and Wisconsin. On a per unit of area basis, the emission rate patterns are very similar to the total emissions in each state, with the highest rates in coastal states of the Southeast, states surrounding the Great Lakes, and California.

Figure A-19: Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2013

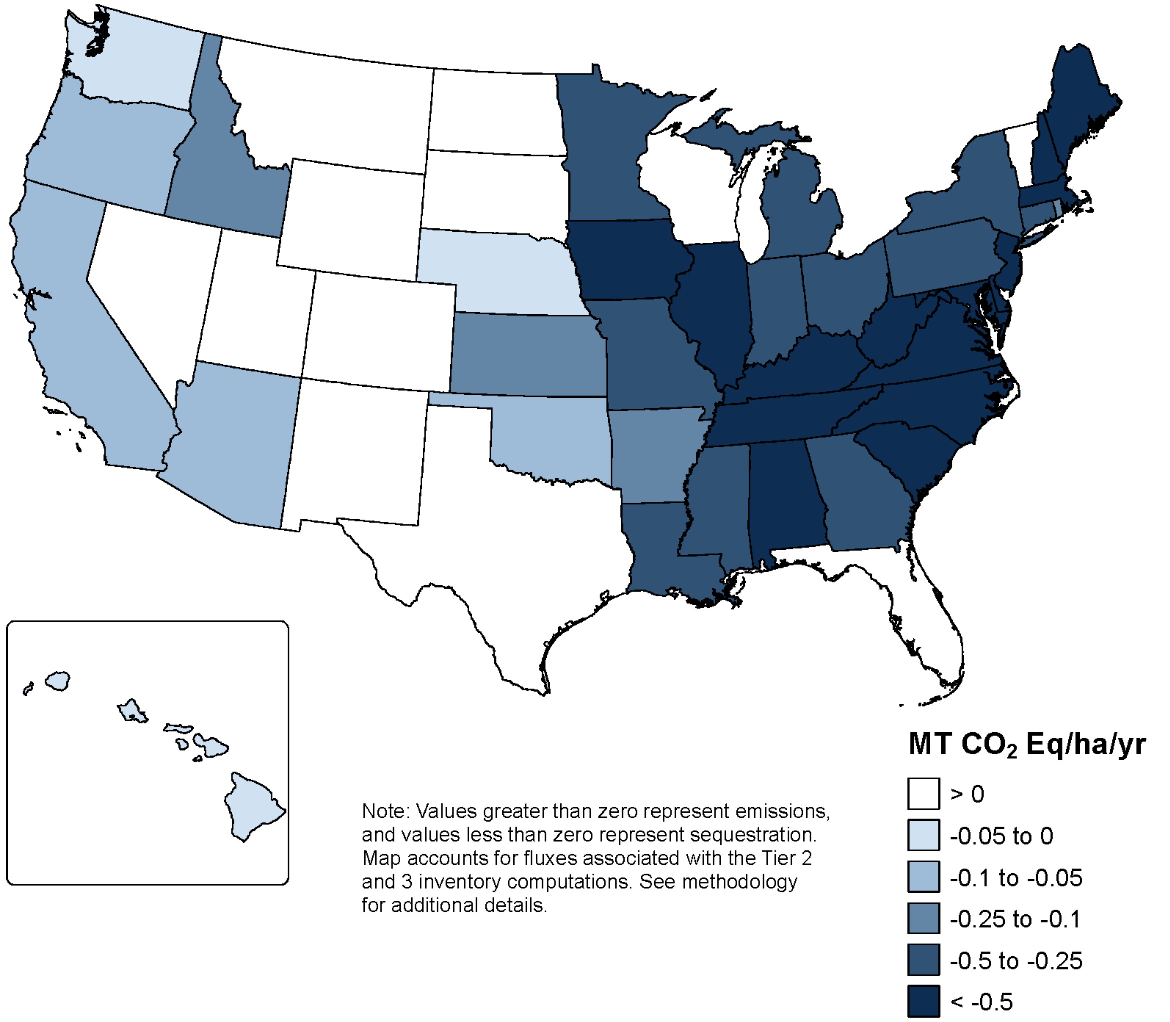
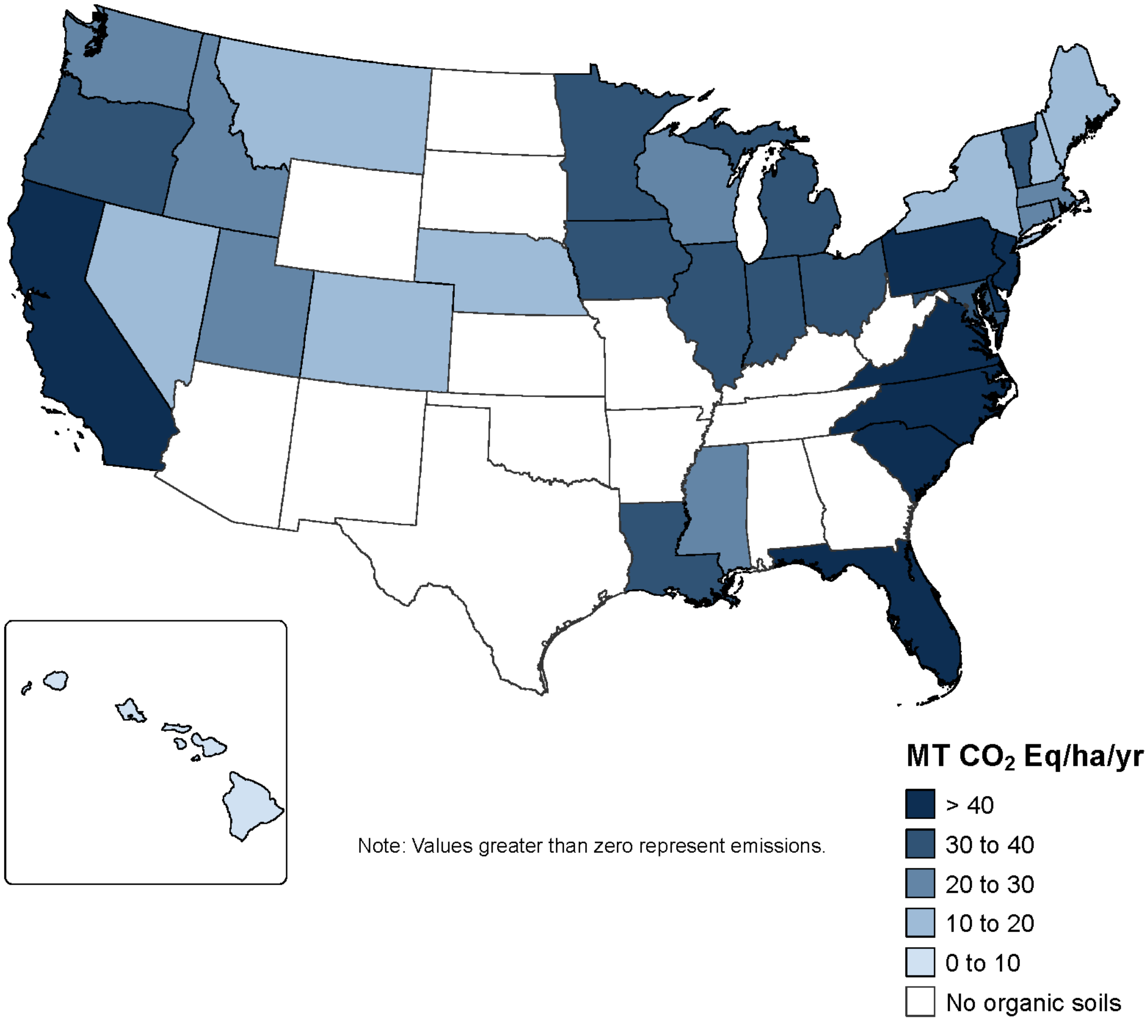


Figure A-20: Net C Stock Change, per Hectare, for Organic Soils Under Agricultural Management, 2013



Note: Values greater than zero represent emissions.

Table A- 238: 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
Sewage Sludge N Applied to Agricultural Land (Mg N)[a]	51,848	55,107	58,480	61,971	64,721	67,505	72,081	75,195	78,353	80,932	83,523	86,124
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
Area covered by Available Sewage Sludge N (ha)[c]	432,067	459,226	487,336	507,957	530,503	553,322	590,828	616,357	642,240	663,381	684,612	705,932
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
Contribution to Soil C (MMT CO_2/yr)[e,f]	**(0.60)**	**(0.64)**	**(0.68)**	**(0.71)**	**(0.74)**	**(0.77)**	**(0.82)**	**(0.86)**	**(0.89)**	**(0.92)**	**(0.95)**	**(0.98)**

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Sewage Sludge N Applied to Agricultural Land (Mg N)[a]	88,736	91,358	93,991	98,400	101,314	104,222	107,123	110,018	112,909	115,797	118,681	121,563
Assimilative Capacity (Mg N/ha)[b]	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]	727,341	748,836	770,418	806,559	830,447	854,276	878,055	901,790	925,487	949,154	972,796	996,417
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
Contribution to Soil C (MMT CO_2/yr)[e,f]	**(1.01)**	**(1.04)**	**(1.07)**	**(1.12)**	**(1.16)**	**(1.19)**	**(1.22)**	**(1.26)**	**(1.29)**	**(1.32)**	**(1.36)**	**(1.39)**

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 1993-2013.

[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-239: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

Region	Cropland IPCC	Cropland U.S. Revised	Grassland IPCC	Grassland 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	1	11.2±2.5	0.25	2.8±0.5[a]

[a] There are 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 is an assumption that is used for the IPCC default organic soil C losses on grassland.

Table A- 240: Indirect N_2O Emissions from Volatilization (MMT CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Croplands	13.1	14.3	14.2	14.3	14.6	14.2	14.0	14.1	14.3	14.6	14.4	14.5	15.1	14.6	14.6	14.4	14.4	14.8	14.9	14.7
Grasslands	4.2	4.3	4.1	4.2	4.5	4.1	4.0	4.2	4.1	4.2	4.7	4.5	4.2	4.5	4.5	4.5	4.5	4.5	4.5	4.4
Total	**17.3**	**18.6**	**18.3**	**18.5**	**19.0**	**18.3**	**18.1**	**18.3**	**18.4**	**18.8**	**19.2**	**19.1**	**19.3**	**19.1**	**19.0**	**18.8**	**18.9**	**19.2**	**19.4**	**19.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.

Table A- 241: Indirect N_2O Emissions from Leaching and Runoff (MMT CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Croplands	13.2	16.6	17.7	14.8	18.4	19.2	12.1	13.8	14.1	12.7	17.5	13.5	12.5	15.7	17.7	17.5	17.4	17.8	18.0	17.4
Grasslands	2.7	2.6	2.3	2.6	2.9	2.5	2.0	2.7	3.0	2.2	2.5	2.4	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	**15.9**	19.2	20.0	17.4	21.3	21.7	14.0	16.5	17.0	14.9	20.0	15.9	14.5	18.2	20.2	19.9	19.9	20.3	20.4	19.9

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.

Table A-242: Total N_2O Emissions from Agricultural Soil Management (MMT CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Direct	**190.8**	**210.8**	**226.4**	**222.4**	**203.1**	**194.2**	**180.5**	**204.7**	**195.6**	**188.6**	**209.4**	**208.6**	**201.5**	**224.2**	**227.0**	**225.3**	**225.4**	**226.3**	**226.1**	**224.7**
Direct Emissions from Mineral Cropland Soils	**114.4**	**124.7**	**137.2**	**133.6**	**122.3**	**123.5**	**113.2**	**126.2**	**123.5**	**119.0**	**126.2**	**128.0**	**126.6**	**131.7**	**134.9**	**133.5**	**133.7**	**134.7**	**135.1**	**133.2**
Synthetic Fertilizer	49.4	51.0	60.0	57.6	51.5	53.3	49.6	52.7	52.3	50.7	53.2	54.3	53.2	58.4	59.3	57.8	59.2	60.2	60.7	58.8
Organic Amendment[a]	11.2	12.2	12.6	12.6	11.9	12.2	12.0	12.5	12.6	12.3	12.2	12.5	12.9	13.0	13.2	13.1	13.0	13.2	13.3	13.2
Residue N[b]	6.2	6.3	6.7	6.5	6.1	6.3	5.8	6.2	5.6	5.8	6.2	6.3	5.9	6.1	6.2	6.3	6.2	6.0	5.9	6.2
Mineralization and Asymbiotic Fixation	47.7	55.2	58.0	56.9	52.8	51.7	45.7	54.8	52.9	50.1	54.6	54.9	54.7	54.1	56.2	56.3	55.3	55.3	55.2	54.9
Direct Emissions from Drained Organic Cropland Soils	**2.7**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.5**	**2.7**	**2.6**	**2.7**	**2.6**	**2.6**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Direct Emissions from Mineral Grassland Soils	**71.4**	**81.2**	**84.4**	**84.0**	**76.0**	**66.0**	**62.7**	**73.5**	**67.2**	**64.8**	**78.3**	**75.8**	**70.2**	**87.8**	**87.4**	**87.2**	**87.1**	**86.9**	**86.4**	**86.9**
Synthetic Mineral Fertilizer	1.9	1.5	1.8	1.7	1.7	1.8	1.9	2.2	2.3	1.7	2.1	1.8	1.9	1.9	1.9	1.9	1.9	2.0	2.1	2.2
PRP Manure	16.5	20.0	22.0	20.5	18.0	17.7	16.3	18.7	17.6	16.3	17.3	17.5	17.1	18.6	18.4	18.2	18.0	17.6	17.2	17.2
Managed Manure	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sewage Sludge	0.2	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	0.6	0.6
Residue[b]	1.8	2.2	2.4	2.2	2.0	1.7	1.4	1.9	1.7	1.7	2.0	2.1	1.9	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Mineralization and Asymbiotic Fixation	50.7	56.8	57.6	59.0	53.6	44.0	42.5	50.0	44.9	44.4	56.2	53.6	48.5	64.2	64.0	64.0	64.0	64.1	63.9	64.3
Direct Emissions from Drained Organic Grassland Soils	**2.3**	**2.2**	**2.2**	**2.1**	**2.2**	**2.2**	**2.1**	**2.3**	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Total Indirect	**33.2**	**37.8**	**38.3**	**35.9**	**40.3**	**40.0**	**32.1**	**34.8**	**35.4**	**33.7**	**39.2**	**35.0**	**33.8**	**37.3**	**39.2**	**38.8**	**38.8**	**39.5**	**39.8**	**39.0**
Volatilization	17.3	18.6	18.3	18.5	19.0	18.3	18.1	18.3	18.4	18.8	19.2	19.1	19.3	19.1	19.0	18.8	18.9	19.2	19.4	19.1
Leaching/Runoff	15.9	19.2	20.0	17.4	21.3	21.7	14.0	16.5	17.0	14.9	20.0	15.9	14.5	18.2	20.2	19.9	19.9	20.3	20.4	19.9
Total Emissions	**224.0**	**248.6**	**264.7**	**258.3**	**243.5**	**234.2**	**212.6**	**239.4**	**231.0**	**222.4**	**248.5**	**243.6**	**235.4**	**261.5**	**266.2**	**264.1**	**264.3**	**265.8**	**266.0**	**263.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Less than 0.05 MMT 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- 243 Total 2013 N_2O Emissions (Direct and Indirect) from Agricultural Soil Management by State (MMT CO_2 Eq.)

State	Croplands[a]	Grasslands[b]	Total	Lower Bound	Upper Bound
AL	0.98	0.67	1.69	1.37	2.64
AR	4.69	1.17	5.92	4.87	8.02
AZ	0.84	1.09	1.99	1.58	3.24
CA	7.20	2.00	9.64	7.07	18.30
CO	3.74	5.44	9.22	7.09	12.75
CT	0.13	0.03	0.16	0.12	0.24
DE	0.22	0.01	0.23	0.17	0.37
FL	2.07	1.75	3.91	2.90	7.49
GA	1.32	0.37	1.76	1.34	3.23
HI[c]	0.00	NE	0.00	0.00	0.00
IA	14.53	2.11	16.68	13.21	22.43
ID	3.62	2.26	6.06	4.88	9.52
IL	12.56	1.03	13.63	11.37	17.44
IN	6.84	0.55	7.53	6.21	10.21
KS	9.05	4.56	13.65	11.30	17.77
KY	1.42	1.42	2.90	2.29	4.15
LA	2.59	0.54	3.17	2.56	4.10
MA	0.25	1.05	0.30	0.21	0.47
MD	0.70	0.13	0.84	0.67	1.22
ME	0.24	0.10	0.35	0.23	0.65
MI	4.15	0.82	5.15	4.29	7.48
MN	9.12	1.41	11.00	9.24	14.75
MO	6.09	4.61	10.76	8.71	14.37
MS	2.28	0.53	2.79	2.24	4.26
MT	1.88	8.92	10.83	8.25	14.63
NC	2.10	0.27	2.51	1.76	5.21
ND	6.04	1.40	7.43	6.21	9.22
NE	11.95	4.57	16.56	9.16	28.21
NH	0.11	0.03	0.16	0.11	0.26
NJ	0.23	0.04	0.27	0.21	0.38
NM	1.27	3.01	4.23	3.40	6.09
NV	0.25	1.24	1.08	0.87	1.54
NY	4.28	1.34	5.69	4.67	7.72
OH	5.96	0.70	6.96	5.23	11.77
OK	3.42	5.70	9.15	7.45	12.00
OR	1.43	3.52	5.01	4.19	6.53
PA	3.53	0.74	4.31	3.47	6.27
RI	0.02	0.01	0.03	0.02	0.27
SC	0.61	0.16	0.78	0.60	1.27
SD	2.95	4.02	6.98	5.60	9.19
TN	1.46	0.72	2.24	1.84	3.27
TX	10.81	15.26	26.18	22.00	34.15
UT	0.59	1.43	2.05	1.64	2.94

VA	0.98	0.95		1.92	1.57	2.63
VT	0.79	0.19		1.00	0.76	1.52
WA	1.94	2.12		4.16	3.22	6.00
WI	3.75	1.46		5.58	4.18	9.36
WV	0.21	0.32		0.53	0.40	0.77
WY	0.86	4.02		4.92	3.98	6.56

[a] Emissions from non-manure organic N inputs for crops not simulated by DAYCENT were not estimated (NE) at the state level.
[b] Emissions from sewage sludge applied to grasslands and were not estimated (NE) at the state level
[c] N_2O emissions are not reported for Hawaii except from cropland organic soils.

Table A- 244 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 (MMT CO_2 Eq.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Net emissions based on Tier 3 Century-based analysis (Step 2)																								
CRC	(82.7)	(83.5)	(80.3)	(58.0)	(64.3)	(52.0)	(57.5)	(54.5)	(43.2)	(50.5)	(57.0)	(51.6)	(38.6)	(36.8)	(45.6)	(47.6)	(48.9)	(49.3)	(48.8)	(48.8)	(48.8)	(48.8)	(49.1)	(49.3)
GCC	17.6	17.2	17.9	17.7	12.1	16.4	13.5	15.4	10.4	11.9	10.8	11.3	13.3	11.8	11.6	13.2	11.2	9.8	9.9	9.9	9.9	9.9	9.8	9.8
GRG	(5.7)	(4.5)	(6.0)	(5.2)	(17.4)	4.8	(19.1)	(5.0)	(9.7)	(2.4)	(32.8)	(12.9)	(14.3)	(12.6)	(0.1)	2.2	(19.0)	10.2	9.8	9.8	9.9	9.9	9.8	10.3
CCG	(4.6)	(5.3)	(4.6)	(3.9)	(5.8)	(5.2)	(5.6)	(6.1)	(6.3)	(6.4)	(8.0)	(8.4)	(7.3)	(7.5)	(7.3)	(7.7)	(8.9)	(7.5)	(7.5)	(7.5)	(7.5)	(7.4)	(7.4)	(7.3)
Net emissions based on the IPCC Tier 2 analysis (Step 3)																								
Mineral Soils																								
CRC	(6.5)	(6.5)	(6.5)	(7.6)	(7.6)	(7.6)	(7.6)	(7.6)	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
GCC	2.3	2.3	2.3	2.0	2.0	2.0	2.0	2.0	1.8	1.8	1.8	1.8	1.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
FCC	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	0.8	0.8	0.8	0.8	0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
OCC	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	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SCC	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
WCC	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	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
GRG	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CCG	(1.7)	(1.7)	(1.7)	(1.6)	(1.6)	(1.6)	(1.6)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
FCG	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
OCG	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
SCG	(0.4)	(0.4)	(0.4)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
WCG	(0.1)	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils																								
CRC	24.0	23.7	23.7	23.0	22.4	22.2	21.8	21.7	21.7	21.6	21.5	22.0	21.9	22.9	22.6	22.4	22.3	22.1	22.1	22.1	22.1	22.1	22.1	22.1
GCC	2.5	2.6	2.4	2.7	3.1	3.1	3.3	3.3	3.4	3.3	3.3	4.7	4.3	4.0	4.4	4.3	4.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0
FCC	(0.2)	(0.2)	0.8	0.8	0.9	0.8	0.9	0.9	0.8	0.8	0.7	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
OCC	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SCC	(0.0)	(0.0)	0.1	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
WCC	(0.2)	(0.2)	0.6	0.7	0.8	0.8	0.8	0.8	0.9	0.7	0.6	0.6	0.5	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
GRG	4.6	4.5	4.5	4.4	4.3	4.1	4.0	3.9	3.8	3.7	3.7	3.3	3.2	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
CCG	0.5	0.5	0.5	0.6	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9	1.1	0.9	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9
FCG	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	0.1	0.1	0.1	0.1	0.1	0.1	0.1
OCG	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SCG	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WCG	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

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)	(0.7)	(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)	(1.3)	(1.4)	(1.4)
Additional changes in net emissions from mineral soils based on additional enrollment of CRP land (Step 4)																								
CRC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.4	2.0	3.6	3.7	4.8	6.6
Total Stock Changes by Land Use/Land-Use Change Category (Step 5)																								
CRC	(65.2)	(66.3)	(63.0)	(42.6)	(49.5)	(37.5)	(43.3)	(40.4)	(28.4)	(35.8)	(42.4)	(36.6)	(23.6)	(16.7)	(25.8)	(28.0)	(29.5)	(30.0)	(28.1)	(27.5)	(25.9)	(25.8)	(25.0)	(23.4)
GCC	22.5	22.1	22.7	22.5	17.3	21.5	18.7	20.8	15.6	17.1	15.8	17.8	19.4	16.7	16.7	18.3	16.2	14.6	14.7	14.7	14.7	14.7	14.6	14.6
FCC	1.2	1.2	2.2	2.2	2.2	2.2	2.3	2.3	1.7	1.6	1.5	1.2	1.1	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
OCC	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	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SCC	0.5	0.5	0.6	0.9	1.1	1.1	1.1	1.1	1.0	1.0	0.9	0.9	0.9	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
WCC	0.0	(0.0)	0.8	0.9	1.0	1.0	1.1	1.1	1.1	0.9	0.8	0.8	0.7	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
GRG	(1.9)	(0.8)	(2.4)	(1.6)	(13.9)	8.1	(15.9)	(2.0)	(6.8)	0.4	(30.1)	(10.6)	(12.1)	(10.5)	2.0	4.2	(17.1)	12.1	11.7	11.7	11.7	11.7	11.5	12.1
CCG	(5.8)	(6.5)	(5.8)	(4.9)	(6.6)	(6.0)	(6.5)	(6.9)	(7.2)	(7.2)	(8.8)	(9.2)	(8.0)	(7.9)	(7.6)	(8.0)	(9.2)	(7.9)	(7.9)	(7.9)	(7.9)	(7.8)	(7.7)	(7.7)
FCG	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
OCG	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
SCG	(0.4)	(0.4)	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
WCG	(0.0)	(0.0)	(0.0)	(0.1)	(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)	(0.0)	(0.0)	(0.0)
Total *	**(50.0)**	**(51.0)**	**(46.2)**	**(24.0)**	**(49.9)**	**(10.9)**	**(43.9)**	**(25.5)**	**(24.3)**	**(23.4)**	**(63.6)**	**(37.0)**	**(22.9)**	**(17.9)**	**(14.1)**	**(13.0)**	**(39.0)**	**(10.7)**	**(9.1)**	**(8.5)**	**(6.9)**	**(6.7)**	**(6.1)**	**(4.0)**

Note: Totals may not sum due to independent rounding.

Table A- 245: Soil C Stock Change for Mineral and Organic Soils in 2013 within individual states (MMT CO_2 Eq.)

State	Mineral Soil	Organic Soil	Total
AL	(1.38)	-	(1.38)
AR	(0.84)	-	(0.84)
AZ	(0.73)	-	(0.73)
CA	(0.93)	1.03	0.10
CO	0.50	0.00	0.50
CT	(0.03)	0.00	(0.03)
DE	(0.11)	0.01	(0.09)
FL	0.41	10.11	10.52
GA	(0.90)	-	(0.90)
HI	-	0.25	0.25
IA	(6.45)	0.51	(5.94)
ID	(0.80)	0.08	(0.71)
IL	(6.12)	0.62	(5.49)
IN	(2.46)	2.37	(0.09)
KS	(3.17)	-	(3.17)
KY	(1.75)	-	(1.75)
LA	(1.33)	0.33	(0.99)
MA	(0.07)	0.12	0.06
MD	(0.37)	0.02	(0.34)
ME	(0.14)	0.00	(0.13)
MI	(1.07)	2.83	1.75
MN	(3.89)	5.69	1.80
MO	(3.14)	-	(3.14)
MS	(1.13)	0.00	(1.13)
MT	3.46	0.16	3.62
NC	(1.15)	1.90	0.75
ND	0.22	-	0.22
NE	(0.54)	0.00	(0.54)
NH	(0.06)	0.05	(0.01)
NJ	(0.18)	0.06	(0.12)
NM	0.81	-	0.81
NV	0.05	0.00	0.05
NY	(1.18)	0.40	(0.78)
OH	(2.19)	0.47	(1.72)
OK	(0.58)	-	(0.58)
OR	(0.39)	0.34	(0.05)
PA	(0.82)	0.02	(0.80)
RI	(0.00)	0.02	0.01
SC	(0.68)	0.02	(0.67)
SD	0.50	-	0.50
TN	(2.01)	-	(2.01)
TX	1.48	-	1.48
UT	2.36	0.08	2.44
VA	(1.55)	0.00	(1.55)
VT	0.02	0.06	0.07
WA	(0.28)	0.31	0.03
WI	0.36	2.20	2.56
WV	(0.49)	-	(0.49)
WY	2.19	-	2.19

Note: Parentheses indicate net C accumulation. Estimates do not include soil C stock change associated with CRP enrollment after 2007 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 2007 are not included, and differences arise due to rounding of values in this table.

3.13. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands

This sub-annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products as well as emissions from forest fires. Some of the details of C conversion factors and procedures for calculating net carbon dioxide (CO_2) flux for forests are provided below; full details of selected topics may be found in the cited references.

Carbon stocks and net stock change in forest ecosystems

The inventory-based methodologies for estimating forest C stocks are based on Smith et al. (2010) and are consistent with IPCC (2003, 2006) stock-difference methods. Estimates of ecosystem C are based on data from forest inventory plots; either direct measurements or attributes of forest inventories are the basis for estimating metric tons per hectare of C in trees, woody debris and litter, and soil organic C. Plot-level estimates are summed to total stocks for large areas as defined by the forest inventories, such as individual states, for example. Net annual C stock change is calculated as the difference between successive forest inventories divided by the interval, in years for a selected state or sub-state area.

Forest inventory data

The estimates of forest C stocks are based on data 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 2014a, USDA Forest Service 2014b). Forest Inventory and Analysis data include remote sensing information and a collection of measurements in the field at sample locations called plots. Tree measurements include diameter, height, and species. On a subset of plots, additional measurements or samples are taken of downed dead wood, litter, and soil attributes. The technical advances needed to estimate C stocks from these data are ongoing (Woodall et al. 2012). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2014c). 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 6.0 (USDA Forest Service 2014b, USDA Forest Service 2014c); 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, representing an estimated 12 percent of the total forest land in Alaska, contribute to the forest C 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.

Summing state-level C stocks to calculate U.S. 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). Recent modification to the methods of Smith et al. (2010) such as by Domke et al. (2013) reflect the ongoing research and data collection, which are ultimately aimed toward the goal of accurately representing forest C by the land-use categories of Chapter 6, *Land Use, Land-Use Change, and Forestry*. The two principal aims of these ongoing improvements are to assure the appropriate use of FIA's inventory data and to refine the inventory-to-C conversion process. Change in forest C should reflect change in forest condition or structure, not changes in definitions or methods associated with data collection. Thus, consistent series of stocks depend on the appropriate interpretation and application of the forest inventories. Similarly, greater site specificity in C conversion factors are preferred to regional (or low tier) factors. The current forest C estimates include recent modification in the selection and use of inventory data (e.g., woodlands that do not meet the definition of forest) and C factors (e.g., the new model to estimate litter). These are each addressed below in their respective sections of this annex.

The C 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 (Smith et al. 2010). There are generally two or more surveys available for download for each state. Carbon 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). As a result, information on less productive forest land or lands reserved from harvest was limited, yet the C estimates are intended to represent all forest land.[1] Inventory field crews periodically measured all the plots in a state at a frequency of every five 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-246: Source of Unique Forest Inventory and Average Year of Field Survey Used to Estimate Statewide Carbon Stocks

State/Sub-state[a]	Source of Inventory Data, Report/Inventory Year[b]	Average Year Assigned to Inventory[c]
Alabama	FIADB 6.0, 1982	1982
	FIADB 6.0, 1990	1990
	FIADB 6.0, 2000	1999
	FIADB 6.0, 2005	2003
	FIADB 6.0, 2012	2009
	FIADB 6.0, 2013	2010
Alaska, Chugach NF	FIADB 6.0, 2012	2007
Alaska, SC non-NFS	FIADB 6.0, 2012	2009
Alaska, SE non-NFS	FIADB 6.0, 2012	2009
Alaska, Tongass NF	FIADB 6.0, 2012	2008
Arizona, NFS non-woodlands	1987 RPA	1985
	FIADB 6.0, 1999	1996
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Arizona, NFS woodlands	1987 RPA	1984
	FIADB 6.0, 1999	1996
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Arizona, non-NFS non-woodlands	FIADB 6.0, 1985	1986
	FIADB 6.0, 1999	1996
	FIADB 6.0, 2010	2007
	FIADB 6.0, 2012	2008

[1] Forest land within the United States is defined in Oswalt et al. (2014) as "Land at least 120 feet (37 meters) wide and at least 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 meters) at maturity in situ. The definition here includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (37 meters) wide or an acre in size. Forest land does not include land that is predominantly under agricultural or urban land use." Timberland is productive forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. This is an important subclass of forest land because timberland is the primary source of carbon as incorporated into harvested wood products. Productivity is at a minimum rate of 20 cubic feet per acre (1.4 cubic meters per hectare) per year of industrial wood (Woudenberg and Farrenkopf 1995). There are about 205 million hectares of timberland in the conterminous United States, which represents 80 percent of all forest lands over the same area (Oswalt et al. 2014).

Arizona, non-NFS woodlands	FIADB 6.0, 1999	1990
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Arkansas	FIADB 6.0, 1988	1988
	FIADB 6.0, 1995	1996
	FIADB 6.0, 2005	2003
	FIADB 6.0, 2010	2008
	FIADB 6.0, 2013	2011
California, NFS	IDB, 1990s	1997
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
California, non-NFS	IDB, 1990s	1993
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Colorado, NFS non-woodlands	1997 RPA	1981
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Colorado, NFS woodlands	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Colorado, non-NFS non-woodlands	Westwide, 1983	1980
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Colorado, non-NFS woodlands	Westwide, 1983	1983
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Connecticut	FIADB 6.0, 1985	1985
	FIADB 6.0, 1998	1998
	FIADB 6.0, 2007	2006
	FIADB 6.0, 2012	2011
Delaware	FIADB 6.0, 1986	1986
	FIADB 6.0, 1999	1999
	FIADB 6.0, 2008	2007
	FIADB 6.0, 2012	2011
Florida	FIADB 6.0, 1987	1987
	FIADB 6.0, 1995	1995
	FIADB 6.0, 2007	2005
	FIADB 6.0, 2013	2011
Georgia	FIADB 6.0, 1989	1989
	FIADB 6.0, 1997	1997
	FIADB 6.0, 2004	2002
	FIADB 6.0, 2009	2007
	FIADB 6.0, 2012	2010
Idaho, Caribou-Targhee NF	Westwide, 1991	1992
	FIADB 6.0, 2012	2009
Idaho, Kootenai NF	1987 RPA	1988
	FIADB 6.0, 1991	1995
	FIADB 6.0, 2012	2009
Idaho, Payette NF	1987 RPA	1982

	FIADB 6.0, 2012	2009
Idaho, Salmon-Challis NF	1987 RPA	1978
	FIADB 6.0, 2012	2009
Idaho, Sawtooth NF	Westwide, 1991	1983
	FIADB 6.0, 1991	1996
	FIADB 6.0, 2012	2008
Idaho, non-NFS non-woodlands	FIADB 6.0, 1991	1990
	FIADB 6.0, 2012	2009
Idaho, non-NFS woodlands	FIADB 6.0, 1991	1982
	FIADB 6.0, 2012	2008
Idaho, other NFS	Westwide, 1991	1988
	FIADB 6.0, 1991	2000
	FIADB 6.0, 2012	2009
Illinois	FIADB 6.0, 1985	1985
	FIADB 6.0, 1998	1998
	FIADB 6.0, 2005	2004
	FIADB 6.0, 2010	2008
	FIADB 6.0, 2013	2011
Indiana	FIADB 6.0, 1986	1986
	FIADB 6.0, 1998	1998
	FIADB 6.0, 2003	2001
	FIADB 6.0, 2008	2007
	FIADB 6.0, 2013	2011
Iowa	FIADB 6.0, 1990	1990
	FIADB 6.0, 2003	2002
	FIADB 6.0, 2008	2006
	FIADB 6.0, 2013	2011
Kansas	FIADB 6.0, 1981	1981
	FIADB 6.0, 1994	1994
	FIADB 6.0, 2005	2003
	FIADB 6.0, 2010	2009
	FIADB 6.0, 2012	2011
Kentucky	FIADB 6.0, 1988	1987
	FIADB 6.0, 2004	2002
	FIADB 6.0, 2009	2008
	FIADB 6.0, 2012	2011
Louisiana	FIADB 6.0, 1984	1984
	FIADB 6.0, 1991	1991
	FIADB 6.0, 2005	2004
	FIADB 6.0, 2012	2009
Maine	Eastwide, 1982	1983
	FIADB 6.0, 1995	1995
	FIADB 6.0, 2003	2002
	FIADB 6.0, 2008	2007
	FIADB 6.0, 2013	2011
Maryland	FIADB 6.0, 1986	1986
	FIADB 6.0, 1999	2000
	FIADB 6.0, 2008	2007
	FIADB 6.0, 2012	2011
Massachusetts	FIADB 6.0, 1985	1985

	FIADB 6.0, 1998	1998
	FIADB 6.0, 2007	2006
	FIADB 6.0, 2012	2011
Michigan	FIADB 6.0, 1980	1980
	FIADB 6.0, 1993	1993
	FIADB 6.0, 2004	2003
	FIADB 6.0, 2009	2007
	FIADB 6.0, 2013	2011
Minnesota	FIADB 6.0, 1990	1989
	FIADB 6.0, 2003	2001
	FIADB 6.0, 2008	2006
	FIADB 6.0, 2013	2011
Mississippi	FIADB 6.0, 1987	1987
	FIADB 6.0, 1994	1994
	FIADB 6.0, 2006	2007
	FIADB 6.0, 2013	2010
Missouri	FIADB 6.0, 1989	1988
	FIADB 6.0, 2003	2002
	FIADB 6.0, 2008	2006
	FIADB 6.0, 2013	2011
Montana, NFS	1987 RPA	1988
	FIADB 6.0, 1989	1996
	FIADB 6.0, 2012	2008
Montana, non-NFS non-reserved	FIADB 6.0, 1989	1989
	FIADB 6.0, 2012	2008
Montana, non-NFS reserved	1997 RPA	1990
	FIADB 6.0, 2012	2008
Nebraska	FIADB 6.0, 1983	1983
	FIADB 6.0, 1994	1995
	FIADB 6.0, 2005	2004
	FIADB 6.0, 2010	2008
	FIADB 6.0, 2013	2012
Nevada, NFS non-woodlands	1987 RPA	1974
	FIADB 6.0, 1989	1997
	FIADB 6.0, 2012	2010
Nevada, NFS woodlands	1987 RPA	1978
	FIADB 6.0, 1989	1997
	FIADB 6.0, 2012	2010
Nevada, non-NFS non-woodlands	1997 RPA	1985
	FIADB 6.0, 2012	2010
Nevada, non-NFS woodlands	FIADB 6.0, 1989	1980
	FIADB 6.0, 2012	2010
New Hampshire	FIADB 6.0, 1983	1983
	FIADB 6.0, 1997	1997
	FIADB 6.0, 2007	2005
	FIADB 6.0, 2012	2011
New Jersey	FIADB 6.0, 1987	1987
	FIADB 6.0, 1999	1999

	FIADB 6.0, 2008	2007
	FIADB 6.0, 2012	2011
New Mexico, NFS non-woodlands	1987 RPA	1986
	FIADB 6.0, 1999	1997
	FIADB 6.0, 2013	2011
New Mexico, NFS woodlands	1987 RPA	1986
	FIADB 6.0, 1999	1997
	FIADB 6.0, 2013	2011
New Mexico, non-NFS non-timberlands	FIADB 6.0, 2013	2011
New Mexico, non-NFS timberlands	FIADB 6.0, 1987	1987
	FIADB 6.0, 1999	1999
	FIADB 6.0, 2013	2011
New York, non-reserved	Eastwide, 1980	1981
	FIADB 6.0, 1993	1993
	FIADB 6.0, 2007	2005
	FIADB 6.0, 2012	2011
New York, reserved	1987 RPA	1988
	FIADB 6.0, 2007	2005
	FIADB 6.0, 2012	2011
North Carolina	FIADB 6.0, 1984	1984
	FIADB 6.0, 1990	1990
	FIADB 6.0, 2002	2001
	FIADB 6.0, 2007	2006
	FIADB 6.0, 2012	2009
North Dakota	FIADB 6.0, 1980	1979
	FIADB 6.0, 1995	1995
	FIADB 6.0, 2005	2003
	FIADB 6.0, 2010	2009
	FIADB 6.0, 2013	2011
Ohio	FIADB 6.0, 1991	1991
	FIADB 6.0, 2006	2005
	FIADB 6.0, 2011	2010
	FIADB 6.0, 2012	2011
Oklahoma, Central & West	FIADB 6.0, 2013	2012
Oklahoma, East	FIADB 6.0, 1986	1986
	FIADB 6.0, 1993	1993
	FIADB 6.0, 2008	2008
	FIADB 6.0, 2013	2011
Oregon, NFS East	IDB, 1990s	1995
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Oregon, NFS West	IDB, 1990s	1996
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Oregon, non-NFS East	Westwide, 1992	1991
	IDB, 1990s	1999
	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Oregon, non-NFS West	Westwide, 1992	1989
	IDB, 1990s	1997

	FIADB 6.0, 2010	2006
	FIADB 6.0, 2012	2008
Pennsylvania	FIADB 6.0, 1989	1990
	FIADB 6.0, 2004	2003
	FIADB 6.0, 2009	2008
	FIADB 6.0, 2012	2011
Rhode Island	FIADB 6.0, 1985	1985
	FIADB 6.0, 1998	1999
	FIADB 6.0, 2007	2006
	FIADB 6.0, 2012	2011
South Carolina	FIADB 6.0, 1986	1986
	FIADB 6.0, 1993	1993
	FIADB 6.0, 2001	2001
	FIADB 6.0, 2006	2005
	FIADB 6.0, 2011	2009
	FIADB 6.0, 2013	2011
South Dakota, NFS	1997 RPA	1986
	FIADB 6.0, 1995	1999
	FIADB 6.0, 2005	2004
	FIADB 6.0, 2010	2009
	FIADB 6.0, 2013	2012
South Dakota, non-NFS	1987 RPA	1986
	FIADB 6.0, 1995	1995
	FIADB 6.0, 2005	2004
	FIADB 6.0, 2010	2008
	FIADB 6.0, 2013	2012
Tennessee	FIADB 6.0, 1989	1989
	FIADB 6.0, 1999	1998
	FIADB 6.0, 2004	2003
	FIADB 6.0, 2009	2008
	FIADB 6.0, 2012	2011
Texas, Central & West	FIADB 6.0, 2011	2008
Texas, East	FIADB 6.0, 1986	1986
	FIADB 6.0, 1992	1992
	FIADB 6.0, 2003	2003
	FIADB 6.0, 2008	2006
	FIADB 6.0, 2013	2011
Utah, non-woodlands	FIADB 6.0, 1993	1993
	FIADB 6.0, 2009	2005
	FIADB 6.0, 2012	2008
Utah, woodlands	FIADB 6.0, 1993	1994
	FIADB 6.0, 2009	2005
	FIADB 6.0, 2012	2008
Vermont	FIADB 6.0, 1983	1983
	FIADB 6.0, 1997	1997
	FIADB 6.0, 2007	2006
	FIADB 6.0, 2012	2011
Virginia	FIADB 6.0, 1985	1985

	FIADB 6.0, 1992	1991
	FIADB 6.0, 2001	2000
	FIADB 6.0, 2007	2005
	FIADB 6.0, 2011	2010
	FIADB 6.0, 2012	2011
Washington, NFS East	IDB, 1990s	1996
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Washington, NFS West	IDB, 1990s	1996
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Washington, non-NFS East	IDB, 1990s	1992
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
Washington, non-NFS West	IDB, 1990s	1990
	FIADB 6.0, 2011	2007
	FIADB 6.0, 2012	2008
West Virginia	FIADB 6.0, 1989	1988
	FIADB 6.0, 2000	2001
	FIADB 6.0, 2008	2007
	FIADB 6.0, 2012	2011
Wisconsin	FIADB 6.0, 1983	1982
	FIADB 6.0, 1996	1995
	FIADB 6.0, 2004	2002
	FIADB 6.0, 2009	2007
	FIADB 6.0, 2013	2011
Wyoming, NFS	1997 RPA	1982
	FIADB 6.0, 2000	2000
	FIADB 6.0, 2012	2012
Wyoming, non-NFS non-reserved non-woodlands	FIADB 6.0, 1984	1984
	FIADB 6.0, 2000	2002
	FIADB 6.0, 2012	2012
Wyoming, non-NFS non-reserved woodlands	FIADB 6.0, 1984	1984
	FIADB 6.0, 2000	2002
	FIADB 6.0, 2012	2013
Wyoming, non-NFS reserved	1997 RPA	1985
	FIADB 6.0, 2000	2000
	FIADB 6.0, 2012	2012

[a] Sub-state 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 2014c), 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 2014d). Alaska is represented by a portion of forest land, in the southcentral and southeast part of the state.
[b] FIADB 6.0 is the current, publicly available, format of FIA inventory data, and these files were downloaded from the Internet 21 July 2014 (USDA Forest Service 2014b). 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 national plot design and annualized sampling (USDA Forest Service 2014a) were 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. 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 some western states have begun remeasuring with a second annual cycle. Annually updated estimates of forest C stocks are affected by the 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 in order to include the most recent available data for each state. The use of the most-recent FIA population summaries (known as evaluations within the FIADB) for all stock-change calculations represents a slight modification of the approach in previous years where most of the newest evaluations were in use and the only restrictions were to avoid a high proportion of redundancy in the underlying plots data between the two populations. The specific surveys used in this report are listed in Table A-246, and this list can be compared with the full set of summaries available for download (USDA Forest Service 2014b).

Current and most recent inventories—as represented in the FIADB—provide all necessary information to produce whole-state forest summaries (USDA Forest Service 2014c). It should be noted that as the FIA program explores expansion of its vegetation inventory beyond the forest land use to other land uses (e.g., woodlands and urban areas) subsequent inventory observations will need to be delineated between forest and other land uses as opposed to a strict forest land use inventory. The forest C estimates provided here (i.e., *Forest Land Remaining Forest Land*) represent C stocks and stock change on managed forest lands (IPCC 2006, see 6.1 Representation of the United States Land Base), which is how all forest lands are classified on the 48 conterminous states. However, Alaska is considered to have significant areas of both managed and unmanaged forest lands. A new model delineating managed versus unmanaged lands for the United States. (Ogle et al. in preparation) is consistent with the assumption of managed forest lands on the 48 states. However, the model of Ogle et al. (in preparation) identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of "managed" for these forest lands included in the FIADB. Therefore, the estimates for coastal Alaska as included here reflect that adjustment, which effectively reduces the forest area included here by about 5 percent. A second modification to the use of the FIADB-defined forest land introduced this year is to identify plots that do not meet the height component of the definition of forestland (Coulston et al. in preparation). These plots were identified as "other wooded lands" (i.e., not forest land use) and were removed from forest estimates and classified as grassland. Compare estimates of forest C stock and forest area as provided here (especially tables A-248 and A-249) relative to those reported previously (U.S. EPA 2014), and see Coulston et al. (in preparation) for additional information on the lands affected by this re-classification. Note that minor differences in identifying and classifying woodland as "forest" versus "other wooded" exist between the current Resources Planning Act Assessment (RPA) data (Oswalt et al. 2014) and the FIADB (USDA Forest Service 2014b) due to a refined modelling approach developed specifically for this submission (Coulston et al. in preparation).

Carbon stocks are estimated by linear interpolation between survey years for each pool in each state in each year. 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. This report's stock-change estimates for coastal Alaska are an exception to this general method. The 2012 survey (Table A-246) provided a one-time stock estimate and change was based on Barrett and Christensen (2011, PNW-GTR-835) and Barrett (2014, PNW-GTR-889). Net annual change in forest area (as well as stock-change for litter and soil organic carbon) was set as 0.07 percent, and non-NFS biomass change was from GTR-835-Table 9 (Barrett and Christensen 2011). Biomass change in the National Forests as well as dead wood stock-change throughout were based on GTR-889-Tables 16 and 29 (Barrett 2014). Carbon stock and flux estimates for each pool are summed over all forest land in all states as identified in the FIADB to form estimates for the United States. Summed net annual stock change and stocks are presented in Table A-247 and Table A-248, respectively. An estimate of forest area based on the interpolation and extrapolation procedure described above is also provided in Table A-249. Estimated net stock change of non-soil forest ecosystem C for each of the states is shown in Table A-249, which also includes estimated forest area and total non-soil forest C stock. The state-level forest areas and C stocks are from the most recent inventory available

(USDA Forest Service 2014b), and the estimate for net stock change is the 10-year mean of the 2004 through 2013 estimates from the C calculator (Smith et al. 2010).

Table A-247: Estimated Net Annual Changes in C Stocks (MMT C yr^{-1}) in Forest and Harvested Wood Pools, 1990–2013

Year	Total Net Flux	Forest Total	Live, aboveground	Live, belowground	Dead Wood	Litter	Soil Organic C	Harvested Wood Total	Products in Use	SWDS
1990	(174.4)	(138.5)	(88.5)	(17.2)	(12.5)	(7.3)	(12.9)	(35.9)	(17.7)	(18.3)
1991	(172.2)	(138.4)	(88.4)	(17.2)	(12.7)	(7.4)	(12.6)	(33.8)	(14.9)	(18.8)
1992	(170.3)	(136.6)	(89.4)	(17.5)	(12.8)	(7.1)	(9.9)	(33.8)	(16.3)	(17.4)
1993	(170.7)	(137.8)	(95.3)	(18.6)	(13.5)	(6.0)	(4.4)	(32.9)	(15.0)	(17.9)
1994	(178.2)	(144.8)	(98.4)	(19.3)	(13.6)	(6.0)	(7.4)	(33.4)	(15.9)	(17.5)
1995	(180.2)	(147.9)	(101.6)	(20.0)	(12.9)	(5.0)	(8.5)	(32.3)	(15.1)	(17.2)
1996	(174.6)	(144.0)	(100.7)	(19.8)	(18.6)	(3.3)	(1.7)	(30.6)	(14.1)	(16.5)
1997	(164.7)	(132.7)	(101.7)	(20.0)	(17.2)	(2.3)	8.6	(32.0)	(14.7)	(17.3)
1998	(153.5)	(122.4)	(96.8)	(19.0)	(17.2)	(2.0)	12.7	(31.1)	(13.4)	(17.7)
1999	(138.9)	(106.4)	(92.7)	(18.3)	(16.9)	(0.9)	22.4	(32.5)	(14.1)	(18.4)
2000	(133.5)	(102.7)	(90.0)	(17.7)	(19.1)	0.2	24.0	(30.8)	(12.8)	(18.0)
2001	(156.4)	(130.9)	(99.0)	(19.5)	(19.6)	(0.3)	7.4	(25.5)	(8.7)	(16.8)
2002	(183.8)	(157.0)	(100.8)	(19.8)	(20.8)	(1.0)	(14.6)	(26.8)	(10.0)	(17.1)
2003	(211.2)	(185.5)	(107.5)	(21.1)	(19.9)	(2.2)	(34.8)	(25.7)	(9.0)	(16.0)
2004	(222.4)	(194.0)	(110.1)	(21.7)	(19.4)	(2.8)	(40.0)	(28.4)	(12.0)	(17.0)
2005	(220.1)	(192.1)	(109.9)	(21.6)	(18.2)	(3.2)	(39.2)	(28.0)	(12.0)	(16.0)
2006	(229.6)	(200.2)	(117.0)	(23.3)	(20.0)	(3.5)	(36.5)	(29.4)	(12.0)	(17.0)
2007	(226.4)	(198.4)	(117.8)	(23.6)	(23.0)	(3.2)	(30.8)	(28.0)	(11.0)	(18.0)
2008	(215.7)	(194.7)	(116.8)	(23.5)	(24.9)	(3.3)	(26.2)	(21.0)	(3.0)	(17.0)
2009	(208.6)	(193.8)	(118.3)	(23.8)	(25.7)	(3.1)	(22.9)	(14.8)	1.0	(16.0)
2010	(208.7)	(192.2)	(118.3)	(23.8)	(25.9)	(3.0)	(21.2)	(16.5)	1.0	(17.0)
2011	(211.0)	(192.2)	(118.3)	(23.8)	(25.9)	(3.0)	(21.2)	(18.8)	(2.0)	(17.0)
2012	(210.8)	(192.2)	(118.3)	(23.8)	(25.9)	(3.0)	(21.2)	(18.6)	(2.0)	(17.0)
2013	(211.5)	(192.2)	(118.3)	(23.8)	(25.9)	(3.0)	(21.2)	(19.3)	(3.0)	(17.0)

Table A-248: Estimated C Stocks (MMT C) in Forest and Harvested Wood Pools, 1990–2014

		Forest						Harvested Wood			
Year	Total C Stock	Total	Live, aboveground	Live, belowground	Dead Wood	Litter	Soil Organic C	Total	Products in Use	SWDS	Forest Area (1000 ha)
1990	38,168	36,309	12,266	2,430	2,138	2,749	16,726	1,859	1,231	628	265,938
1991	38,343	36,448	12,354	2,448	2,150	2,756	16,739	1,895	1,249	646	266,289
1992	38,515	36,586	12,443	2,465	2,163	2,764	16,752	1,929	1,264	665	266,649
1993	38,685	36,723	12,532	2,482	2,176	2,771	16,762	1,963	1,280	683	266,983
1994	38,856	36,860	12,627	2,501	2,189	2,777	16,766	1,996	1,295	701	267,277
1995	39,034	37,005	12,726	2,520	2,203	2,783	16,773	2,029	1,311	718	267,565
1996	39,214	37,153	12,827	2,540	2,216	2,788	16,782	2,061	1,326	735	267,843
1997	39,389	37,297	12,928	2,560	2,234	2,791	16,784	2,092	1,340	752	267,977
1998	39,554	37,430	13,030	2,580	2,251	2,794	16,775	2,124	1,355	769	268,016
1999	39,707	37,552	13,126	2,599	2,269	2,796	16,762	2,155	1,368	787	268,051
2000	39,846	37,659	13,219	2,617	2,286	2,797	16,740	2,188	1,382	805	267,987
2001	39,980	37,761	13,309	2,635	2,305	2,796	16,716	2,218	1,395	823	267,856
2002	40,136	37,892	13,408	2,655	2,324	2,797	16,709	2,244	1,404	840	267,791
2003	40,320	38,049	13,509	2,674	2,345	2,798	16,723	2,271	1,414	857	267,826
2004	40,531	38,235	13,616	2,695	2,365	2,800	16,758	2,296	1,423	873	268,045
2005	40,754	38,429	13,727	2,717	2,384	2,803	16,798	2,325	1,435	890	268,334
2006	40,974	38,621	13,836	2,739	2,403	2,806	16,837	2,353	1,447	906	268,676
2007	41,203	38,821	13,953	2,762	2,423	2,809	16,874	2,382	1,459	923	268,979
2008	41,430	39,019	14,071	2,786	2,446	2,813	16,904	2,411	1,470	941	269,215
2009	41,645	39,214	14,188	2,809	2,470	2,816	16,931	2,431	1,473	958	269,396
2010	41,854	39,408	14,306	2,833	2,496	2,819	16,954	2,446	1,472	974	269,536
2011	42,062	39,600	14,425	2,857	2,522	2,822	16,975	2,462	1,471	991	269,661
2012	42,273	39,792	14,543	2,881	2,548	2,825	16,996	2,481	1,473	1,008	269,786
2013	42,485	39,985	14,661	2,904	2,574	2,828	17,017	2,500	1,475	1,025	269,911
2014	42,697	40,177	14,780	2,928	2,600	2,831	17,038	2,520	1,478	1,042	270,035

A recent methodological change implemented to address missing forest area data in coastal Alaska resulted in discrepancies between the coastal Alaska managed forest area of 1990–2014, as contributes to this table, and the areas presented in Section 6.1 "Representation of the U.S. Land Base". Coastal Alaska managed forest lands contributing to this table changed linearly from 5.77 million hectares in 1990 to 5.86 million hectares in 2014. The estimates used for Section 6.1 changed linearly from 5.48 million hectares in 1990 to 5.95 million hectares in 2014. This represents a change of 5.3 and −1.5 percent for 1990 and 2014 in coastal Alaska, respectively. This discrepancy will be corrected in the next Inventory submission.

Table A-249: State-Level Forest Area, C Stock, and Net Annual Stock Change. Estimates are Forest Ecosystem C and Do Not Include Harvested Wood

State	Mean year of field data collection	Forest area (1,000 ha)	Nonsoil C stock (MMT C)	Mean net annual nonsoil stock change 2004–2013 (MMT C/yr)
Alabama	2010	9,272	681	(8.2)
Alaska (coastal)	2008	5,841	863	(0.5)
Arizona	2008	6,234	236	1.6
Arkansas	2011	7,675	580	(6.2)
California	2008	13,022	1,544	(10.6)
Colorado	2008	8,435	578	(0.5)
Connecticut	2011	702	88	(1.2)
Delaware	2011	141	17	(0.1)
Florida	2011	6,990	487	(4.2)
Georgia	2010	10,017	734	(5.9)
Idaho	2009	8,626	782	(1.5)
Illinois	2011	1,984	164	(2.6)
Indiana	2011	1,973	181	(2.3)
Iowa	2011	1,201	87	(1.2)
Kansas	2011	1,045	62	(1.4)
Kentucky	2011	5,063	450	(4.2)
Louisiana	2009	6,018	432	(4.2)
Maine	2011	7,137	571	(3.2)
Maryland	2011	990	122	(0.8)
Massachusetts	2011	1,225	146	(1.3)
Michigan	2011	8,238	644	(9.2)
Minnesota	2011	7,033	411	(4.1)
Mississippi	2010	7,879	573	(9.0)
Missouri	2011	6,253	449	(4.4)
Montana	2008	10,251	808	(5.1)
Nebraska	2012	623	34	(0.6)
Nevada	2010	3,547	101	0.1
New Hampshire	2011	1,956	207	(1.3)
New Jersey	2011	796	80	(0.6)
New Mexico	2011	7,115	282	0.0
New York	2011	7,691	802	(6.5)
North Carolina	2009	7,536	680	(7.7)
North Dakota	2011	309	16	(0.1)
Ohio	2011	3,297	315	(3.3)
Oklahoma	2011	4,913	229	(0.7)
Oregon	2008	12,061	1,597	(14.4)
Pennsylvania	2011	6,778	731	(6.4)
Rhode Island	2011	147	17	(0.3)
South Carolina	2011	5,279	431	(5.9)
South Dakota	2012	781	38	(0.2)
Tennessee	2011	5,633	571	(2.8)
Texas	2009	18,856	745	(0.3)
Utah	2008	5,962	264	0.3
Vermont	2011	1,860	207	(1.3)
Virginia	2011	6,428	635	(5.1)
Washington	2008	9,039	1,467	(9.2)
West Virginia	2011	4,921	537	(6.4)
Wisconsin	2011	6,921	470	(5.2)
Wyoming	2012	4,010	304	2.3

Table A-250 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 21 July 2014 (USDA Forest Service 2014b). Carbon density values reflect the most recent survey for each state as available in the FIADB, not potential maximum C storage. Carbon 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-250: Average C Density (T C/ha) by C 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 2010

Region (States) Forest Types	Above-ground Biomass	Below-ground Biomass	Dead Wood	Litter	Soil Organic C	Forest Area
	C Density (T C/ha)					(1,000 ha)
Northeast						
(CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV)						
White/Red/Jack Pine	79.1	16.3	7.0	17.0	78.1	1,722
Spruce/Fir	40.4	8.5	7.6	16.5	98.0	3,052
Oak/Pine	71.0	14.0	5.6	12.1	66.9	1,230
Oak/Hickory	79.0	14.9	6.4	11.1	53.1	13,000
Elm/Ash/Cottonwood	55.4	10.5	5.4	8.9	111.7	1,513
Maple/Beech/Birch	71.3	13.6	6.8	14.7	69.6	13,773
Aspen/Birch	42.6	8.4	5.9	16.4	87.4	1,547
Minor Types and Nonstocked	47.0	9.3	5.7	12.7	73.6	1,805
All	68.8	13.2	6.6	13.4	69.1	37,642
Northern Lake States						
(MI,MN,WI)						
White/Red/Jack Pine	46.8	9.7	5.6	11.6	120.8	1,933
Spruce/Fir	29.6	6.2	5.7	10.8	261.8	3,225
Oak/Hickory	55.2	10.4	7.1	8.5	97.1	4,042
Elm/Ash/Cottonwood	42.5	8.1	5.7	8.7	179.9	2,275
Maple/Beech/Birch	59.7	11.4	6.8	11.4	134.3	4,484
Aspen/Birch	32.1	6.2	6.1	10.7	146.1	5,069
Minor Types and Nonstocked	29.7	5.9	6.2	8.1	118.9	1,165
All	43.7	8.5	6.3	10.2	151.4	22,192
Northern Prairie States						
(IA,IL,IN,KS,MO,ND,NE,SD)						
Ponderosa Pine	31.7	6.6	4.6	9.1	48.5	543
Oak/Pine	39.2	7.6	4.6	7.3	41.1	570
Oak/Hickory	53.6	10.1	6.0	7.1	49.6	9,501
Elm/Ash/Cottonwood	55.9	10.5	6.5	5.5	83.1	2,090
Minor Types and Nonstocked	31.3	6.1	5.2	7.5	59.9	1,465
All	50.2	9.5	5.9	7.0	55.2	14,168
South Central						
(AL,AR,KY,LA,MS,OK,TN,TX)						
Loblolly/Shortleaf Pine	49.5	10.2	7.5	7.2	41.9	13,987
Pinyon/Juniper	15.0	2.9	4.7	5.2	37.7	2,302
Oak/Pine	45.9	9.0	6.7	6.8	41.7	5,064
Oak/Hickory	48.4	9.1	7.4	6.5	38.6	24,842
Oak/Gum/Cypress	64.1	12.2	7.5	6.9	52.8	5,306
Elm/Ash/Cottonwood	38.3	7.2	6.0	5.2	49.9	4,042
Woodland Hardwoods	12.7	2.1	2.3	3.1	65.0	4,806
Minor Types and Nonstocked	28.3	5.5	6.7	5.8	54.4	4,959
All	43.8	8.4	6.8	6.3	44.5	65,309
Southeast						
(FL,GA,NC,SC,VA)						
Longleaf/Slash Pine	42.1	8.7	4.8	10.1	110.0	4,136
Loblolly/Shortleaf Pine	53.7	11.1	4.3	8.5	72.9	9,369
Oak/Pine	51.7	10.1	4.1	10.0	61.4	4,059
Oak/Hickory	65.8	12.4	5.3	9.4	45.3	11,763
Oak/Gum/Cypress	65.1	12.6	5.2	9.9	158.0	4,592
Elm/Ash/Cottonwood	49.6	9.4	3.9	6.4	95.7	846
Minor Types and Nonstocked	31.8	6.1	6.9	10.5	110.9	1,483
All	56.6	11.1	4.9	9.4	79.8	36,248

Coastal Alaska (approximately 12 percent of forest land in Alaska)						
Spruce/Fir	14.8	2.9	7.6	42.5	62.1	358
Fir/Spruce/Mountain Hemlock	64.7	13.6	17.4	27.2	62.1	2,165
Hemlock/Sitka Spruce	115.9	24.4	27.7	28.5	116.3	2,708
Aspen/Birch	27.9	5.2	7.6	32.4	42.5	245
Minor Types and Nonstocked	29.4	5.7	7.9	19.2	72.3	364
All	81.6	17.1	20.5	28.5	87.1	5,841
Pacific Northwest, Westside (Western OR and WA)						
Douglas-fir	139.5	29.2	31.4	15.1	94.8	5,956
Fir/Spruce/Mountain Hemlock	129.4	27.3	35.6	20.0	62.1	1,238
Hemlock/Sitka Spruce	166.7	35.1	42.0	25.7	116.3	1,490
Alder/Maple	80.6	15.8	16.6	10.0	115.2	1,124
Minor Types and Nonstocked	56.4	11.1	17.2	12.2	86.8	1,287
All	126.4	26.3	30.1	16.2	95.2	11,094
Pacific Northwest, Eastside (Eastern OR and WA)						
Douglas-fir	64.6	13.5	19.1	16.4	94.8	2,011
Ponderosa Pine	41.3	8.6	9.6	13.1	50.7	2,767
Fir/Spruce/Mountain Hemlock	75.3	15.9	27.5	17.4	62.1	1,806
Lodgepole Pine	35.1	7.4	13.7	13.4	52.0	1,001
Western Larch	72.6	15.2	21.5	17.8	45.1	228
Other Western Softwoods	12.2	2.3	3.3	7.5	78.8	1,156
Minor Types and Nonstocked	27.8	5.5	18.1	11.3	80.6	1,037
All	47.5	9.8	15.6	13.8	68.0	10,005
Pacific Southwest (CA)						
Pinyon/Juniper	14.9	2.8	2.5	5.7	26.3	553
Douglas-fir	144.5	30.0	23.5	14.1	40.1	446
Ponderosa Pine	53.9	11.2	9.9	12.6	41.3	952
Fir/Spruce/Mountain Hemlock	110.7	23.3	29.6	19.0	51.9	855
Redwood	232.8	48.6	33.5	7.8	53.8	291
Other Western Softwoods	23.2	4.4	5.5	9.2	49.8	836
California Mixed Conifer	104.6	21.9	21.2	21.5	49.8	3,225
Western Oak	50.1	9.5	5.5	7.7	27.6	3,745
Tanoak/Laurel	126.2	24.8	12.3	11.7	27.6	767
Minor Types and Nonstocked	48.6	9.8	16.0	12.0	36.8	1,351
All	76.3	15.5	13.9	13.1	39.0	13,022
Rocky Mountain, North (ID,MT)						
Douglas-fir	11.7	2.3	2.0	5.3	41.7	508
Ponderosa Pine	50.9	10.7	13.1	15.3	38.8	5,421
Fir/Spruce/Mountain Hemlock	32.2	6.6	8.0	10.4	34.3	1,753
Lodgepole Pine	56.1	11.8	22.1	17.6	44.1	4,714
Western Larch	44.2	9.4	17.1	15.1	37.2	2,707
Other Western Softwoods	27.2	5.6	13.2	11.0	31.4	643
Aspen/Birch	21.6	4.0	14.6	10.7	56.6	501
Minor Types and Nonstocked	33.1	6.7	20.9	11.6	41.5	2,629
All	44.4	9.3	16.3	14.3	40.2	18,877
Rocky Mountain, South (AZ,CO,NM,NV,UT,WY)						
Pinyon/Juniper	16.7	3.3	2.1	5.8	19.7	16,040
Douglas-fir	47.5	10.0	14.4	13.4	30.9	1,709
Ponderosa Pine	37.3	7.8	7.7	9.9	24.1	3,195
Fir/Spruce/Mountain Hemlock	52.5	11.1	23.9	17.8	31.5	4,313
Lodgepole Pine	44.2	9.4	20.2	15.0	27.0	1,875
Aspen/Birch	38.5	7.3	11.1	12.6	58.8	2,558
Woodland Hardwoods	17.1	3.1	5.8	6.6	25.9	3,064
Minor Types and Nonstocked	10.2	1.8	11.3	5.2	25.4	2,550
All	27.0	5.5	8.5	9.0	26.2	35,304

United States (forest land included in Inventory)	53.1	10.5	9.2	10.5	63.0	269,702

Note: The forest area values in this table do not equal the forest area values reported in Table A-248, because the forest area values in this table are estimated using the most recent dataset per state, with an average year of 2010. The time series of forest area values reported in Table A-248, in contrast, is constructed following the carbon calculator tool (CCT) methods used to construct the C stock series. The forest area values reported in Table A-248 and Table A-250 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 FIADB 6.0 data (USDA Forest Service 2014b), but it also draws on older FIA survey data where necessary. The 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 2014a), and compilations of analytical estimates based on these databases are found in Waddell et al. (1989) and Smith et al. (2001). Having only plot-level information (such as volume per hectare of the RPA data) 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.

A 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 (for further discussion see Domke et al. 2014). This approach to filling gaps in older data also extends to timberlands where individual-tree data was 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 C estimates (Smith et al. 2010, Heath et al. 2011) were initially developed as an offshoot of the forest C 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 of these categories 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 (T per hectare) for the various forest pools. Carbon density for live trees, standing dead trees, understory vegetation, downed 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 downed 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 (2006).

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, diameter, and, in some regions, tree height and site quality. The estimated sound volume (i.e., after rotten/missing deductions provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree (Woodall et al. 2011). The estimated volumes of wood and bark are converted to biomass based on the density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates from 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 (see Woodall et al. 2011 for details). 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. Carbon is estimated by multiplying the estimated oven-dry biomass by a C constant of 0.5 because biomass is 50 percent of dry weight (IPCC 2006). Further discussion and example calculations are provided in Woodall et al. 2011 and Domke et al. 2012.

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 less than 4 percent of the forest land inventory-plot-to-C conversions within the 214 state-level surveys utilized here.

Understory vegetation

Understory vegetation is a minor component of total forest ecosystem 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 model:

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density}))}$$

In this model, the ratio is the ratio of understory C density (T C/ha) to live tree C density (above- and below-ground) according to Jenkins et al. (2003) and expressed in T C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients are in Table A-251. 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:

$$\text{Understory (T C/ha)} = (\text{live tree C density}) \times e^{(0.855 - 1.03 \times \ln(\text{tree C density}))}$$

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 model. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked (i.e., currently lacking tree cover but still in the forest land use) and pinyon/juniper forest types (see Table A-251) are set to coefficient A, which is a C density (T C/ha) for these types only.

Table A-251: Coefficients for Estimating the Ratio of C Density of Understory Vegetation (above- and belowground, T C/ha)[a] by Region and Forest Type. The Ratio is Multiplied by Tree C 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
	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
PSW	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
	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
PWE	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
	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
PWW	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
	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
RMN	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
	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
RMS	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
	Bottomland Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
SC	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
	Bottomland Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
SE	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 model: 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 T C/ha.
[b] Regions and types as defined in Smith et al. (2003).
[c] Maximum ratio: any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio.

Dead Wood

The standing dead tree estimates are primarily based on plot-level measurements (Domke et al. 2011, Woodall et al. 2011). This C pool includes 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 21 percent of the forest land inventory-plot-to-C conversions within the 214 state-level surveys utilized here.

Downed dead wood, inclusive of logging residue, are sampled on a subset of FIA plots. Despite a reduced sample intensity, a single down woody material population estimate (Woodall et al. 2010, Domke et al. 2013, Woodall et al. 2013) per state is now incorporated into these empirical downed dead wood estimates. Downed 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. It also includes stumps and roots of harvested trees. Ratio estimates of downed dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for downed dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in Table A-252. An additional component of downed 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-253. These amounts are added to explicitly account for downed dead wood following harvest. The sum of these two components are then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates (Domke et al. 2013). An example of this 3-part calculation for downed dead wood in a 25-year-old naturally regenerated loblolly pine forest with 82.99 T C/ha in live trees (Jenkins et al. 2003) in Louisiana is as follows:

First, an initial estimate from live tree C density and Table A-252 (SC, Natural Pine)

C density = 82.99 × 0.068 = 5.67 (T C/ha)

Second, an average logging residue from age and Table A-253 (SC, softwood)

C density = $5.5 \times e^{(-25/17.9)}$ = 1.37 (T C/ha)

Third, adjust the sum by the downed dead wood ratio plot-to-model for Louisiana, which was 27.6/31.1 = 0.886

C density = (5.67 + 1.37) × 0.886 = 6.24 (T C/ha)

Table A-252: Ratio for Estimating Downed Dead Wood by Region and Forest Type. The Ratio is Multiplied by the Live Tree C Density on a Plot to Produce Downed Dead Wood C Density (T C/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
PSW	Douglas-fir	0.091
	Fir-Spruce	0.109
	Hardwoods	0.042
	Other Conifer	0.100
	Pinyon-Juniper	0.031
	Redwood	0.108
	Nonstocked	0.022
PWE	Douglas-fir	0.103
	Fir-Spruce	0.106
	Hardwoods	0.027
	Lodgepole Pine	0.093
	Pinyon-Juniper	0.032
	Ponderosa Pine	0.103
	Nonstocked	0.024
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.082
	Nonstocked	0.020
SC	Bottomland Hardwood	0.063
	Misc. Conifer	0.068
	Natural Pine	0.068
	Oak-Pine	0.072
	Planted Pine	0.077
	Upland Hardwood	0.067
	Nonstocked	0.013
SE	Bottomland Hardwood	0.064
	Misc. Conifer	0.081
	Natural Pine	0.081
	Oak-Pine	0.063
	Planted Pine	0.075
	Upland Hardwood	0.059
	Nonstocked	0.012

[a] Regions and types as defined in Smith et al. (2003).

Table A-253: Coefficients for Estimating Logging Residue Component of Downed Dead Wood

Region[a]	Forest Type Group[b] (softwood/ hardwood)	Initial C Density (T/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

Carbon in the litter layer is currently sampled on a subset of the FIA plots. 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. Because litter attributes are only collected on a subset of FIA plots, a model was developed to predict C density based on plot/site attributes for plots that lacked litter information (Domke et al. in preparation).

As the litter, or forest floor, estimates are an entirely new model this year, a more detailed overview of the methods is provided here. The first step in model development was to evaluate all relevant variables—those that may influence the formation, accumulation, and decay of forest floor organic matter—from annual inventories collected on FIADB plots (P2) using all available estimates of forest floor C (n = 4,530) from the P3 plots (hereafter referred to as the research dataset) compiled from 2000–2014 (Domke et al. in preparation).

Random forest, a machine learning tool (Domke et al. in preparation), was used to evaluate the importance of all relevant forest floor C predictors available from P2 plots in the research dataset. Given many of the variables were not available due to regional differences in sampling protocols during periodic inventories, the objective was to reduce the random forest regression model to the minimum number of relevant predictors without substantial loss in explanatory power. The form of the full random forest model was:

$$P(FFC_{Full}) = f(lat, lon, elev, fortypgrp, above, ppt, t\max, gmi) + u$$

Where:

- lat = latitude
- lon = longitude
- elev = elevation
- fortypgrp = forest type group
- above = aboveground live tree C (trees ≥ 2.54 cm dbh)
- ppt = mean annual precipitation
- tmax = average maximum temperature
- gmi = the ratio of precipitation to potential evapotranspiration
- u = the uncertainty in the prediction resulting from the sample-based estimates of the model parameters and observed residual variability around this prediction.

For each replacement, u was independently and randomly generated from a N(0,σ) distribution with σ incorporating the variability from both sources. This process of randomly selecting and incorporating u may be considered an imputation. Each model prediction was replaced independently m times and m separate estimates were combined where m = 1,000 in this analysis.

The full model performance was first evaluated within random forest using the RMSE and R^2 metrics. The predictions from the selected model were then evaluated directly against the observations from Phase 3 plots using an equivalence testing framework. This method assumes the values are not equivalent unless the data demonstrate that the predictions and observations are similar to within a predefined tolerance. A broad region of indifference (±25 percent, absolute value of the mean of the difference is less than 25 percent of the standard deviation) and a narrow region of indifference (±10 percent) were defined. Finally, the random forest model predictions were evaluated using a metric known as modeling efficiency; this approach provides an index of model performance on a relative scale where "1" indicates a 'perfect' fit, "0" suggests the model is no better than the mean and negative values indicate a poor model fit.

Due to data limitation in certain regions and inventory periods a series of reduced random forest regression models were used rather than replacing missing variables with imputation techniques in random forest. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied to replace forest floor model predictions from Smith and Heath (2002). Forest floor C predictions are expressed in $T \cdot ha^{-1}$.

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.

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 C. 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 C 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 C to and from the atmosphere within national boundaries. Carbon 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-257). 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-258). 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-257. 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) Carbon in imports of wood, pulp, and paper to the United States,

(4) Carbon in exports of wood, pulp and paper from the United States, and

(5) Carbon in annual harvest of wood from forests in the United States.

Table A-254: Harvested Wood Products from Wood Harvested in the United States—Annual Additions of C to Stocks and Total Stocks Under the Production Approach (Parentheses Indicate Net C Sequestration (i.e., a Net Removal of C from the Atmosphere)

Year	Net C additions per year (MMT C per year)							Total C stocks (MMT C)		
		Products in use			Products in SWDS					
	Total	Total	Solid wood products	Paper products	Total	Solid wood products	Paper products	Total	Products in use	Products in SWDS
1990	(35.9)	(17.7)	(14.4)	(3.3)	(18.3)	(9.9)	(8.3)	1,859	1,231	628
1991	(33.8)	(14.9)	(11.9)	(3.1)	(18.8)	(11.1)	(7.7)	1,895	1,249	646
1992	(33.8)	(16.3)	(12.6)	(3.7)	(17.4)	(9.5)	(7.9)	1,929	1,264	665
1993	(32.9)	(15.0)	(12.2)	(2.8)	(17.9)	(9.7)	(8.3)	1,963	1,280	683
1994	(33.4)	(15.9)	(12.1)	(3.8)	(17.5)	(9.8)	(7.7)	1,996	1,295	701
1995	(32.3)	(15.1)	(11.2)	(3.8)	(17.2)	(10.7)	(6.5)	2,029	1,311	718
1996	(30.6)	(14.1)	(11.5)	(2.6)	(16.5)	(10.6)	(6.0)	2,061	1,326	735
1997	(32.0)	(14.7)	(11.8)	(3.0)	(17.3)	(10.3)	(6.9)	2,092	1,340	752
1998	(31.1)	(13.4)	(11.4)	(2.0)	(17.7)	(10.2)	(7.5)	2,124	1,355	769
1999	(32.5)	(14.1)	(12.1)	(2.0)	(18.4)	(10.6)	(7.8)	2,155	1,368	787
2000	(30.8)	(12.8)	(11.9)	(1.0)	(18.0)	(10.7)	(7.3)	2,188	1,382	805
2001	(25.5)	(8.7)	(10.1)	1.4	(16.8)	(10.7)	(6.0)	2,218	1,395	823
2002	(26.8)	(9.6)	(10.7)	1.1	(17.2)	(11.1)	(6.1)	2,244	1,404	840
2003	(25.6)	(9.5)	(9.9)	0.4	(16.2)	(11.0)	(5.1)	2,271	1,414	857
2004	(28.4)	(12.1)	(11.3)	(0.8)	(16.3)	(11.3)	(5.0)	2,296	1,423	873
2005	(28.0)	(11.7)	(11.3)	(0.4)	(16.3)	(11.5)	(4.8)	2,325	1,435	890
2006	(29.4)	(12.1)	(10.5)	(1.6)	(17.3)	(11.6)	(5.7)	2,353	1,447	906
2007	(28.0)	(10.6)	(8.5)	(2.1)	(17.4)	(11.6)	(5.7)	2,382	1,459	923
2008	(21.0)	(3.9)	(2.9)	(1.0)	(17.1)	(11.4)	(5.7)	2,411	1,470	941
2009	(14.8)	1.8	0.5	1.3	(16.6)	(11.2)	(5.4)	2,431	1,473	958
2010	(16.5)	0.1	0.2	(0.1)	(16.6)	(11.3)	(5.3)	2,446	1,472	974
2011	(18.8)	(2.0)	(1.2)	(0.8)	(16.8)	(11.4)	(5.4)	2,462	1,471	991
2012	(18.6)	(1.7)	(1.7)	0.0	(16.9)	(11.5)	(5.4)	2,481	1,473	1,008
2013	(19.3)	(2.3)	(3.1)	0.7	(17.0)	(11.6)	(5.4)	2,500	1,475	1,025
2014	-	-	-	-	-	-	-	2,520	1,478	1,042

- Not reported or zero

Table A-255: Comparison of Net Annual Change in Harvested Wood Products C Stocks Using Alternative Accounting Approaches

	HWP Contribution to LULUCF Emissions/ removals (MMT 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	(137.2)	(122.8)	(114.2)
1999	(147.1)	(127.4)	(119.2)
2000	(141.2)	(120.4)	(113.0)
2001	(125.0)	(100.4)	(93.5)
2002	(130.7)	(103.3)	(98.2)
2003	(125.8)	(98.7)	(94.0)
2004	(143.2)	(108.5)	(104.0)
2005	(142.1)	(107.3)	(102.7)
2006	(138.1)	(113.9)	(107.7)
2007	(115.1)	(111.5)	(102.8)
2008	(73.1)	(88.4)	(76.8)
2009	(42.3)	(69.8)	(54.4)
2010	(49.2)	(79.4)	(60.6)
2011	(52.4)	(91.8)	(68.9)
2012	(58.0)	(91.9)	(68.3)
2013	(67.8)	(96.0)	(70.8)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-256: 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 C to the atmosphere from HWP consumption (from fuelwood and products in use and products in SWDS)	7 Annual release of C 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	$\uparrow C_{HWP\ DC}$	$\uparrow C_{HWP\ DH}$	
									kt C/yr	kt 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	19,654	17,769	13,404	17,738	18,994	15,057	134,206	100,720	103,064	(114,188)
1999	21,444	18,662	14,146	18,359	20,599	15,245	134,193	99,440	101,689	(119,182)

2000	20,000	18,508	12,840	17,970	21,858	16,185	133,694	100,859	102,884	(112,969)
2001	16,491	17,610	8,713	16,781	22,051	15,336	127,896	100,510	102,402	(93,479)
2002	17,414	18,235	9,566	17,213	23,210	15,744	126,866	98,683	100,087	(98,188)
2003	16,986	17,326	9,453	16,175	23,707	16,303	126,477	99,569	100,850	(93,967)
2004	21,409	17,644	12,080	16,275	26,428	16,953	131,738	102,160	103,383	(103,967)
2005	20,990	17,765	11,711	16,294	26,793	17,312	132,482	103,207	104,477	(102,683)
2006	19,083	18,587	12,095	17,268	25,442	18,836	129,529	98,466	100,165	(107,666)
2007	13,092	18,308	10,639	17,387	21,650	20,657	123,640	93,233	95,614	(102,763)
2008	2,420	17,511	3,864	17,090	16,982	21,159	106,096	81,988	85,142	(76,830)
2009	(5,104)	16,642	(1,821)	16,646	13,115	20,616	96,032	76,993	81,206	(54,361)
2010	(2,896)	16,301	(59)	16,573	14,161	22,420	97,555	75,892	81,042	(60,550)
2011	(1,887)	16,171	1,998	16,804	13,923	24,672	100,848	75,815	82,046	(68,943)
2012	(299)	16,112	1,724	16,906	14,067	23,324	103,470	78,400	84,839	(68,313)
2013	2,298	16,188	2,319	16,994	15,142	22,851	107,005	80,810	87,692	(70,815)

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-257. 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-258. 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-247 and Table A-248. The decline in net additions to HWP C stocks continued through 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 C 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 C additions to HWP in use and in landfills combined.

Table A-257: 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 C in harvested wood products for the United States" *Forest Products Journal* 58:56–72.

Table A-258: 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 C 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 effects 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 estimate 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 (T/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 CRM for estimating biomass are not available, so an assumed 10 percent error on biomass from volume is applied to the volume portion of the estimate; 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. Downed 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 C 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 C 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 U.S. 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 C 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 Forest Fires

CO_2 Emissions from Forest Fires

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, such as a forest fire, removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss from such disturbances 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. Using the methodology provided in IPCC (2003), C emissions from forest fires were calculated as:

$$\text{C Emissions} = \text{Forest area burned (ha)} \times \text{C density (Mg per ha of dry matter)}$$

$$\times \text{ Combustion efficiency (45\%)} \times \text{Mg to MMT conversion factor } (10^{-6})$$

where a default value of 0.45 from IPCC (2006) was assumed for the amount of biomass burned by wildfires as well as prescribed fires (combustion efficiency factor).

This 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 2014b**)**. 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 2013. 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 2013. 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 2013 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 2013 from the National Interagency Fire Center (NIFC 2014)**.** 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 2014). Data are acres of land which experienced fire activity on forest service land. The majority of wildfires in Alaska that occur on lands protected by the USDA Forest Service occur in the coastal areas (Southeast and South Central); as this is where the National Forest System land is located. 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 2008). 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 63.0 and 73.1 T/ha, according to annual (1990–2013) 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 C and soil C unburnt. 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 5.8 and 67.7 MMT C. For Alaska, the average C density reported by the USDA Forest Service varies between 130.6 and 130.8 T/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 0.0 to 0.2 MMT C emitted. Based on data from the USDA Forest Service, the average C density for prescribed fires varied between 17.7 and 19.4 T C/ha. For prescribed fires, the methodology assumes that only the litter and deadwood C 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 2008). 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 1.5 and 5.3 MMT C.

Carbon density estimates for T C/ha were multiplied by estimates of forest area burned by year; the resulting estimates are displayed in Table A-259. Carbon estimates were multiplied by 92.8 percent to account for the proportion of C 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 2013 were estimated to be 79.6 MMT/yr.

Table A-259: Areas (Hectares) from Wildfire Statistics and Corresponding Estimates of C and CO_2 (MMT/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)	C emitted (MMT/yr)	CO_2 emitted (MMT/yr)	Reported area burned[2] (ha)	Forest area burned[3] (ha)	C emitted (MMT/yr)	CO_2 emitted (MMT/yr)	Forest area burned[4] (acres)	Forest area burned (ha)	C emitted (MMT/yr)	CO_2 emitted (MMT/yr)
1990	579,589	298,146	8	29	355,432	182,838	1	5	8	3	0.000	0.001
1991	486,807	250,753	7	24	355,432	183,082	1	5	557	225	0.013	0.045
1992	785,892	405,363	12	40	355,432	183,332	1	5	47	19	0.001	0.004
1993	438,865	226,653	7	22	355,432	183,564	1	5	110	45	0.003	0.009
1994	1,540,987	796,729	23	79	355,432	183,767	1	5	23	9	0.001	0.002
1995	727,051	410,495	12	41	355,432	200,678	2	6	7	3	0.000	0.001
1996	2,212,309	1,285,738	38	128	355,432	206,568	2	6	103	42	0.002	0.008
1997	335,914	195,322	6	20	355,432	206,671	2	6	33	13	0.001	0.003
1998	489,246	284,516	8	29	355,432	206,698	2	6	2	1	0.000	0.000
1999	1,869,918	1,093,678	33	111	806,780	471,870	4	13	7	3	0.000	0.001
2000	2,685,981	1,570,569	47	161	482,475	282,117	2	8	1	1	0.000	0.000
2001	1,356,830	792,967	24	82	667,428	390,062	3	11	2,078	841	0.049	0.168
2002	2,023,976	1,178,435	36	122	1,086,503	632,603	5	18	28	11	0.001	0.002
2003	1,358,986	693,666	21	73	1,147,695	585,817	5	17	17	7	0.000	0.001
2004	637,258	330,669	10	35	996,453	517,052	4	15	23	9	0.001	0.002
2005	1,629,067	905,174	28	96	934,965	519,503	4	15	353	143	0.008	0.029
2006	3,888,011	2,163,110	68	230	1,100,966	612,527	5	18	8	3	0.000	0.001
2007	3,512,122	1,703,083	54	183	1,274,383	617,969	5	18	2	1	0.000	0.000
2008	2,099,842	1,019,143	32	110	783,068	380,056	3	11	1	0	0.000	0.000
2009	1,201,996	583,771	19	63	1,024,306	497,473	4	14	22	9	0.001	0.002
2010	929,687	451,753	15	49	980,903	476,640	4	14	12	5	0.000	0.001
2011	3,406,788	1,656,182	54	183	855,025	415,663	4	12	5	2	0.000	0.000
2012	3,658,098	1,779,168	58	198	797,974	388,106	3	11	2	0.6	0.000	0.000
2013	1,215,376	591,386	19	66	809,388	393,897	3	12	4	1	0.000	0.000

[1] Note that these emissions have already been accounted for in the estimates of net annual changes in C 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 (2014).
[3] Ratios calculated using forest land area estimates from FIA (USDA Forest Service 2014b) and wildland area under protection estimates from USDA Forest Service (1992) and the National Association of State Foresters (2011).
[4] 1990–2007 Alaskan forest fires data are from the Alaska Department of Natural Resources (2008). 2008–2013 data are from Alaska Interagency Coordination Center (2014).

Non-CO_2 Emissions from Forest Fires

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. The default IPCC (2003) methodology and default IPCC (2006) combustion factor for wildfires were used to calculate the C emissions from forest fires as discussed above. Carbon dioxide emissions were estimated by multiplying total C emitted by the C to CO_2 conversion factor of 44/12 and by 92.8 percent, which is the estimated proportion of C emitted as CO_2 (Smith 2008). 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 from IPCC (2006). The models used are:

$$CH_4 \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

Where the CH_4 and N_2O to CO_2 emission ratios were derived from IPCC (2006), in Table A- 260 below.

Table A- 260: Emission Factors for Extra Tropical Forest Burning and Emissions Ratios of CH_4 and N_2O to CO_2

Emission Factor (g per kg dry matter burned)[1]		Emissions Ratios	
CH_4	4.70	CH_4 to CO_2	0.003
N_2O	0.26	N_2O to CO_2	0.0002
CO_2	1,569	CO_2 to CO_2	1.000

[1] IPCC 2006

The resulting estimates are presented in Table A- 261.

Table A- 261: Estimated C Released and Estimates of Non-CO_2 Emissions (MMT/yr) for U.S. forests

Year	C emitted (MMT/yr)	CH_4 emitted (MMT/yr)	N_2O (MMT/yr)
1990	9.910	0.101	0.006
1991	8.622	0.088	0.005
1992	13.084	0.133	0.007
1993	8.005	0.082	0.005
1994	24.564	0.250	0.014
1995	13.584	0.138	0.008
1996	39.371	0.401	0.022
1997	7.445	0.076	0.004
1998	10.142	0.103	0.006
1999	36.581	0.373	0.021
2000	49.609	0.506	0.028
2001	27.308	0.278	0.015
2002	41.220	0.420	0.023
2003	26.200	0.267	0.015
2004	14.554	0.148	0.008
2005	32.538	0.332	0.018
2006	72.868	0.743	0.041
2007	58.881	0.600	0.033
2008	35.558	0.362	0.020
2009	22.898	0.233	0.013
2010	18.629	0.190	0.011
2011	57.275	0.584	0.032
2012	61.460	0.626	0.035
2013	22.883	0.233	0.013

Note: Calculated based on C emission estimates in Table A-259 and default factors in IPCC (2003, 2006)

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.[1] 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 the CH_4 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.[2] 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 of landfills in the United States. Consequently, to estimate CH_4 generation, a methodology was developed (i.e., the first order decay waste model) based on the quantity of waste placed in landfills nationwide each year 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 waste landfills were developed. A database of measured CH_4 generation rates at MSW 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 waste landfills, CH_4 emissions from industrial waste 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 at MSW landfills[3] and the amount oxidized in the soil at MSW and industrial landfills. The steps taken to estimate CH_4 emissions from U.S. landfills for the years 1990 through the current inventory year are discussed in greater detail below.

Figure A- 21 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 2013, estimates of the annual quantity of waste placed in MSW landfills were developed from a survey of State agencies as reported in the State of Garbage (SOG) in America surveys (Shin 2014; BioCycle 2010), adjusted to include U.S. territories.[4] The SOG survey is the only continually updated nationwide survey of waste disposed in landfills in the United States. Table A-262 shows estimates of waste quantities contributing to CH_4 emissions. The table shows SOG estimates of total waste generated and total waste landfilled (adjusted for U.S. territories) for various years over the 1990 to 2013 timeframe.

State-specific landfill waste generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey for every two years (i.e., 2002, 2004, 2006, and 2008 as published in BioCycle 2006, 2008, and 2010). The most recent SOG survey was published in 2014 (Shin 2014) for the 2011 year. A linear interpolation was used for the amount of waste generated in 2001, 2003, 2005, 2007, 2009, 2010, 2012, and 2013 because no SOG surveys were published for those years. Upon publication of the next SOG survey, the waste landfilled for 2012 and 2013 will be updated. Estimates of the quantity of waste landfilled from 1989 to the current inventory year are determined by applying a waste disposal factor to the total amount of waste generated (i.e., the SOG data). A waste disposal factor is determined for each year a SOG survey is published and is the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in-between the SOG surveys. Methodological changes

[1] 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.

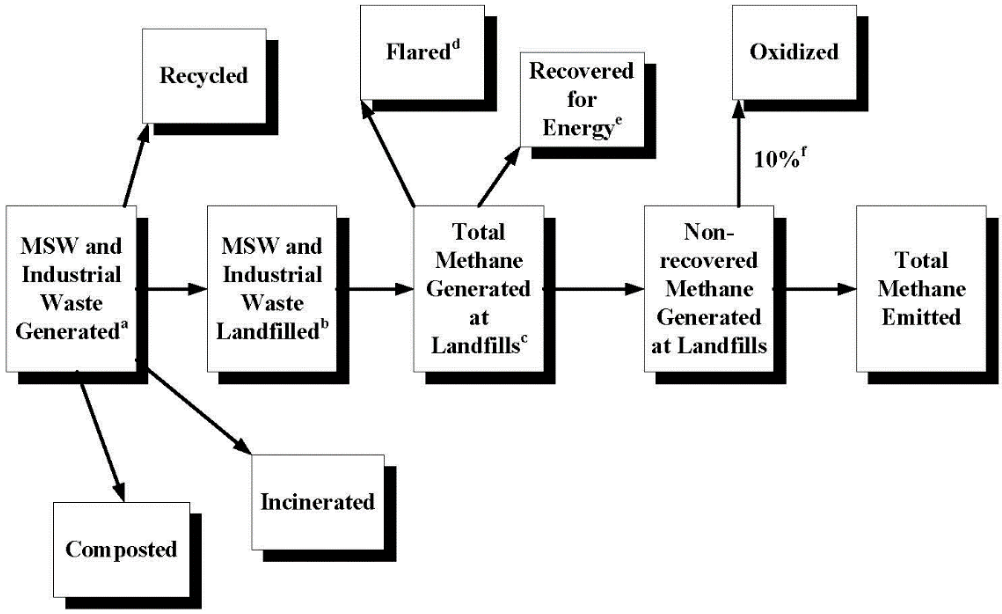
[2] See Box 7-1 "Biogenic Emissions and Sinks of Carbon" in the Waste chapter for additional background on how biogenic emissions of landfill CO_2 are addressed in the U.S. Inventory.

[3] Landfill gas recovery is only estimated for MSW landfills due to a lack of national data on industrial waste landfills. Approximately 1 percent of the industrial waste landfills reporting under the GHGRP have active landfill gas collection systems.

[4] Since the SOG 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 2013) and the per capita rate for waste landfilled from BioCycle (2010).

have occurred over the time that the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

Figure A- 21: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



[a] Shin 2014 and BioCycle 2010 for MSW and activity factors for industrial waste.
[b] 1960 through 1988 based on EPA 1988 and EPA 1993; 1989 through 2008 based on BioCycle 2010.
[c] 2006 IPCC Guidelines – First Order Decay Model
[d] EIA 2007 and flare vendor database
[e] EIA 2007 and EPA (LMOP) 2014.
[f] 2006 IPCC Guidelines; Mancinelli and McKay 1985, Czepiel et al 1996

Table A-262: Solid Waste in MSW Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

Description	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Waste Generated[a]	271	302	459	455	430	404	405	407	409	412	415
Percent of Wastes Landfilled[a]	77%	63%	64%	65%	67%	69%	66%	66%	63%	63%	63%
Total Wastes Landfilled[a]	205	187	290	289	283	275	265	266	256	258	259
Waste in Place (30 years)[b]	4,671	5,054	5,991	6,126	6,257	6,378	6,488	6,585	6,679	6,760	6,840
Waste Contributing to Emissions[c]	6,808	7,772	10,214	10,503	10,786	11,061	11,326	11,591	11,847	12,104	12,364

[a] Source: Shin (2014); *BioCycle* (2006, 2008, 2010), adjusted for missing data using U.S. Census Bureau (2009, 2014) 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, 2003, 2005, 2007, 2009, 2010, 2012, and 2013 are based on an interpolation between survey years and the increase in population because there were no surveys in these years.
[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) for years 1940 to years 1988 (not presented in table), *BioCycle* (2006, 2008, 2010) for years 1989 to 2008, and Shin (2014) for years 2009 through 2013.
[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, kt C/kt 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 are 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 decay 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- 263 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A- 263: 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-264.

Table A-264: Percent of U.S. Population within Precipitation Ranges (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000	2010
<20	10	13	14	16	19	19	18
20-40	40	39	37	36	34	33	44
>40	50	48	48	48	48	48	38

Source: Years 1950 through 2000 are from RTI (2004) using population data from the U.S. Census Bureau and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration. Year 2010 is based on the methodology from RTI (2004) and the U.S. Bureau of Census and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration where available.

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 waste 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 were used for years 1990 to 2001 and production data published by the U.S. Department of Agriculture were used for years 2002 through 2013. 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 for the years 1990 through 2013 (ERG 2014). 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 waste 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 (RTI 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) (RTI 2014). 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 1990 to 2010 inventory year with the intent of updating values for L_o 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.[5] 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, sufficient data were not obtained to warrant a change for the current

[5] Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; and Skog 2000.

inventory year. EPA is considering an update to the L_o and k values for the pulp and paper sector and will work with stakeholders to gather data and other feedback on potential changes to these values.

As with MSW landfills, a similar trend in disposal practices from open dumps to managed landfills was expected for industrial waste 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 that was 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 waste 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 using a combination of four databases:

- the flare vendor database (contains updated sales data collected from vendors of flaring equipment)
- a database of LFGTE projects compiled by LMOP (EPA 2014a)
- a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases containing facility-specific information reported on flares and LFGTE projects (EIA 2007), and
- the GHGRP dataset for MSW landfills that contains detailed facility-specific information, including annual amounts of recovered CH_4.

EPA's GHGRP MSW landfills database was first introduced as a data source for the current Inventory (i.e., 1990-2013). The GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification and is considered to contain the least uncertain data of the four databases. However, this database is unique in that it only contains a portion of the landfills in the U.S. (although, presumably the highest emitters since only those landfills that meet the methane generation threshold must report) and only contains data from 2010 and later.

The destruction efficiencies reported through EPA's GHGRP were applied to the landfills in the GHGRP MSW landfills database. The median value of the reported destruction efficiencies was 99 percent for all reporting years (2010 through 2013, EPA 2014b). A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided for the other three databases. This value for destruction 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, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-methane components (i.e., volatile organic compounds and non-methane organic compounds) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA 2008. Thus, a value of 99 percent for the destruction efficiency of flares has been used in Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those 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 three sources: (1) a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007); (2) a database compiled by LMOP (EPA 2014a); and (3) the GHGRP MSW landfills dataset. 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. The GHGRP MSW landfills database contains the most detailed data on landfills that reported under the GHGRP for years 2010 through 2013, however the amount of CH_4 recovered is not specifically allocated to a flare versus a LFGTE project. The allocation into flares or LFGTE was performed by matching landfills to the EIA and LMOP databases for LFGTE projects and to the flare database for flares. Detailed information on the landfill name, owner or operator, city, and state are available for both the EIA and LMOP databases; consequently, it was straightforward to identify landfills that were in both databases against those in EPA's GHGRP MSW landfills database. EPA's GHGRP MSW landfills database was given priority because CH_4 recovery and other supporting information were reported for each year and were based on direct measurements. The EIA database was given second priority (for landfills not in the GHGRP MSW landfills database) because CH_4 recovery based on direct measurements was reported by landfill. Landfills in the

LMOP database that were also in EPA's GHGRP MSW landfills database and/or EIA database were dropped to avoid double or triple counting.

Step 4b: Estimate CH_4 Emissions Avoided Through Flaring

The quantity of CH_4 flared was based on data from EPA's GHGRP MSW landfills database, the EIA database, and on information provided by flaring equipment vendors. To avoid double counting, flares associated with landfills in EPA's GHGRP, 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, GHGRP, 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 GHGRP MSW landfills, 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 EPA's GHGRP, 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 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 the rate of oxidation because oxidation is difficult to measure and varies considerably with the presence of a gas collection system, 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.

Sites with landfill gas collection systems are generally designed and managed better to improve gas recovery. More recent research (2006 to 2012) 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. A continued effort will be made to review the peer-reviewed literature to better understand how climate, cover type, and gas recovery influence the rate of oxidation at active and closed landfills. At this time, the IPCC recommended oxidation factor of 10 percent will continue to be used for all landfills.

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- 265.

Table A- 265: CH_4 Emissions from Landfills (kt)

Activity	1990	1995	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
MSW CH_4 Generation	8,215	9,146	10,095	10,396	10,783	11,150	11,498	11,826	12,136	12,414	12,657	12,860	13,030	13,166	13,303
Industrial CH_4 Generation	553	617	704	711	719	724	732	736	741	748	753	756	758	760	763
Potential Emissions	**8,768**	**9,763**	**10,800**	**11,106**	**11,502**	**11,875**	**12,230**	**12,562**	**12,877**	**13,161**	**13,411**	**13,615**	**13,787**	**13,925**	**14,065**
Landfill Gas-to-Energy	(321)	(749)	(2,102)	(2,146)	(2,099)	(2,206)	(2,256)	(2,408)	(2,593)	(2,835)	(3,266)	(6,809)	(6,991)	(7,377)	(7,557)
Flare	(170)	(768)	(1,801)	(2,005)	(2,151)	(2,512)	(2,618)	(2,795)	(2,901)	(2,965)	(3,119)	(1,393)	(1,406)	(1,426)	(1,414)
Emissions Avoided	**(491)**	**(1,517)**	**(3,903)**	**(4,151)**	**(4,250)**	**(4,718)**	**(4,874)**	**(5,203)**	**(5,494)**	**(5,800)**	**(6,385)**	**(8,201)**	**(8,397)**	**(8,803)**	**(8,970)**
Oxidation at MSW Landfills	**(772)**	**(763)**	**(619)**	**(624)**	**(653)**	**(643)**	**(662)**	**(662)**	**(664)**	**(661)**	**(627)**	**(466)**	**(463)**	**(436)**	**(433)**
Oxidation at Industrial Landfills	**(55)**	**(62)**	**(70)**	**(71)**	**(72)**	**(72)**	**(73)**	**(74)**	**(74)**	**(75)**	**(75)**	**(76)**	**(76)**	**(76)**	**(76)**
Net Emissions	**7,450**	**7,422**	**6,207**	**6,260**	**6,527**	**6,441**	**6,620**	**6,623**	**6,645**	**6,625**	**6,324**	**4,873**	**4,851**	**4,611**	**4,585**

Note: Totals may not sum exactly to the last significant figure due to rounding.
Note: MSW generation in Table A-248 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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