3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

The steps outlined in this annex were used to estimate methane emissions from enteric fermentation for the years 1990 through 2017. As explained in the Enteric Fermentation chapter, a simplified approach was used to estimate emissions for 2018. The methodology used for 2018 relied on 2018 population estimates and 2017 implied emission factors and is explained in further detail within Chapter 5.1 Enteric Fermentation (CRF Source Category 3A). 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 (IPCC 2006).

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 the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and uses information on population, energy requirements, digestible energy, and CH_4 conversion rates to estimate CH_4 emissions.[73] 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 CEFM's 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 2019). State-level cattle population estimates are shown by animal type for 2018 in Table A-156. A national-level summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-157. Cattle populations used in the Enteric Fermentation source category for the 1990 to 2017 Inventory 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). For 2018, state populations were estimated by calculating ratios of 2017 state populations to the 2017 total national population, then applying those state-specific ratios to the 2018 national total population estimate, see the Enteric Fermentation chapter for more details about this approach.

Table A-156: 2018 Cattle Population Estimates, by Animal Type and State (1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 7-11 Months	Dairy Repl. Heif. 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 7-11 Months	Beef Repl. Heif. 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	4	7	1	3	50	356	699	27	65	25	20	6
Alaska	0	0	0	0	3	2	5	0	1	0	0	0
Arizona	101	198	35	83	20	94	185	8	21	130	19	300
Arkansas	3	6	1	2	60	469	921	39	94	54	35	13
California	901	1771	227	536	70	336	660	29	71	294	82	513
Colorado	80	156	30	71	55	413	812	42	103	417	285	1105
Conn.	10	19	3	7	1	3	5	0	1	1	1	0
Delaware	3	5	1	2	0	1	3	0	0	1	0	0

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

Florida	63	123	10	25	60	466	915	28	68	15	16	4
Georgia	43	84	9	21	33	255	501	25	60	18	27	6
Hawaii	1	2	0	1	4	38	74	3	7	5	2	1
Idaho	308	606	93	219	40	257	504	27	65	152	104	315
Illinois	48	94	16	37	25	199	390	17	41	118	59	303
Indiana	95	187	24	56	17	108	212	11	27	53	27	131
Iowa	110	217	40	95	70	495	973	41	100	642	296	1388
Kansas	77	151	30	71	95	806	1583	69	168	1005	784	2704
Kentucky	29	58	12	28	70	525	1031	34	81	105	63	21
Louisiana	6	12	1	3	31	230	452	19	46	12	11	3
Maine	15	30	4	11	2	6	11	1	2	2	2	1
Maryland	24	47	9	20	4	22	43	2	6	7	3	11
Mass.	6	12	2	5	1	3	7	0	1	1	1	0
Michigan	218	429	51	120	16	62	121	6	14	83	22	177
Minn.	236	464	88	208	35	190	373	21	52	245	90	450
Miss.	5	9	2	4	38	244	480	21	50	21	17	6
Missouri	44	86	13	32	120	1055	2072	83	201	226	129	128
Montana	7	14	3	6	100	763	1498	95	231	113	140	54
Nebraska	31	61	7	18	110	985	1936	84	203	1123	756	2933
Nevada	15	30	3	8	14	113	222	9	22	22	16	3
N.Hamp.	7	14	2	4	1	3	5	0	1	1	1	0
N.Jersey	3	7	1	3	1	4	8	0	1	1	1	0
N.Mexico	167	328	33	78	35	239	469	22	54	59	49	15
NewYork	318	626	106	250	20	56	111	10	24	22	27	23
N.Car.	23	45	7	16	31	190	373	15	37	21	14	5
N.Dakota	8	16	3	6	65	490	962	46	112	125	118	60
Ohio	135	264	36	85	30	148	290	17	41	108	33	180
Oklahoma	18	35	6	14	161	1075	2112	97	236	441	255	360
Oregon	64	125	19	46	40	280	550	23	57	76	63	98
Penn	270	530	94	222	25	95	186	15	35	78	33	110
R.Island	0	1	0	0	0	1	1	0	0	0	0	0
S.Car.	8	15	2	5	15	87	171	7	18	4	5	1
S.Dakota	60	117	13	32	100	854	1677	88	214	363	290	462
Tenn.	21	41	10	25	65	467	916	32	79	66	49	17
Texas	252	495	78	183	341	2289	4496	181	439	1270	740	2876
Utah	47	93	16	39	27	173	341	19	46	39	33	25
Vermont	66	130	17	39	3	7	14	1	3	2	4	1
Virginia	45	88	11	27	40	330	648	25	61	81	38	24
Wash.	141	278	36	85	18	115	227	13	31	93	64	226
W.Virg.	4	8	1	3	15	106	209	8	21	19	9	5
Wisconsin	657	1292	213	501	30	149	292	18	43	196	27	320
Wyoming	3	6	1	2	40	366	720	41	100	78	75	88

Table A-157: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2018 (1,000 head)

Livestock Type	1990	1995	2000	2005	2012	2013	2014	2015	2016	2017	2018
Dairy											
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,770	4,758	4,740	4,771	4,758	4,785	4,800
Dairy Cows	10,015	9,482	9,183	9,004	9,236	9,221	9,208	9,307	9,310	9,346	9,432
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,348	1,341	1,377	1,415	1,414	1,419	1,423
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,233	3,185	3,202	3,310	3,371	3,343	3,353
Beef											
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	15,288	14,859	14,741	15,000	15,563	15,971	16,021

Bulls	2,160	2,385	2,293	2,214	2,100	2,074	2,038	2,109	2,142	2,244	2,252
Beef Cows	32,455	35,190	33,575	32,674	30,282	29,631	29,085	29,302	30,166	31,213	31,466
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,263	1,291	1,385	1,479	1,515	1,484	1,424
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	2,968	3,041	3,121	3,424	3,578	3,598	3,454
Steer Stockers	10,321	11,716	8,724	8,185	7,173	7,457	7,374	7,496	8,150	7,957	8,032
Heifer Stockers	5,946	6,699	5,371	5,015	4,456	4,455	4,280	4,385	4,810	4,754	4,937
Feedlot Cattle	9,549	11,064	13,006	12,652	13,328	13,267	13,219	12,883	13,450	14,340	15,475

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.[74] 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.

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, described in further detail below.

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-158.

Table A-158: 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

[74] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2016).

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 (2016). 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-159, 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-160. 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-159: 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-160: 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	1,163	1,154	1,378	1,618	1,552	1,541	2,515	4,711	8,199	6,637	3,089	1,542
5	1,155	1,379	1,619	1,553	1,541	2,516	4,712	8,202	6,640	3,091	1,544	1,151
4	1,426	1,660	1,598	1,580	2,556	4,754	8,243	6,688	3,135	1,588	1,194	1,184
3	1,662	1,599	1,581	2,557	4,755	8,246	6,690	3,136	1,588	1,194	1,185	1,459
2	1,600	1,582	2,558	4,757	8,249	6,693	3,138	1,589	1,195	1,186	1,460	1,698
1	1,584	2,560	4,760	8,253	6,695	3,139	1,590	1,195	1,186	1,461	1,699	1,635
0	2,562	4,763	8,257	6,698	3,140	1,590	1,196	1,187	1,462	1,700	1,636	1,618

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: replacements (cattle raised to give birth), or stockers (cattle held for conditioning and growing on grass or other forage diets). 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 (2016).

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-161) 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-161.

Table A-161: 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	185	180	104	37	15	9	8	8	6	3	1	0
22	320	146	49	19	12	9	9	9	6	3	17	181
21	260	69	25	14	11	11	11	8	6	68	218	313
20	123	35	19	14	14	13	10	8	133	331	387	254
19	63	27	19	17	16	13	10	196	472	615	318	120
18	48	27	23	20	16	13	241	610	900	514	149	61
17	47	33	27	19	15	295	709	1,179	759	237	129	47
16	58	38	26	19	363	828	1,380	1,000	348	340	47	46
15	67	36	25	452	977	1,619	1,172	456	603	47	46	57
14	65	36	599	1,172	1,921	1,378	534	862	47	46	57	66
13	64	845	1,478	2,309	1,639	629	1,117	47	46	57	66	63
12	982	1,602	2,556	1,858	755	1,512	214	46	57	66	63	63
11	1,814	2,770	2,056	855	1,872	277	138	76	89	81	80	1,016
10	3,133	2,255	945	2,241	385	189	184	231	209	185	1,135	2,445
9	2,545	1,062	2,502	484	335	341	420	372	371	1,292	2,786	5,299
8	1,200	2,951	664	482	557	759	658	649	1,503	3,247	5,984	4,877
7	3,381	800	794	956	1,160	1,109	1,100	1,876	3,666	6,504	5,243	2,353

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 (2016). 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.[75] 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).[76] 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 2019) divided by 0.63. This ratio represents the dressed weight (i.e., weight of the carcass after removal of the internal organs),

[75] 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.
[76] 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.

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-162.

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-163, and weight gain was held constant starting in 2000.

Table A-163 provides weight gains that vary by year in the CEFM.

Table A-162: Typical Animal Mass (lbs)[77]

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	1,499	899	1,220	1,830	819	691	651	923	845
1991	270	1,499	897	1,224	1,836	821	694	656	933	855
1992	269	1,499	897	1,262	1,893	840	714	673	936	864
1993	270	1,499	898	1,279	1,918	852	721	683	929	863
1994	270	1,499	897	1,279	1,918	853	720	688	943	875
1995	270	1,499	897	1,281	1,921	857	735	700	947	879
1996	269	1,499	898	1,284	1,926	858	739	707	939	878
1997	270	1,499	899	1,285	1,927	860	736	707	938	876
1998	270	1,499	896	1,295	1,942	865	736	709	956	892
1999	270	1,499	899	1,291	1,936	861	730	708	959	894
2000	270	1,499	896	1,271	1,906	849	719	702	960	898
2001	270	1,499	897	1,271	1,906	850	725	707	963	900
2002	270	1,499	896	1,275	1,912	851	725	707	981	915
2003	270	1,499	899	1,307	1,960	871	718	701	972	904
2004	270	1,499	896	1,322	1,983	877	719	702	966	904
2005	270	1,499	894	1,326	1,989	879	717	706	974	917
2006	270	1,499	897	1,340	2,010	889	724	712	983	925
2007	270	1,499	896	1,347	2,020	894	720	706	991	928
2008	270	1,499	897	1,347	2,020	894	720	704	999	938
2009	270	1,499	895	1,347	2,020	894	730	715	1007	947
2010	270	1,499	897	1,347	2,020	896	726	713	996	937
2011	270	1,499	897	1,347	2,020	891	721	712	989	932
2012	270	1,499	899	1,347	2,020	892	714	706	1003	945
2013	270	1,499	898	1,347	2,020	892	718	709	1016	958
2014	270	1,499	895	1,347	2,020	888	722	714	1022	962
2015	270	1,499	896	1,347	2,020	890	717	714	1037	982
2016	269	1,499	899	1,220	1,830	819	691	651	923	845
2017	269	1,499	899	1,220	1,830	819	691	651	923	845

[a] Input into the model.
[b] Annual average calculated in model based on age distribution.

[77] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Table A-163: 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-164) 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-164 provides a summary of the reported feedlot placement statistics for 2017.

Table A-164: Feedlot Placements in the United States for 2017 (Number of animals placed/1,000 Head)[78]

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	380	315	350	348	400	375	360	360	405	675	610	470
600 – 700 lbs	445	330	295	255	315	315	235	285	340	590	545	410
700 – 800 lbs	585	490	630	490	529	430	385	418	490	510	455	445
> 800 lbs	571	559	842	755	875	650	635	865	915	618	489	474
Total	**1,981**	**1,694**	**2,117**	**1,848**	**2,119**	**1,770**	**1,615**	**1,928**	**2,150**	**2,393**	**2,099**	**1,799**

Note: Totals may not sum due to independent rounding.
Source: USDA (2018).

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

[78] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

monthly estimates for daily milk production by beef cows are shown in Table A-165. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2017 are shown in Table A-166. 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-165: Estimates of Average 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-166: Dairy Lactation Rates by State (lbs/ year/cow)[79]

State/Year	1990	1995	2000	2005	2011	2012	2013	2014	2015	2016	2017
Alabama	12,214	14,176	13,920	14,000	14,300	13,000	13,000	13,625	12,625	13,143	14,833
Alaska	13,300	17,000	14,500	12,273	13,800	14,250	10,667	11,667	11,667	11,667	9,667
Arizona	17,500	19,735	21,820	22,679	23,473	23,979	23,626	24,368	24,402	24,679	24,680
Arkansas	11,841	12,150	12,436	13,545	11,917	13,300	11,667	13,714	13,000	13,333	13,167
California	18,456	19,573	21,130	21,404	23,438	23,457	23,178	23,786	23,028	22,968	22,755
Colorado	17,182	18,687	21,618	22,577	23,430	24,158	24,292	24,951	25,733	25,993	26,181
Connecticut	15,606	16,438	17,778	19,200	19,000	19,889	20,556	20,158	20,842	21,526	22,105
Delaware	13,667	14,500	14,747	16,622	18,300	19,542	19,521	20,104	19,700	19,100	18,560
Florida	14,033	14,698	15,688	16,591	19,067	19,024	19,374	20,390	20,656	20,285	20,129
Georgia	12,973	15,550	16,284	17,259	18,354	19,138	19,600	20,877	21,651	21,786	21,905
Hawaii	13,604	13,654	14,358	12,889	14,421	14,200	13,409	13,591	15,909	14,542	16,913
Idaho	16,475	18,147	20,816	22,332	22,926	23,376	23,440	24,127	24,126	24,647	24,378
Illinois	14,707	15,887	17,450	18,827	18,510	19,061	19,063	19,681	20,149	20,340	20,742
Indiana	14,590	15,375	16,568	20,295	20,657	21,440	21,761	21,865	22,115	22,571	22,802
Iowa	15,118	16,124	18,298	20,641	21,191	22,015	22,149	22,449	22,929	23,634	23,725
Kansas	12,576	14,390	16,923	20,505	21,016	21,683	21,881	22,085	22,210	22,801	23,000
Kentucky	10,947	12,469	12,841	12,896	14,342	15,135	15,070	15,905	17,656	18,052	18,589
Louisiana	11,605	11,908	12,034	12,400	12,889	13,059	12,875	13,600	13,429	14,083	13,333
Maine	14,619	16,025	17,128	18,030	18,688	18,576	19,548	19,967	19,800	21,000	21,000
Maryland	13,461	14,725	16,083	16,099	18,654	19,196	19,440	19,740	20,061	19,938	19,854
Massachusetts	14,871	16,000	17,091	17,059	16,923	18,250	17,692	17,923	18,083	18,417	17,583
Michigan	15,394	17,071	19,017	21,635	23,164	23,976	24,116	24,638	25,150	25,957	26,302
Minnesota	14,127	15,894	17,777	18,091	18,996	19,512	19,694	19,841	20,570	20,967	21,537
Mississippi	12,081	12,909	15,028	15,280	14,571	14,214	13,286	14,462	15,000	14,400	15,222
Missouri	13,632	14,158	14,662	16,026	14,611	14,979	14,663	15,539	15,511	14,824	14,588
Montana	13,542	15,000	17,789	19,579	20,571	21,357	21,286	21,500	21,357	21,071	22,154
Nebraska	13,866	14,797	16,513	17,950	20,579	21,179	21,574	22,130	22,930	23,317	24,067
Nevada	16,400	18,128	19,000	21,680	22,966	22,931	22,034	23,793	23,069	22,000	22,156
New Hampshire	15,100	16,300	17,333	18,875	20,429	19,643	20,923	20,143	20,143	20,500	21,000
New Jersey	13,538	13,913	15,250	16,000	16,875	18,571	18,143	18,143	18,143	17,429	19,833
New Mexico	18,815	18,969	20,944	21,192	24,854	24,694	24,944	25,093	24,245	24,479	24,960
New York	14,658	16,501	17,378	18,639	21,046	21,623	22,070	22,325	22,806	23,834	23,936
North Carolina	15,220	16,314	16,746	18,741	20,089	20,435	20,326	20,891	20,957	20,978	21,156
North Dakota	12,624	13,094	14,292	14,182	18,158	19,278	18,944	20,250	20,750	21,500	21,563
Ohio	13,767	15,917	17,027	17,567	19,194	19,833	20,178	20,318	20,573	20,936	21,259
Oklahoma	12,327	13,611	14,440	16,480	17,415	17,896	17,311	18,150	18,641	18,703	18,667
Oregon	16,273	17,289	18,222	18,876	20,488	20,431	20,439	20,565	20,408	20,744	20,395
Pennsylvania	14,726	16,492	18,081	18,722	19,495	19,549	19,797	20,121	20,377	20,454	20,834

[79] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Rhode Island	14,250	14,773	15,667	17,000	17,909	16,636	19,000	19,000	17,667	17,625	16,250
South Carolina	12,771	14,481	16,087	16,000	17,438	17,250	16,500	16,438	17,400	16,667	16,467
South Dakota	12,257	13,398	15,516	17,741	20,582	21,391	21,521	21,753	22,255	22,139	22,376
Tennessee	11,825	13,740	14,789	15,743	16,200	16,100	15,938	16,196	16,489	16,571	17,325
Texas	14,350	15,244	16,503	19,646	22,232	22,009	21,991	22,268	22,248	22,680	23,589
Utah	15,838	16,739	17,573	18,875	22,161	22,863	22,432	22,989	23,125	22,772	23,316
Vermont	14,528	16,210	17,199	18,469	18,940	19,316	19,448	20,197	20,197	20,977	21,147
Virginia	14,213	15,116	15,833	16,990	17,906	17,990	18,337	19,129	19,462	19,144	19,954
Washington	18,532	20,091	22,644	23,270	23,727	23,794	23,820	24,088	23,848	24,094	23,818
West Virginia	11,250	12,667	15,588	14,923	15,700	15,400	15,200	15,556	15,667	14,889	15,875
Wisconsin	13,973	15,397	17,306	18,500	20,599	21,436	21,693	21,869	22,697	23,542	23,725
Wyoming	12,337	13,197	13,571	14,878	20,517	20,650	21,367	21,583	22,567	23,300	23,033

Source: USDA (2018).

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-167. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007 through 2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in and Table A-168. 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-167: 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-168: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2017

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

Note: States in **bold** represent a change in region from the 1990 to 2006 assessment.
Source: Based on data from USDA:APHIS:VS (2010).

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0 ± 1.0 percent for feedlot cattle and 6.5 ± 1.0 percent for all other cattle (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, 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, so COWPOLL was used to determine the Y_m value associated with each of the evaluated diets. The statistical analysis of the resulting Y_m estimates showed a downward trend in predicting Y_m, which inventory team experts modeled using the following best-fit non-liner curve:

$$Y_m = 4.52e^{\left(\frac{1.22}{Year-1980}\right)}$$

The team determined that the most comprehensive approach to estimating annual, region-specific Y_m values was to use the 1990 baseline Y_m values derived from Donovan and Baldwin and then scale these Y_m values for each year beyond 1990 with a factor based on this function. The scaling factor is the ratio of the Y_m value for the year in question to the 1990 baseline Y_m value. The scaling factor for each year was multiplied by the baseline Ym value. The resulting Y_m equation (incorporating both Donovan and Baldwin (1999) and COWPOLL) is shown below (and described in ERG 2016):

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

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 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 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-167 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-168 (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-169. 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-170 and Table A-171 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.[80] 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-172.

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, 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-173 shows the regional DE and Y_m for U.S. cattle in each region for 2017.

[80] 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-172.

Table A-169: 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									

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
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x								
Pearlmillet Pennisetum glaucum, fresh	68.04	x									
Prairie plants, Midwest, hay, sun-cured	55.53			x							x
Rape Brassica napus, fresh, early bloom	80.88	x									
Rye Secale cereale, fresh	71.83	x									
Ryegrass, Perennial Lolium perenne, fresh	73.68	x									
Saltgrass Distichlis spp, fresh, post ripe	58.06		x	x							
Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative	73.27	x									
Squirreltail Stanion spp, fresh, stem-cured	62.00		x			x					
Summercypress, Gray Kochia vestita, fresh, stem-cured	65.11			x	x	x					
Timothy Phleum pratense, fresh, late vegetative	73.12	x									
Timothy Phleum pratense, fresh, midbloom	66.87		x								
Trefoil, Birdsfoot Lotus corniculatus, fresh	69.07	x									
Vetch Vicia spp, hay, sun-cured	59.44			x							
Wheat Triticum aestivum, straw	45.77			x							
Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative	79.78	x									
Wheatgrass, Crested Agropyron desertorum, fresh, full bloom	65.89		x			x					
Wheatgrass, Crested Agropyron desertorum, fresh, post ripe	52.99			x					x		x
Winterfat, Common Eurotia lanata, fresh, stem-cured	40.89								x		
Weighted Average DE		**72.99**	**62.45**	**57.26**	**67.11**	**62.70**	**60.62**	**58.59**	**52.07**	**64.03**	**55.11**
Forage Diet for West	**61.3**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**
Forage Diet for All Other Regions	**64.2**	**33.3%**	**33.3%**	**33.3%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

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).
Sources: Preston (2010) and Archibeque (2011).

Table A-170: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990–2006

Feed	Source of DE (NRC 1984)	Unweighted DE (% of GE)	California[a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	30%	29%	12%	30%	
Barley		85.08	10%	15%					
Bermuda	Table 8, feed #030	66.29							35%
Bermuda Hay	Table 8, feed #031	50.79				40%			
Corn	Table 8, feed #089	88.85	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 8, feed #095	72.88			25%		20%	20%	
Cotton Seed Meal						7%			
Grass Hay	Table 8, feed #126, 170, 274	58.37		40%				30%	

Orchard	Table 8, feed #147	60.13							40%
Soybean Meal Supplement		77.15		5%	5%				5%
Sorghum	Table 8, feed #211	84.23							20%
Soybean Hulls		66.86						7%	
Timothy Hay	Table 8, feed #244	60.51					50%		
Whole Cotton Seed		75.75	5%				5%		
Wheat Middlings	Table 8, feed #257	68.09			15%	13%			
Wheat	Table 8, feed #259	87.95	10%						
Weighted 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).

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

Table A-171: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2017[81]

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%**

[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.

Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (2010).

[81] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Table A-172: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2017[82]

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-168.
[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-173: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2017[83]

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	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
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-167 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-167.
[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)

[82] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.
[83] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

- Net Energy for Activity (C_a, MJ/day)[84]
- Standard Reference Weight (kg)[85]
- 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). Calculated GE values for 2015 are shown by state and animal type in Table A-174.

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

where,

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

Table A-174: Calculated Annual GE by Animal Type and State, for 2017 (MJ/1,000 head)[86]

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	31	851	55	195	4,166	3,179	55,838	1,432	4,017	1,204	978	285
Alaska	1	29	1	5	240	23	404	13	36	13	15	3
Arizona	857	31,012	1,603	5,698	1,779	911	15,827	489	1,365	6,869	1,025	13,100
Arkansas	26	673	41	146	4,999	4,192	73,645	2,064	5,791	2,649	1,739	577

84 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).

85 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.

86 This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
California	7,670	262,323	10,412	37,010	6,226	3,243	56,341	1,673	4,670	15,553	4,391	22,265
Colorado	677	25,460	1,370	4,870	4,892	3,986	69,243	2,446	6,825	22,033	15,223	48,673
Conn.	83	2,810	130	463	42	23	404	24	67	48	27	10
Delaware	22	668	30	107	25	12	202	8	24	46	11	8
Florida	533	17,431	479	1,704	4,999	4,165	73,162	1,491	4,184	722	815	199
Georgia	363	12,451	411	1,461	2,749	2,280	40,045	1,312	3,682	891	1,359	288
Hawaii	10	305	14	49	356	364	6,331	167	467	259	117	46
Idaho	2,622	94,209	4,247	15,096	3,558	2,476	43,008	1,545	4,311	8,036	5,562	13,980
Illinois	406	13,244	712	2,532	2,036	1,729	30,484	872	2,451	5,636	2,861	13,463
Indiana	809	27,876	1,096	3,896	1,385	938	16,542	581	1,634	2,536	1,324	5,696
Iowa	940	33,194	1,849	6,574	5,701	4,312	76,014	2,151	6,045	30,762	14,303	60,064
Kansas	656	22,722	1,370	4,870	7,738	7,016	123,670	3,604	10,129	48,139	37,878	119,093
Kentucky	249	7,791	548	1,948	5,832	4,692	82,428	1,790	5,021	5,178	3,125	932
Louisiana	52	1,355	55	195	2,583	2,055	36,097	1,014	2,845	602	543	149
Maine	131	4,303	205	730	125	51	889	48	134	97	82	23
Maryland	205	6,525	397	1,412	334	198	3,474	132	369	338	164	466
Mass.	50	1,492	96	341	84	30	525	24	67	48	27	10
Michigan	1,857	70,016	2,329	8,278	1,303	536	9,452	291	817	3,969	1,060	7,508
Minn.	2,010	66,977	4,041	14,366	2,851	1,653	29,145	1,105	3,104	11,741	4,370	19,417
Miss.	39	1,108	82	292	3,166	2,183	38,353	1,110	3,113	1,011	842	242
Missouri	371	10,003	616	2,191	9,774	9,183	161,874	4,302	12,090	10,802	6,225	5,696
Montana	61	2,073	123	438	8,894	7,358	127,821	5,470	15,266	5,962	7,494	2,330
Nebraska	262	9,346	342	1,217	8,959	8,580	151,240	4,360	12,253	53,774	36,553	127,896
Nevada	131	4,443	151	536	1,245	1,089	18,924	528	1,473	1,166	849	155
N. Hamp.	59	1,936	82	292	42	23	404	12	34	36	27	8
N. Jersey	28	902	51	180	84	35	606	19	54	51	33	11
N. Mexico	1,420	51,790	1,507	5,357	3,113	2,302	39,998	1,287	3,592	3,111	2,635	696
New York	2,710	96,247	4,863	17,287	1,671	506	8,888	539	1,511	1,087	1,363	1,036
N. Car.	197	6,615	301	1,071	2,583	1,697	29,813	823	2,310	1,036	679	225
N. Dakota	70	2,331	123	438	5,294	4,263	75,147	2,395	6,731	5,988	5,695	2,589
Ohio	1,145	37,854	1,644	5,844	2,443	1,287	22,686	872	2,451	5,166	1,589	7,767
Oklahoma	153	4,701	274	974	13,330	9,610	168,803	5,190	14,562	21,674	12,635	16,052
Oregon	542	17,486	890	3,165	3,558	2,703	46,965	1,351	3,772	4,018	3,367	4,401
Penn.	2,294	74,958	4,315	15,339	2,089	851	14,948	778	2,182	3,865	1,635	4,919
R. Island	3	99	7	24	8	6	113	5	13	12	5	2
S. Car.	66	1,922	96	341	1,250	780	13,698	394	1,105	193	272	60
S. Dakota	507	17,281	616	2,191	8,145	7,436	131,075	4,593	12,906	17,377	14,039	19,676
Tenn.	179	5,396	479	1,704	5,415	4,169	73,242	1,730	4,854	3,251	2,445	746
Texas	2,142	75,504	3,562	12,661	28,327	20,457	359,362	9,665	27,115	62,372	36,682	125,824
Utah	402	14,053	753	2,678	2,401	1,674	29,074	1,094	3,053	2,074	1,756	1,036
Vermont	564	18,581	767	2,727	251	64	1,131	66	185	97	177	35
Virginia	380	12,369	521	1,850	3,333	2,949	51,809	1,336	3,749	3,973	1,902	1,036
Wash.	1,202	42,560	1,644	5,844	1,601	1,114	19,354	747	2,083	4,925	3,425	9,838
W. Virg.	35	983	55	195	1,253	953	16,725	455	1,276	942	463	207
Wisconsin	5,594	197,617	9,727	34,575	2,443	1,296	22,844	930	2,614	9,393	1,324	13,980
Wyoming	26	910	41	146	3,558	3,535	61,416	2,381	6,645	4,147	4,011	3,883

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-175. State-level emission factors are shown by animal type for 2017 in Table A-176.

Table A-175: Calculated Annual National Emission Factors for Cattle by Animal Type, for 2017 (kg CH_4/head/year)[87]

Cattle Type	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017
Dairy												
Calves	12	12	12	12	12	12	12	12	12	12	12	12
Cows	124	125	132	133	142	142	144	144	145	146	147	147
Replacements 7–11 months	48	46	46	45	46	46	46	46	46	46	46	46
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	69	69	69
Beef												
Calves	11	11	11	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98	98	98	98
Cows	89	92	91	94	95	95	95	95	95	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60	60	60	60	60
Feedlot Cattle	38	36	38	38	42	41	42	42	42	43	43	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).

[87] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Table A-176: Emission Factors for Cattle by Animal Type and State, for 2017 (kg CH_4/head/year)[88]

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	12	138	53	80	97	10	94	60	69	58	60	35
Alaska	12	95	46	69	104	11	100	65	74	62	65	35
Arizona	12	154	46	69	104	11	100	65	74	62	65	34
Arkansas	12	118	49	74	97	10	94	60	69	58	60	34
California	12	146	46	69	104	11	100	65	74	62	65	34
Colorado	12	151	43	65	104	11	100	65	74	62	65	35
Conn.	12	153	48	73	98	11	94	60	69	58	60	35
Delaware	12	138	48	73	98	11	94	60	69	58	60	35
Florida	12	162	53	80	97	10	94	60	69	58	60	36
Georgia	12	170	53	80	97	10	94	60	69	58	60	37
Hawaii	12	124	46	69	104	11	100	65	74	62	65	35
Idaho	12	153	46	69	104	11	100	65	74	62	65	35
Illinois	12	131	43	65	95	10	92	58	68	56	59	35
Indiana	12	139	43	65	95	10	92	58	68	56	59	34
Iowa	12	142	43	65	95	10	92	58	68	56	59	34
Kansas	12	140	43	65	95	10	92	58	68	56	59	35
Kentucky	12	155	53	80	97	10	94	60	69	58	60	35
Louisiana	12	118	49	74	97	10	94	60	69	58	60	35
Maine	12	148	48	73	98	11	94	60	69	58	60	36
Maryland	12	143	48	73	98	11	94	60	69	58	60	35
Mass.	12	134	48	73	98	11	94	60	69	58	60	35
Michigan	12	152	43	65	95	10	92	58	68	56	59	33
Minn.	12	134	43	65	95	10	92	58	68	56	59	34
Miss.	12	140	53	80	97	10	94	60	69	58	60	35
Missouri	12	109	43	65	95	10	92	58	68	56	59	35
Montana	12	137	43	65	104	11	100	65	74	62	65	34
Nebraska	12	144	43	65	95	10	92	58	68	56	59	34
Nevada	12	144	46	69	104	11	100	65	74	62	65	37
N. Hamp.	12	148	48	73	98	11	94	60	69	58	60	35
N. Jersey	12	143	48	73	98	11	94	60	69	58	60	36
N. Mexico	12	155	46	69	104	11	100	65	74	62	65	36
New York	12	160	48	73	98	11	94	60	69	58	60	36
N. Car.	12	167	53	80	97	10	94	60	69	58	60	36
N. Dakota	12	134	43	65	95	10	92	58	68	56	59	34
Ohio	12	133	43	65	95	10	92	58	68	56	59	34
Oklahoma	12	141	49	74	97	10	94	60	69	58	60	35
Oregon	12	137	46	69	104	11	100	65	74	62	65	35
Penn.	12	147	48	73	98	11	94	60	69	58	60	35
R. Island	12	128	48	73	98	11	94	60	69	58	60	35
S. Car.	12	145	53	80	97	10	94	60	69	58	60	33
S. Dakota	12	137	43	65	95	10	92	58	68	56	59	34
Tenn.	12	149	53	80	97	10	94	60	69	58	60	35

[88] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Texas	12	161	49	74	97	10	94	60	69	58	60	35
Utah	12	149	46	69	104	11	100	65	74	62	65	32
Vermont	12	149	48	73	98	11	94	60	69	58	60	36
Virginia	12	161	53	80	97	10	94	60	69	58	60	34
Wash.	12	151	46	69	104	11	100	65	74	62	65	34
W. Virg.	12	127	48	73	98	11	94	60	69	58	60	35
Wisconsin	12	142	43	65	95	10	92	58	68	56	59	34
Wyoming	12	140	43	65	104	11	100	65	74	62	65	35

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-177, indicate that U.S. emission factors are comparable to those of other Annex I countries. Results in Table A-177 are presented 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-177: Annex I Countries' Implied Emission Factors for Cattle by Year (kg CH_4/head/year)[89, 90]

	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
2014	118	NA	74	NA

[89] Excluding calves.
[90] This table has not been updated for the current (1990 through 2016) Inventory. It will be updated for the next (1990 through 2017) Inventory submission.

2015	117	NA	75	NA
2016	118	NA	75	NA
2017	119	NA	74	NA
Tier I EFs For North America, from IPCC (2006)		**121**		**53**

NA (Not Applicable)

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-178. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-178: CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2012	2013	2014	2015	2016	2017	2018
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,670**	**1,664**	**1,679**	**1,706**	**1,722**	**1,730**	**1,744**
Calves (4–6 months)	62	59	59	54	58	58	58	58	58	58	58
Cows	1,242	1,183	1,209	1,197	1,326	1,325	1,337	1,355	1,367	1,377	1,390
Replacements 7–11 months	58	56	55	56	62	61	63	65	65	65	65
Replacements 12–23 months	212	201	196	196	224	220	221	228	232	230	231
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**4,763**	**4,722**	**4,660**	**4,722**	**4,919**	**5,052**	**5,125**
Calves (4–6 months)	182	193	186	179	161	157	156	158	164	168	169
Bulls	196	225	215	214	206	203	200	207	210	220	221
Cows	2,884	3,222	3,058	3,056	2,868	2,806	2,754	2,774	2,856	2,954	2,978
Replacements 7–11 months	69	85	74	80	76	78	83	89	91	90	86
Replacements 12–23 months	188	241	204	217	208	213	218	239	250	251	241
Steer Stockers	563	662	509	473	413	431	426	433	472	461	465
Heifer Stockers	306	375	323	299	266	267	256	263	289	286	297
Feedlot Cattle	375	416	502	488	565	568	567	558	587	621	667
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,433**	**6,386**	**6,339**	**6,427**	**6,641**	**6,783**	**6,869**

Note: 2018 estimates are based on estimated 2018 population values. 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 2019) or the Census of Agriculture (USDA 1992, 1997, 2002, 2007, 2012). 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-180). 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-179 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-180 and Table A-181. Enteric fermentation emissions from most livestock types, broken down by state, for 2017 are shown in Table A-182 and Table A-183. Because a simplified calculation approach was used for 2018 emissions, state-level emission estimates were not calculated for 2018. Livestock populations are shown in Table A-184.

Table A-179: 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-180: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2012	2013	2014	2015	2016	2017	2018
Beef Cattle	119.1	135.5	126.7	125.2	119.1	118.0	116.5	118.0	123.0	126.3	128.1
Dairy Cattle	39.4	37.5	38.0	37.6	41.7	41.6	42.0	42.6	43.0	43.3	43.6
Swine	2.0	2.2	2.2	2.3	2.5	2.5	2.4	2.6	2.6	2.7	2.8
Horses	1.0	1.2	1.5	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.2
Sheep	2.3	1.8	1.4	1.2	1.1	1.1	1.0	1.1	1.1	1.1	1.1
Goats	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**178.7**	**170.6**	**168.9**	**166.7**	**165.5**	**164.2**	**166.5**	**171.8**	**175.4**	**177.6**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table A-181: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2012	2013	2014	2015	2016	2017	2018
Beef Cattle	4,763	5,419	5,070	5,007	4,763	4,722	4,660	4,722	4,919	5,052	5,125
Dairy Cattle	1,574	1,498	1,519	1,503	1,670	1,664	1,679	1,706	1,722	1,730	1,744
Swine	81	88	88	92	100	98	96	102	105	108	111
Horses	40	47	61	70	65	62	60	57	54	51	48
Sheep	91	72	56	49	43	43	42	42	42	42	42
Goats	13	12	12	14	13	13	13	13	13	13	14
American Bison	4	9	16	17	13	14	14	14	15	15	15
Mules and Asses	1	1	1	2	3	3	3	3	3	3	3
Total	**6,566**	**7,146**	**6,824**	**6,755**	**6,670**	**6,619**	**6,567**	**6,660**	**6,874**	**7,016**	**7,103**

Note: Totals may not sum due to independent rounding.

Table A-182: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2017[91]

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	44	966	63	224	4,866	3,713	65,220	1,672	4,692	1,406	1,143	257	84,265
Alaska	2	29	1	5	280	27	472	15	42	15	17	3	909
Arizona	1,223	30,231	1,591	5,656	2,078	1,064	18,486	571	1,594	8,023	1,197	12,054	83,770
Arkansas	37	705	44	156	5,839	4,897	86,018	2,411	6,764	3,094	2,031	531	112,527
California	10,947	255,718	10,337	36,743	7,272	3,788	65,807	1,954	5,454	18,166	5,129	20,614	441,929
Colorado	967	23,480	1,288	4,578	5,714	4,655	80,877	2,856	7,972	25,735	17,780	44,357	220,260
Conn.	119	2,901	137	486	49	27	472	28	78	56	32	9	4,393
Delaware	31	690	32	113	29	13	236	10	27	54	13	7	1,254
Florida	761	19,772	552	1,964	5,839	4,865	85,454	1,742	4,887	844	952	174	127,806
Georgia	518	14,123	474	1,683	3,211	2,663	46,774	1,533	4,301	1,041	1,587	247	78,154
Hawaii	15	297	14	48	416	426	7,394	195	545	303	137	42	9,832
Idaho	3,742	91,837	4,216	14,987	4,155	2,892	50,234	1,804	5,035	9,386	6,497	12,632	207,418
Illinois	580	12,214	670	2,381	2,378	2,020	35,606	1,019	2,862	6,583	3,341	12,157	81,810
Indiana	1,154	25,708	1,030	3,663	1,617	1,096	19,321	679	1,908	2,962	1,547	5,272	65,958
Iowa	1,341	30,612	1,739	6,181	6,659	5,037	88,785	2,512	7,060	35,930	16,707	55,763	258,326
Kansas	936	20,954	1,288	4,578	9,038	8,195	144,448	4,210	11,831	56,227	44,241	108,565	414,511
Kentucky	356	8,838	631	2,244	6,812	5,481	96,277	2,090	5,865	6,047	3,650	845	139,136
Louisiana	75	1,419	58	207	3,017	2,400	42,162	1,185	3,323	703	635	133	55,317
Maine	187	4,443	216	767	146	59	1,038	56	157	113	96	21	7,298
Maryland	293	6,737	417	1,483	390	231	4,058	154	431	395	191	427	15,208
Mass.	72	1,540	101	358	98	35	613	28	78	56	32	9	3,020
Michigan	2,651	64,570	2,190	7,783	1,522	626	11,041	340	954	4,635	1,238	7,126	104,675
Minn.	2,869	61,767	3,800	13,506	3,330	1,931	34,042	1,290	3,626	13,714	5,105	18,097	163,076
Miss.	56	1,257	95	337	3,698	2,550	44,797	1,296	3,636	1,181	984	221	60,109
Missouri	530	9,225	580	2,060	11,416	10,726	189,071	5,025	14,121	12,617	7,270	5,129	267,770
Montana	87	1,912	116	412	10,389	8,594	149,296	6,389	17,831	6,964	8,753	2,185	212,929
Nebraska	374	8,619	322	1,145	10,465	10,021	176,650	5,093	14,312	62,809	42,695	117,788	450,292
Nevada	187	4,331	150	532	1,454	1,272	22,103	616	1,720	1,362	992	133	34,853
N. Hamp.	84	1,999	86	307	49	27	472	14	39	42	32	7	3,158

[91] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

N. Jersey	41	931	53	189	98	40	708	22	63	59	38	10	2,252
N. Mexico	2,027	50,486	1,496	5,318	3,636	2,689	46,718	1,503	4,196	3,633	3,077	619	125,399
New York	3,867	99,361	5,108	18,157	1,952	591	10,381	629	1,765	1,270	1,592	912	145,586
N. Car.	281	7,503	347	1,234	3,017	1,982	34,821	962	2,698	1,209	793	197	55,046
N. Dakota	100	2,150	116	412	6,184	4,979	87,773	2,797	7,862	6,994	6,652	2,423	128,442
Ohio	1,634	34,910	1,546	5,494	2,854	1,503	26,498	1,019	2,862	6,034	1,856	7,220	93,430
Oklahoma	218	4,923	292	1,037	15,570	11,224	197,165	6,062	17,008	25,315	14,758	14,436	308,008
Oregon	773	17,045	884	3,142	4,155	3,158	54,856	1,579	4,405	4,693	3,932	3,941	102,564
Penn.	3,275	77,384	4,533	16,111	2,440	994	17,459	909	2,549	4,514	1,910	4,416	136,494
R. Island	5	103	7	26	10	8	132	6	16	14	6	2	334
S. Car.	94	2,181	110	393	1,460	911	15,999	460	1,290	225	317	58	23,498
S. Dakota	724	15,937	580	2,060	9,513	8,685	153,097	5,364	15,075	20,296	16,397	18,574	266,302
Tenn.	256	6,121	552	1,964	6,325	4,870	85,548	2,021	5,669	3,797	2,856	679	120,659
Texas	3,056	79,064	3,794	13,486	33,086	23,895	419,740	11,288	31,671	72,851	42,845	115,505	850,281
Utah	574	13,699	748	2,659	2,805	1,955	33,958	1,278	3,566	2,422	2,052	1,017	66,733
Vermont	805	19,182	806	2,864	293	75	1,321	77	216	113	207	31	25,989
Virginia	543	14,030	600	2,132	3,892	3,445	60,514	1,561	4,379	4,641	2,222	969	98,928
Wash.	1,715	41,488	1,632	5,801	1,870	1,301	22,605	872	2,433	5,753	4,001	9,072	98,544
W. Virg.	50	1,015	58	205	1,464	1,113	19,535	531	1,490	1,100	541	190	27,292
Wisconsin	7,984	182,246	9,145	32,507	2,854	1,514	26,682	1,086	3,053	10,971	1,547	12,871	292,460
Wyoming	37	839	39	137	4,155	4,129	71,735	2,781	7,762	4,844	4,684	3,514	104,657

Table A-183: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2017[92]

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	86	725	99	125	21	120	1,175
Alaska	2	16	99	4	131	1	252
Arizona	240	2,089	1,040	506	6	41	3,921
Arkansas	197	778	99	163	27	87	1,350
California	143	1,879	4,800	746	120	62	7,751
Colorado	1,099	1,830	3,360	103	882	68	7,342
Connecticut	4	420	57	21	10	12	524
Delaware	9	150	99	2	8	1	269
Florida	23	2,186	99	232	32	110	2,681
Georgia	120	1,134	99	297	23	88	1,761
Hawaii	8	66	99	84	8	5	269
Idaho	38	879	2,000	92	292	40	3,341
Illinois	7,969	827	440	147	57	32	9,471
Indiana	6,056	2,045	416	151	108	58	8,835
Iowa	33,375	944	1,400	283	151	44	36,196
Kansas	3,011	1,077	544	176	546	34	5,387
Kentucky	615	1,947	384	150	116	135	3,347
Louisiana	9	1,063	99	80	7	84	1,341
Maine	7	213	57	35	22	4	337
Maryland	39	478	99	23	36	12	688
Massachusetts	11	362	57	45	8	3	486
Michigan	1,725	1,347	680	131	156	40	4,080
Minnesota	12,675	767	1,040	153	254	26	14,916
Mississippi	855	937	99	92	4	96	2,083
Missouri	4,969	1,538	720	554	168	86	8,035
Montana	269	1,631	1,840	42	1,206	49	5,036
Nebraska	5,156	1,135	664	85	1,903	43	8,986
Nevada	1	478	504	154	7	7	1,150
New Hampshire	5	149	57	29	25	1	266
New Jersey	19	453	99	29	16	8	624
New Mexico	2	861	776	131	424	18	2,213
New York	72	1,716	640	165	82	41	2,715
North Carolina	13,650	997	240	172	26	96	15,180
North Dakota	221	824	528	26	786	14	2,399
Ohio	4,181	1,963	936	168	70	72	7,391
Oklahoma	3,218	2,741	384	264	796	137	7,540
Oregon	14	926	1,360	142	115	27	2,583
Pennsylvania	1,800	2,222	744	206	108	94	5,173
Rhode Island	3	24	57	5	-	1	91
South Carolina	278	1,107	99	169	11	63	1,726
South Dakota	2,265	1,217	2,000	112	2,765	14	8,373
Tennessee	353	919	368	262	28	126	2,057
Texas	1,459	6,350	5,680	3,089	360	642	17,581
Utah	979	1,047	2,200	61	93	37	4,417
Vermont	6	181	57	73	9	14	340
Virginia	360	1,500	640	193	85	71	2,849

[92] This table has not been updated for the current (1990 through 2018) Inventory. It will be updated for the next (1990 through 2019) Inventory submission.

Washington	38	711	384	106	79	34	1,352
West Virginia	8	274	272	49	4	30	635
Wisconsin	458	1,565	608	331	349	58	3,368
Wyoming	135	1,160	2,880	50	787	29	5,041

"-" Indicates there are no emissions, as there is no significant population of this animal type.

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3.11. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management[93]

The following steps were used to estimate methane (CH_4) and nitrous oxide (N_2O) emissions from the management of livestock manure for the years 1990 through 2018.

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2018 for all livestock types, except American bison, goats, horses, mules and asses were obtained from the USDA NASS. The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Quick Stats Database (USDA 2019a). 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, 2014a, 2014b, 2015a 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019b, and 2019c). Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017 were obtained from the Census of Agriculture (USDA 2019d), as were horse, mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 and American bison population for 2002, 2007, 2012, and 2017. 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 lambs and sheep on feed are not available after 1993 (USDA 1994). The number of lambs and sheep on feed for 1994 through 2015 were calculated using the average of the percent of lambs and sheep on feed from 1990 through 1993. In addition, all of the sheep and lambs “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 lambs in feedlots for all years, it was assumed that the percentage of sheep and lambs 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, 2012, and 2017 (USDA 2019d). The data for 1992 were used for 1990 through 1992. Data for 1993 through 1996, 1998 through 2001, 2003

[93] Note that direct N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector. Indirect N_2O emissions dung and urine spread onto fields after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are also included in the Agricultural Soil Management source category. For the years 1997-2018 there are differences in the PRP manure N data used in Agricultural Soil Management and Manure Management. EPA is assessing this issue and will update in subsequent Inventory reports.

through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

Horses: Annual horse population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

Mules and Asses: Annual mule and ass (burro and donkey) population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

American Bison: Annual American bison population data by state were available for 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1999 were obtained from the Bison Association (1999). Data for 2000, 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the Bison Association and 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 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, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019b, and 2019c). 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 (Lange 2000). 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-184.

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-185 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 for non-cattle animal groups. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and Nex for most non-cattle animal groups across the time series of the Inventory, as shown in Table A-186 (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 (ASABE), 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. Expert sources agreed interpolating the two data sources across the time series would be appropriate as each methodology reflect the best available for that time period and the more recent data may not appropriately reflect the historic time series (ERG 2010b). 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). Differing trends in VS and Nex values are due to the updated Nex calculation method from 2008 AWMFH. VS calculations did not follow the same procedure and were updated based on a fixed ratio of VS to total solids and past ASABE standards (ERG 2010b).
- *Poultry:* Due to the change in USDA reporting of hens and pullets in 2005, 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 for cattle (including 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 as 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:

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

where,

GE	=	Gross energy intake (MJ)
DE	=	Digestible energy (MJ)
(UE × GE)	=	Urinary energy expressed as fraction of GE, assumed to be 0.04 except for feedlots which are reduced 0.02 as a result of the high grain content of their diet.
ASH	=	Ash content of manure calculated as a fraction of the dry matter feed intake (assumed to be 0.08).
18.45	=	Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

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 *2006 IPCC Guidelines* 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, based on the 10th Corrigenda for the *2006 IPCC Guidelines* (IPCC 2018).[94]

$$Nex_{(T)} = N_{intake} \times \left(1 - N_{retention\_fract(T)}\right)$$

where,

$Nex_{(T)}$	= Annual N excretion rates (kg N animal^{-1} yr^{-1})
$N_{intake(T)}$	= The annual N intake per head of animal of species/category *T* (kg N animal^{-1} yr^{-1})
$N_{retention(T)}$	= Fraction of annual N intake that is retained by animal

N intake is estimated as:

$$N_{intake(T)} = \frac{GE}{18.45} \bullet \left(\frac{\frac{CP\%}{100}}{6.25} \right)$$

where,

$N_{intake(T)}$	= Daily N consumed per animal of category T (kg N animal^{-1} day^{-1})
GE	= Gross energy intake of the animal based on digestible energy, milk production, pregnancy, current weight, mature weight, rate of weight gain, and IPCC constants (MJ animal^{-1} day^{-1})
18.45	= Conversion factor for dietary GE per kg of dry matter (MJ kg^{-1})
CP%	= Percent crude protein in diet, input
6.25	= Conversion from kg of dietary protein to kg of dietary N (kg feed protein per kg N)

The portion of consumed N that is retained as product equals the nitrogen in milk plus the nitrogen required for weight gain. The N content of milk produced is calculated using milk production and percent protein, along with conversion factors. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NE_g), weight gain (WG), and other conversion factors and constants. The equation matches the 10th Corrigenda to the *2006 IPCC Guidelines*, and is as follows:

$$N_{retention(T)} = \left[\frac{Milk \times \left(\frac{Milk\ PR\%}{100}\right)}{6.38}\right] + \left[\frac{WG \times \left[268 - \left(\frac{7.03 \times NE_g}{WG}\right)\right]}{1000 \times 6.25}\right]$$

where,

$N_{retention(T)}$	= Daily N retained per animal of category T (kg N animal^{-1} day^{-1})
Milk	= Milk production (kg animal^{-1} day^{-1})
268	= Constant from *2006 IPCC Guidelines*
7.03	= Constant from *2006 IPCC Guidelines*
NE_g	= Net energy for growth, calculated in livestock characterization, based on current weight, mature weight, rate of weight gain, and IPCC constants, (MJ day^{-1})
1,000	= Conversion from grams to kilograms (g kg^{-1})
6.25	= Conversion from kg dietary protein to kg dietary N (kg protein per kg N)
Milk PR%	= Percent of protein in milk (%)
6.38	= Conversion from milk protein to milk N (kg protein per kg N)
WG	= Weight gain, as input into the CEFM transition matrix (kg day^{-1})

[94] Note that although this equation was updated since the previous Inventory submission, the equations are functionally the same and do not impact Inventory emissions estimates. The updated equation clarifies the relationship between intake of N and milk and growth (i.e., the fraction of N retained).

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-187 presents the state-specific VS and Nex production rates used for cattle in 2018. As shown in Table A-187, the differences in the VS daily excretion and Nex rate trends between dairy cattle animal types is due to milk production. Milk production by cow varies from state to state and is used in calculating net energy for lactating, which is used to calculate VS and Nex for dairy cows. Milk production is zero for dairy heifers (dairy heifers do not produce milk because they have not yet had a calf). Over time, the differences in milk production are also a big driver for the higher variability of VS and Nex rates in dairy cows.

Step 3: Waste Management System Usage Data

Table A-188 and Table A-189 summarize 2018 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. Note that the Inventory WMS estimates are based on state or regional WMS usage data and not built upon farm-level WMS estimates. 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-190.

Beef Cattle, Dairy Heifers and American Bison: The beef feedlot and dairy heifer WMS data were developed using regional 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 EPA and USDA data and expert opinions (documented in ERG 2000a), the runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* 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 (ERG 2000a). 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 NOF.

Dairy Cows: The WMS data for dairy cows were developed using state and regional data from the Census of Agriculture, EPA's Office of Water, USDA, and the expert sources noted below. Farm-size distribution data are reported in the 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture (USDA 2019d). It was assumed that the Census data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2017 were the same as that for 2018. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

For 1990 through 1996 the following methodology and sources were used to estimate dairy WMS:

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 at the regional level 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, 2007, 2012, and 2017 (USDA 2019d) 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 2018, which were obtained from the USDA NASS (USDA 2018a).

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).

Starting in 2016, EPA estimate dairy WMS based on 2016 USDA Economic Research Service (ERS) Agricultural Resource Management Survey (ARMS) data. These data were obtained from surveys of nationally representative dairy producers. WMS data for 2016 were assumed the same for 2017 and 2018. WMS for 1997 through 2015 were interpolated between the data sources used for the 1990-1997 dairy WMS (noted above) and the 2016 ARMs data (ERG 2019).

Finally, the percentage of manure managed with anaerobic digestion (AD) systems with methane capture and combustion was added to the WMS distributions at the state-level. AD system data were obtained from EPA's AgSTAR Program's project database (EPA 2019). This database includes basic information for AD systems in the United States, based on publicly available data and data submitted by farm operators, project developers, financiers, and others involved in the development of farm AD projects.

Swine: The regional distribution of manure managed in each WMS was estimated using data from a 1998 USDA APHIS survey, EPA's Office of Water site visits, and 2009 USDA ERS ARMS data (Bush 1998, ERG 2000a, ERG 2018). The USDA APHIS data are based on a statistical sample of farms in the 16 U.S. states with the most hogs. The ERS ARMS data are based on surveys of nationally representative swine producers. Prior to 2009, operations with less than 200 head were assumed to use pasture, range, or paddock systems and swine operations with greater than 200 head were assigned WMS as obtained from USDA APHIS (Bush 1998). WMS data for 2009 were obtained from USDA ERS ARMS; WMS data for 2010 through 2018 were assumed to be the same as 2009 (ERG 2018). 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, 2007, 2012, and 2017 Census of Agriculture (USDA 2019d) 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. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, and 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data.

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 state-level WMS distribution based on data from EPA's AgSTAR database (EPA 2019).

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 2018 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 United States, 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 2018 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 2019), 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 used to update the WMS distributions based on information from EPA's AgSTAR database (EPA 2019).

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-191. 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 2019) 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 latest guidelines from 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, 2007, 2012, and 2017 Census data (USDA 2019d). 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 interpolated based on 1992 and 1997 data; county population distribution data for 1998 through 2001 were interpolated based on 1997 and 2002 data; county population distribution data for 2003 through 2006 were interpolated based on 2002 and 2007 data; county population distribution data for 2008 through 2011 were interpolated based on 2007 and 2012 data; county population distribution data for 2013 through 2016 were interpolated based on 2012 and 2017 data; county population distributions for 2018 were assumed to be the same as 2017.

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 due to the biological activity in the lagoon which keeps the temperature above freezing.
- 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 B_0.

The annual MCF is then calculated as:

$$MCF_{annual} = \frac{CH_4\ generated_{annual}}{VS\ produced_{annual} \times B_o}$$

where,

MCF_{annual}	= Methane conversion factor
VS produced $_{annual}$	= Volatile solids excreted annually
B_0	= 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-192 by state, WMS, and animal group for 2018.

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-193.

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-194.

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:

$$VS\ excreted_{State,Animal,WMS} = Population_{State,Animal} \times \frac{TAM}{1000} \times VS \times WMS \times 365.25$$

where,

VS excreted $_{State,\ Animal,\ WMS}$	= Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{State,\ Animal}$	= 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_0	= 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 25° 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 B_0 of the manure. This value is applied for all climate regions and AD system types. However, this is a conservative assumption as 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:

$$CH_4\ ProductionAD_{ADSystem} = ProductionAD_{ADSystem} \times \frac{TAM}{1000} \times VS \ \times B_O \times 0.662 \ \times 365.25 \times 0.90$$

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_0	= Maximum CH_4 producing capacity (CH_4 m^3/kg VS)
0.662	= Density of CH_4 at 25° 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 from the system (e.g., from the cover, piping, tank, etc.) 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 United States 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:

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

where,

CH_4 Emissions AD	= CH_4 emissions from AD systems, (kg/yr)
CH_4 Production $AD_{AD\ system}$	= CH_4 production from a particular AD system, (kg/yr)
$CE_{AD\ system}$	= 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

Total N_2O emissions from manure management systems 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 $_{State,\ Animal,\ WMS}$	= Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{state}$	= 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	= 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 $_{State,\ Animal,\ WMS}$	= Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{state}$	= 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	= Nitrogen excretion rate (kg N/animal/year)

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

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

where,

Direct N_2O	= Direct N_2O emissions (kg N_2O/yr)
N excreted $_{State,\ Animal,\ WMS}$	= Amount of N excreted in manure managed in each WMS for each animal type

(kg/yr)

EF_{WMS} = Direct N_2O emission factor from IPCC guidelines (kg N_2O-N /kg N)

44/28 = Conversion factor of N_2O-N to N_2O

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

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

where,

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

N excreted $_{\text{State, Animal, WMS}}$ = 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-195 and Table A-196 respectively. Emission estimates for 2018 are presented by animal type and state in Table A-197 and Table A-198 respectively.

Table A-184: Livestock Population (1,000 Head)

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Dairy Cattle	19,512	18,681	17,793	18,078	18,190	18,422	18,560	18,297	18,442	18,587	18,505	18,527	18,803	18,853	18,893	19,008
Dairy Cows	*10,015*	*9,482*	*9,004*	*9,104*	*9,145*	*9,257*	*9,333*	*9,087*	*9,156*	*9,236*	*9,221*	*9,208*	*9,307*	*9,310*	*9,346*	*9,432*
Dairy Heifer	*4,129*	*4,108*	*4,162*	*4,294*	*4,343*	*4,401*	*4,437*	*4,545*	*4,577*	*4,581*	*4,525*	*4,579*	*4,725*	*4,785*	*4,762*	*4,776*
Dairy Calves	*5,369*	*5,091*	*4,628*	*4,680*	*4,703*	*4,765*	*4,791*	*4,666*	*4,709*	*4,770*	*4,758*	*4,740*	*4,771*	*4,758*	*4,785*	*4,800*
Swine[a]	53,941	58,899	61,073	61,887	65,417	67,183	65,842	64,723	65,572	66,363	65,437	64,195	68,178	70,065	72,125	73,793
Market <50 lb.	*18,359*	*19,656*	*20,228*	*20,514*	*21,812*	*19,933*	*19,411*	*19,067*	*19,285*	*19,472*	*19,002*	*18,939*	*19,843*	*20,572*	*20,973*	*21,494*
Market 50-119 lb.	*11,734*	*12,836*	*13,519*	*13,727*	*14,557*	*17,163*	*16,942*	*16,645*	*16,904*	*17,140*	*16,834*	*16,559*	*17,577*	*18,175*	*18,767*	*19,133*
Market 120-179 lb.	*9,440*	*10,545*	*11,336*	*11,443*	*12,185*	*12,825*	*12,517*	*12,377*	*12,514*	*12,714*	*12,674*	*12,281*	*13,225*	*13,575*	*13,982*	*14,365*
Market >180 lb.	*7,510*	*8,937*	*9,997*	*10,113*	*10,673*	*11,161*	*11,067*	*10,856*	*11,078*	*11,199*	*11,116*	*10,525*	*11,555*	*11,714*	*12,282*	*12,497*
Breeding	*6,899*	*6,926*	*5,993*	*6,090*	*6,190*	*6,102*	*5,905*	*5,778*	*5,791*	*5,839*	*5,812*	*5,892*	*5,978*	*6,030*	*6,122*	*6,303*
Beef Cattle[b]	81,576	90,361	82,193	83,263	82,801	81,532	80,993	80,484	78,937	76,858	76,075	75,245	76,080	79,374	81,560	83,061
Feedlot Steers	*6,357*	*7,233*	*8,116*	*8,724*	*8,674*	*8,474*	*8,434*	*8,584*	*8,771*	*8,586*	*8,614*	*8,695*	*8,570*	*9,019*	*9,572*	*10,329*
Feedlot Heifers	*3,192*	*3,831*	*4,536*	*4,801*	*4,730*	*4,585*	*4,493*	*4,620*	*4,830*	*4,742*	*4,653*	*4,525*	*4,313*	*4,431*	*4,768*	*5,146*
NOF Bulls	*2,160*	*2,385*	*2,214*	*2,258*	*2,214*	*2,207*	*2,188*	*2,190*	*2,165*	*2,100*	*2,074*	*2,038*	*2,109*	*2,142*	*2,244*	*2,252*
Beef Calves	*16,909*	*18,177*	*16,918*	*16,814*	*16,644*	*16,231*	*16,051*	*16,067*	*15,817*	*15,288*	*14,859*	*14,741*	*15,000*	*15,563*	*15,971*	*16,021*
NOF Heifers	*10,182*	*11,829*	*9,550*	*9,716*	*9,592*	*9,356*	*9,473*	*9,349*	*8,874*	*8,687*	*8,787*	*8,787*	*9,288*	*9,903*	*9,835*	*9,815*
NOF Steers	*10,321*	*11,716*	*8,185*	*8,248*	*8,302*	*8,244*	*8,560*	*8,234*	*7,568*	*7,173*	*7,457*	*7,374*	*7,496*	*8,150*	*7,957*	*8,032*
NOF Cows	*32,455*	*35,190*	*32,674*	*32,703*	*32,644*	*32,435*	*31,794*	*31,440*	*30,913*	*30,282*	*29,631*	*29,085*	*29,302*	*30,166*	*31,213*	*31,466*
Sheep	11,358	8,989	6,135	6,200	6,120	5,950	5,747	5,620	5,470	5,375	5,360	5,235	5,270	5,295	5,270	5,265
Sheep On Feed	*1,180*	*1,771*	*2,971*	*3,026*	*3,000*	*2,911*	*2,806*	*2,778*	*2,687*	*2,666*	*2,655*	*2,585*	*2,584*	*2,621*	*2,615*	*2,619*
Sheep NOF	*10,178*	*7,218*	*3,164*	*3,174*	*3,120*	*3,039*	*2,941*	*2,842*	*2,783*	*2,709*	*2,705*	*2,650*	*2,686*	*2,674*	*2,655*	*2,646*
Goats	2,516	2,357	2,897	3,019	3,141	3,037	2,933	2,829	2,725	2,622	2,637	2,652	2,668	2,683	2,699	2,714
Poultry[c]	1,537,074	1,826,977	2,150,410	2,154,236	2,166,936	2,175,990	2,088,828	2,104,335	2,095,951	2,168,697	2,106,502	2,116,333	2,134,445	2,173,216	2,214,462	2,252,265
Hens >1 yr.	*273,467*	*299,071*	*348,203*	*349,888*	*346,613*	*339,859*	*341,005*	*341,884*	*338,944*	*346,965*	*361,403*	*370,637*	*351,656*	*377,299*	*388,006*	*396,870*
Pullets	*73,167*	*81,369*	*96,809*	*96,596*	*103,816*	*99,458*	*102,301*	*105,738*	*102,233*	*104,460*	*106,646*	*106,490*	*118,114*	*112,061*	*117,173*	*124,135*
Chickens	*6,545*	*7,637*	*8,289*	*7,938*	*8,164*	*7,589*	*8,487*	*7,390*	*6,922*	*6,827*	*6,853*	*6,403*	*7,211*	*6,759*	*6,859*	*6,568*
Broilers	*1,066,209*	*1,331,940*	*1,613,091*	*1,612,327*	*1,619,400*	*1,638,055*	*1,554,582*	*1,567,927*	*1,565,018*	*1,625,945*	*1,551,600*	*1,553,636*	*1,579,764*	*1,595,764*	*1,620,691*	*1,643,109*
Turkeys	*117,685*	*106,960*	*84,018*	*87,487*	*88,943*	*91,029*	*82,453*	*81,396*	*82,833*	*84,500*	*80,000*	*79,167*	*77,700*	*81,333*	*81,733*	*81,583*
Horses	*2,212*	*2,632*	*3,875*	*3,952*	*4,029*	*3,947*	*3,866*	*3,784*	*3,703*	*3,621*	*3,467*	*3,312*	*3,157*	*3,002*	*2,847*	*2,692*
Mules and Asses	63	101	212	248	284	286	287	289	291	293	298	303	308	313	318	323
American Bison	47	104	212	205	198	191	184	177	169	162	166	171	175	179	184	188

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.

Source(s): See *Step 1: Livestock Population Characterization Data.*

Table A-185: Waste Characteristics Data

	Typical Animal Mass, TAM		Total Nitrogen Excreted, Nex[a]		Maximum Methane Generation Potential, B_0		Volatile Solids Excreted, VS[a]	
Animal Group	Value (kg)	Source	Value	Source	Value (m^3 CH_4/kg VS added)	Source	Value	Source
Dairy Cows	680	CEFM	Table A-187	CEFM	0.24	Morris 1976	Table A-187	CEFM
Dairy Heifers	406-408	CEFM	Table A-187	CEFM	0.17	Bryant et al. 1976	Table A-187	CEFM
Feedlot Steers	419-457	CEFM	Table A-187	CEFM	0.33	Hashimoto 1981	Table A-187	CEFM
Feedlot Heifers	384-430	CEFM	Table A-187	CEFM	0.33	Hashimoto 1981	Table A-187	CEFM
NOF Bulls	831-917	CEFM	Table A-187	CEFM	0.17	Hashimoto 1981	Table A-187	CEFM
NOF Calves	118	ERG 2003b	Table A-186	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-186	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-187	CEFM	0.17	Hashimoto 1981	Table A-187	CEFM
NOF Steers	314-335	CEFM	Table A-187	CEFM	0.17	Hashimoto 1981	Table A-187	CEFM
NOF Cows	554-611	CEFM	Table A-187	CEFM	0.17	Hashimoto 1981	Table A-187	CEFM
American Bison	578.5	Meagher 1986	Table A-187	CEFM	0.17	Hashimoto 1981	Table A-187	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-186	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-186	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-186	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-186	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-186	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-186	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-186	ASAE 1998	0.17	EPA 1992	Table A-186	ASAE 1998
Horses	450	ASAE 1998	Table A-186	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-186	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-186	IPCC 2006	0.33	EPA 1992	Table A-186	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A-186	USDA 1996, 2008	0.39	Hill 1982	Table A-186	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-186	USDA 1996, 2008	0.39	Hill 1982	Table A-186	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-186	USDA 1996, 2008	0.39	Hill 1982	Table A-186	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-186	USDA 1996, 2008	0.36	Hill 1984	Table A-186	USDA 1996, 2008

Turkeys	6.8	ASAE 1998	Table A-186	USDA 1996, 2008	0.36	Hill 1984	Table A-186	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A-187 shows state-level values for 2018 only.

Table A-186: Estimated Volatile Solids (VS) and Total 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	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
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
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
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
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
Swine, Breeding	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	2.7
NOF Cattle Calves	6.4	6.4	7.4	7.5	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Sheep	9.2	9.2	8.6	8.5	8.4	8.3	8.3	8.3	8.3	8.3	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
Hens >1yr.	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Pullets	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Chickens	10.8	10.8	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Broilers	15.0	15.0	16.5	16.7	16.8	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Turkeys	9.7	9.7	8.8	8.7	8.6	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Horses	10.0	10.0	7.3	6.9	6.5	6.1	6.1	6.1	6.1	6.1	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
Nex																
Swine, Market <50 lbs.	0.60	0.60	0.84	0.87	0.89	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Swine, Market 50-119 lbs.	0.42	0.42	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market 120-179 lbs.	0.42	0.42	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.42	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Breeding	0.24	0.24	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NOF Cattle Calves	0.30	0.30	0.41	0.43	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sheep	0.42	0.42	0.44	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Goats	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Hens >1yr.	0.70	0.70	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Pullets	0.70	0.70	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Chickens	0.83	0.83	1.03	1.06	1.08	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Broilers	1.10	1.10	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Turkeys	0.74	0.74	0.65	0.64	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Horses	0.30	0.30	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mules and Asses	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

Table A-187: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2018 (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	2,262	1,252	1,664	1,100	975	691	669	1,721	1,721	136	69	73	50	42	56	57	83	83
Alaska	1,821	1,252	1,891	1,252	1,120	691	669	1,956	1,956	115	69	59	41	33	56	57	69	69
Arizona	2,943	1,252	1,891	1,236	1,120	691	670	1,956	1,956	163	69	59	40	33	56	57	69	69
Arkansas	2,087	1,252	1,664	1,096	975	691	670	1,721	1,721	126	69	73	50	42	56	57	83	83
California	2,780	1,252	1,891	1,230	1,120	691	670	1,956	1,956	155	69	59	39	33	56	57	69	69
Colorado	3,055	1,252	1,891	1,205	1,120	691	669	1,956	1,956	168	69	59	38	33	56	57	69	69
Connecticut	2,751	1,252	1,674	1,097	981	691	669	1,731	1,731	155	69	74	51	42	56	57	84	84
Delaware	2,486	1,252	1,674	1,094	981	691	669	1,731	1,731	143	69	74	51	42	56	57	84	84
Florida	2,657	1,252	1,664	1,103	975	691	668	1,721	1,721	153	69	73	51	42	56	57	83	83
Georgia	2,790	1,252	1,664	1,093	975	691	668	1,721	1,721	158	69	73	50	42	55	57	83	83
Hawaii	2,363	1,252	1,891	1,262	1,120	691	669	1,956	1,956	138	69	59	41	33	56	57	69	69
Idaho	2,920	1,252	1,891	1,220	1,120	691	669	1,956	1,956	162	69	59	39	33	56	57	69	69
Illinois	2,649	1,252	1,589	1,013	927	691	669	1,643	1,643	150	69	75	50	43	56	57	85	85
Indiana	2,803	1,252	1,589	1,022	927	691	670	1,643	1,643	157	69	75	50	43	56	57	85	85
Iowa	2,872	1,252	1,589	995	927	691	670	1,643	1,643	160	69	75	48	43	56	57	85	85
Kansas	2,817	1,252	1,589	986	927	691	669	1,643	1,643	158	69	75	48	43	56	57	85	85
Kentucky	2,542	1,252	1,664	1,081	975	691	669	1,721	1,721	148	69	73	49	42	56	57	83	83
Louisiana	2,100	1,252	1,664	1,103	975	691	669	1,721	1,721	127	69	73	51	42	56	57	83	83
Maine	2,668	1,252	1,674	1,088	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
Maryland	2,582	1,252	1,674	1,095	981	691	670	1,731	1,731	147	69	74	51	42	56	57	84	84
Massachusetts	2,413	1,252	1,674	1,097	981	691	669	1,731	1,731	140	69	74	51	42	56	57	84	84
Michigan	3,064	1,252	1,589	1,010	927	691	670	1,643	1,643	168	69	75	49	43	56	57	85	85
Minnesota	2,708	1,252	1,589	1,008	927	691	670	1,643	1,643	153	69	75	49	43	56	57	85	85
Mississippi	2,291	1,252	1,664	1,098	975	691	669	1,721	1,721	137	69	73	50	42	56	57	83	83
Missouri	2,189	1,252	1,589	1,033	927	691	669	1,643	1,643	131	69	75	51	43	56	57	85	85
Montana	2,754	1,252	1,891	1,248	1,120	691	670	1,956	1,956	155	69	59	40	33	56	57	69	69
Nebraska	2,897	1,252	1,589	991	927	691	670	1,643	1,643	161	69	75	48	43	56	57	85	85
Nevada	2,754	1,252	1,891	1,244	1,120	691	668	1,956	1,956	155	69	59	40	33	55	56	69	69
New Hampshire	2,668	1,252	1,674	1,081	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
New Jersey	2,581	1,252	1,674	1,088	981	691	668	1,731	1,731	147	69	74	50	42	56	57	84	84
New Mexico	2,964	1,252	1,891	1,237	1,120	691	669	1,956	1,956	164	69	59	40	33	56	57	69	69
New York	2,887	1,252	1,674	1,078	981	691	668	1,731	1,731	161	69	74	49	42	56	57	84	84
North Carolina	2,734	1,252	1,664	1,097	975	691	668	1,721	1,721	156	69	73	50	42	56	57	83	83
North Dakota	2,710	1,252	1,589	1,021	927	691	670	1,643	1,643	153	69	75	50	43	56	57	85	85

	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
Ohio	2,687	1,252	1,589	1,027	927	691	670	1,643	1,643	152	69	75	51	43	56	57	85	85
Oklahoma	2,498	1,252	1,664	1,073	975	691	669	1,721	1,721	144	69	73	49	42	56	57	83	83
Oregon	2,623	1,252	1,891	1,231	1,120	691	669	1,956	1,956	149	69	59	40	33	56	57	69	69
Pennsylvania	2,656	1,252	1,674	1,083	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
Rhode Island	2,313	1,252	1,674	1,097	981	691	669	1,731	1,731	136	69	74	51	42	56	57	84	84
South Carolina	2,384	1,252	1,664	1,100	975	691	671	1,721	1,721	141	69	73	50	42	56	58	83	83
South Dakota	2,771	1,252	1,589	1,014	927	691	670	1,643	1,643	156	69	75	50	43	56	57	85	85
Tennessee	2,448	1,252	1,664	1,086	975	691	669	1,721	1,721	144	69	73	50	42	56	57	83	83
Texas	2,866	1,252	1,664	1,061	975	691	670	1,721	1,721	160	69	73	48	42	56	57	83	83
Utah	2,841	1,252	1,891	1,244	1,120	692	671	1,956	1,956	159	69	59	40	33	56	58	69	69
Vermont	2,679	1,252	1,674	1,077	981	691	668	1,731	1,731	152	69	74	49	42	56	57	84	84
Virginia	2,644	1,252	1,664	1,086	975	691	670	1,721	1,721	152	69	73	50	42	56	57	83	83
Washington	2,878	1,252	1,891	1,213	1,120	691	670	1,956	1,956	160	69	59	39	33	56	57	69	69
West Virginia	2,285	1,252	1,674	1,100	981	691	670	1,731	1,731	135	69	74	51	42	56	57	84	84
Wisconsin	2,872	1,252	1,589	1,033	927	691	670	1,643	1,643	160	69	75	51	43	56	57	85	85
Wyoming	2,820	1,252	1,891	1,242	1,120	691	669	1,956	1,956	158	69	59	40	33	56	57	69	69

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

Table A-188: 2018 Manure Distribution Among Waste Management Systems by Operation (Percent)

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Alabama	100	1	100	48	0	0	14	2	22	14	17	38	0	45
Alaska	100	1	100	25	12	0	26	5	9	22	6	90	1	4
Arizona	100	0	100	10	0	11	42	6	30	2	10	90	0	0
Arkansas	100	1	100	47	0	0	13	3	23	14	15	28	0	57
California	100	1	100	5	0	3	26	3	54	9	11	88	1	1
Colorado	100	0	100	11	0	11	41	5	30	2	1	98	0	1
Connecticut	100	1	100	15	3	0	16	6	33	28	43	51	0	6
Delaware	100	1	100	14	2	0	18	7	29	31	44	50	0	6
Florida	100	1	100	48	0	0	7	0	40	4	22	61	1	17
Georgia	100	1	100	48	0	0	9	1	36	6	18	42	0	40
Hawaii	100	1	100	4	0	4	27	2	54	9	0	99	1	1

State	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Idaho	100	0	100	5	0	3	26	2	53	10	1	99	0	0
Illinois	100	1	100	24	0	0	23	3	33	18	8	87	0	5
Indiana	100	1	100	21	0	0	21	2	41	16	13	79	0	8
Iowa	100	1	100	20	0	0	21	3	41	16	10	83	0	6
Kansas	100	1	100	14	0	0	16	1	55	13	5	92	0	3
Kentucky	100	1	100	51	0	0	14	2	23	11	14	24	0	61
Louisiana	100	1	100	48	0	0	13	3	23	12	14	26	0	60
Maine	100	1	100	18	4	0	16	5	30	28	45	48	0	7
Maryland	100	1	100	21	4	0	16	6	23	29	44	49	0	7
Massachusetts	100	1	100	25	5	0	17	6	17	30	45	47	0	7
Michigan	100	1	100	11	3	0	22	6	36	22	6	91	0	3
Minnesota	100	1	100	16	6	0	24	6	26	23	10	84	0	6
Mississippi	100	1	100	50	0	0	14	2	23	11	15	28	0	57
Missouri	100	1	100	29	0	0	25	2	26	17	14	77	0	8
Montana	100	0	100	19	0	0	21	4	38	18	4	93	0	3
Nebraska	100	1	100	15	0	0	18	2	50	15	6	90	0	4
Nevada	100	0	100	11	0	0	14	2	61	13	0	99	0	0
New Hampshire	100	1	100	21	4	0	17	5	22	31	44	49	0	7
New Jersey	100	1	100	27	5	0	16	6	16	29	45	47	0	8
New Mexico	100	0	100	10	0	11	42	6	30	2	10	90	0	0
New York	100	1	100	14	3	0	15	5	38	25	45	48	0	7
North Carolina	100	1	100	48	0	0	10	2	31	9	15	31	0	54
North Dakota	100	1	100	18	0	0	19	3	44	16	11	83	0	6
Ohio	100	1	100	24	0	0	23	2	35	17	14	78	0	8
Oklahoma	100	0	100	11	0	8	41	5	23	12	6	94	0	0
Oregon	100	1	100	9	0	3	24	4	50	11	0	80	1	20
Pennsylvania	100	1	100	27	6	0	16	5	18	29	47	44	0	9
Rhode Island	100	1	100	29	6	0	17	5	14	30	47	44	0	9
South Carolina	100	1	100	45	0	0	10	2	33	11	15	31	0	54
South Dakota	100	1	100	14	0	0	16	2	54	14	8	87	0	5
Tennessee	100	1	100	48	0	0	12	2	26	11	15	26	0	59
Texas	100	0	100	11	0	10	41	5	30	3	8	92	0	0
Utah	100	0	100	12	0	9	40	5	28	7	1	98	0	1
Vermont	100	1	100	14	3	0	16	5	36	26	44	49	0	7

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Virginia	100	1	100	49	0	0	12	2	26	11	15	28	0	57
Washington	100	1	100	8	0	3	25	3	51	10	0	83	1	17
West Virginia	100	1	100	29	6	0	17	5	13	30	45	48	0	7
Wisconsin	100	1	100	15	5	0	24	6	27	23	12	82	0	7
Wyoming	100	0	100	16	0	0	18	2	49	15	12	81	0	7

[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.
Source(s): *See Step 3: Waste Management System Usage Data*.

Table A-189: 2018 Manure Distribution Among Waste Management Systems by Operation (Percent) Continued

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Alabama	15	0	29	30	12	14	42	58	1	99
Alaska	57	0	3	2	34	4	25	75	1	99
Arizona	19	0	28	29	11	13	60	40	1	99
Arkansas	6	0	60	26	5	2	0	100	1	99
California	15	0	28	29	13	14	12	88	1	99
Colorado	2	0	53	0	23	22	60	40	1	99
Connecticut	66	0	2	2	26	4	5	95	1	99
Delaware	29	0	4	5	56	5	5	95	1	99
Florida	53	0	20	14	9	5	42	58	1	99
Georgia	13	0	56	28	3	1	42	58	1	99
Hawaii	42	0	22	18	11	7	25	75	1	99
Idaho	16	0	16	3	57	8	60	40	1	99
Illinois	2	0	15	7	71	5	2	98	1	99
Indiana	1	0	3	12	78	7	0	100	1	99
Iowa	1	0	10	4	80	5	0	100	1	99
Kansas	1	0	13	35	21	30	2	98	1	99
Kentucky	8	0	19	21	31	21	5	95	1	99
Louisiana	67	0	17	9	6	2	60	40	1	99
Maine	74	0	2	1	20	4	5	95	1	99
Maryland	37	0	10	2	44	6	5	95	1	99
Massachusetts	60	0	2	2	31	4	5	95	1	99
Michigan	3	0	12	6	69	9	2	98	1	99
Minnesota	1	0	3	2	88	5	0	100	1	99
Mississippi	2	0	31	36	13	18	60	40	1	99
Missouri	2	0	16	33	34	15	0	100	1	99
Montana	3	0	21	2	64	9	60	40	1	99
Nebraska	2	0	9	22	49	19	2	98	1	99
Nevada	12	0	29	32	12	15	0	100	1	99
New Hampshire	65	0	2	2	27	4	5	95	1	99
New Jersey	54	0	3	3	36	4	5	95	1	99
New Mexico	67	0	17	9	6	2	60	40	1	99
New York	41	0	6	3	44	5	5	95	1	99

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
North Carolina	1	0	33	49	1	16	42	58	1	99
North Dakota	2	0	21	2	65	9	2	98	1	99
Ohio	1	0	10	9	67	13	0	100	1	99
Oklahoma	1	0	11	53	3	32	60	40	1	99
Oregon	51	0	20	15	9	5	25	75	1	99
Pennsylvania	1	0	8	5	77	9	0	100	1	99
Rhode Island	64	0	2	2	28	4	5	95	1	99
South Carolina	6	0	30	34	13	16	60	40	1	99
South Dakota	1	0	17	11	57	14	2	98	1	99
Tennessee	7	0	30	33	13	16	5	95	1	99
Texas	6	0	31	34	13	17	12	88	1	99
Utah	1	0	22	2	65	9	60	40	1	99
Vermont	69	0	2	1	24	4	5	95	1	99
Virginia	6	0	14	29	15	35	5	95	1	99
Washington	35	0	12	2	45	7	12	88	1	99
West Virginia	82	0	1	0	13	3	5	95	1	99
Wisconsin	15	0	23	1	57	4	2	98	1	99
Wyoming	3	0	21	2	64	9	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.
Source(s): *See Step 3: Waste Management System Usage Data.*

Table A-190: 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 and indirect N_2O emissions are accounted for under Manure Management. Direct 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 and the classification of manure as managed or unmanaged 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-191: 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)	3	3	30
Cattle Deep Litter (>1 month)	21	44	76
Composting - In Vessel	0.5	0.5	0.5
Composting - Static Pile	0.5	0.5	0.5
Composting-Extensive/ Passive	0.5	1	1.5
Composting-Intensive	0.5	1	1.5
Daily Spread	0.1	0.5	1
Dry Lot	1	1.5	5
Fuel	10	10	10
Pasture	1	1.5	2
Poultry with bedding	1.5	1.5	1.5
Poultry without bedding	1.5	1.5	1.5
Solid Storage	2	4	5

Source: IPCC (2006).

Table A-192: Methane Conversion Factors by State for Liquid Systems for 2018 (Percent)

	Dairy		Swine		Beef	Poultry
State	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
Alabama	77	42	77	42	44	77
Alaska	49	15	49	15	15	49
Arizona	78	60	76	48	46	75
Arkansas	75	38	76	40	39	75
California	74	33	74	33	45	74
Colorado	66	22	69	25	25	65
Connecticut	71	27	71	27	27	71
Delaware	75	34	75	34	33	75
Florida	79	58	79	56	53	79
Georgia	78	44	77	42	49	77
Hawaii	77	59	77	59	59	77
Idaho	68	24	64	21	22	64
Illinois	73	31	73	31	30	74
Indiana	72	29	72	29	30	72
Iowa	70	27	71	27	27	71
Kansas	74	34	74	33	33	74
Kentucky	75	34	75	35	34	75
Louisiana	78	50	78	49	52	78
Maine	65	22	65	22	21	65
Maryland	74	32	75	33	32	74
Massachusetts	69	25	70	26	26	70
Michigan	69	25	70	26	26	69
Minnesota	68	25	69	25	25	67
Mississippi	77	45	77	44	46	78
Missouri	74	34	74	34	34	74
Montana	59	19	61	20	20	61
Nebraska	71	28	71	28	27	71

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
Nevada	71	27	71	27	24	73
New Hampshire	66	23	67	23	22	67
New Jersey	73	30	73	31	29	73
New Mexico	73	33	70	28	31	71
New York	68	24	69	25	25	69
North Carolina	76	36	78	41	36	76
North Dakota	65	23	65	23	23	65
Ohio	72	29	72	29	29	72
Oklahoma	76	40	75	37	37	76
Oregon	65	22	64	21	22	64
Pennsylvania	72	28	72	28	28	73
Rhode Island	71	27	71	27	27	71
South Carolina	77	43	78	44	41	77
South Dakota	69	25	69	26	26	69
Tennessee	75	35	76	38	36	75
Texas	75	42	76	44	41	77
Utah	68	23	67	23	24	68
Vermont	65	22	65	22	22	65
Virginia	73	30	76	35	31	74
Washington	64	21	64	21	23	65
West Virginia	72	29	72	29	29	72
Wisconsin	68	24	69	25	25	69
Wyoming	61	20	62	20	21	62

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

Table A-193: Direct Nitrous Oxide Emission Factors (kg N_2O-N/kg N excreted)

Waste Management System	Direct N_2O Emission
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
Pit Storage	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: *2006 IPCC Guidelines.*

Table A-194: Indirect Nitrous Oxide Loss Factors (Percent)

			Runoff/Leaching Nitrogen Loss[a]				
Animal Type	Waste Management System	Volatilization Nitrogen Loss	Central	Pacific	Mid-Atlantic	Midwest	South
Beef Cattle	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Beef Cattle	Liquid/Slurry	26	0	0	0	0	0
Beef Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Anaerobic Lagoon	43	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Daily Spread	10	0	0	0	0	0
Dairy Cattle	Deep Pit	24	0	0	0	0	0
Dairy Cattle	Dry Lot	15	0.6	2	1.8	0.9	2.2
Dairy Cattle	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Solid Storage	27	0.2	0	0	0	0
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
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

[a] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff. Source: EPA (2002b, 2005).

Table A-195: Total Methane Emissions from Livestock Manure Management (kt)[a]

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Dairy Cattle	**589**	**684**	**970**	**990**	**1,105**	**1,106**	**1,112**	**1,124**	**1,144**	**1,188**	**1,167**	**1,190**	**1,233**	**1,259**	**1,270**	**1,292**
Dairy Cows	*581*	*676*	962	981	1,095	1,096	1,102	1,115	1,134	1,177	1,157	1,180	1,222	1,248	1,259	1,281
Dairy Heifer	*7*	*7*	7	7	8	8	8	8	8	9	8	8	9	9	9	9
Dairy Calves	*2*	*2*	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Swine	**622**	**763**	**812**	**789**	**851**	**786**	**740**	**797**	**791**	**821**	**756**	**719**	**808**	**846**	**840**	**888**
Market Swine	483	607	665	643	698	645	608	657	653	678	623	585	665	699	697	736
Market <50 lbs.	*102*	*121*	*128*	*125*	*136*	*94*	*88*	*95*	*94*	*98*	*88*	*86*	*95*	*101*	*100*	*106*
Market 50-119 lbs.	*101*	*123*	*131*	*127*	*138*	*143*	*134*	*144*	*142*	*149*	*136*	*130*	*145*	*155*	*153*	*161*
Market 120-179 lbs.	*136*	*170*	*184*	*177*	*193*	*185*	*173*	*188*	*185*	*193*	*179*	*169*	*192*	*203*	*200*	*213*
Market >180 lbs.	*144*	*193*	*222*	*214*	*232*	*223*	*214*	*229*	*231*	*238*	*220*	*201*	*232*	*241*	*244*	*256*
Breeding Swine	139	155	147	146	152	140	132	140	138	143	133	133	143	146	143	152
Beef Cattle	**126**	**139**	**133**	**137**	**134**	**130**	**130**	**132**	**131**	**128**	**122**	**120**	**126**	**132**	**136**	**135**
Feedlot Steers	*14*	*14*	*15*	*16*	*16*	*16*	*16*	*16*	*17*	*16*	*16*	*16*	*16*	*17*	*18*	*20*
Feedlot Heifers	*7*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*10*
NOF Bulls	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*
Beef Calves	*6*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*6*	*6*	*7*	*7*	*7*	*7*
NOF Heifers	*12*	*15*	*13*	*13*	*13*	*13*	*13*	*13*	*12*	*12*	*12*	*12*	*13*	*14*	*14*	*13*
NOF Steers	*12*	*14*	*10*	*11*	*10*	*10*	*11*	*10*	*10*	*9*	*9*	*9*	*9*	*10*	*10*	*10*
NOF Cows	*69*	*76*	*73*	*75*	*73*	*70*	*70*	*71*	*71*	*69*	*65*	*63*	*67*	*69*	*71*	*70*
Sheep	**7**	**5**	**3**	**3**	**3**	**3**	**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**
Poultry	**131**	**128**	**129**	**131**	**134**	**129**	**128**	**129**	**127**	**128**	**129**	**132**	**136**	**136**	**137**	**141**
Hens >1 yr.	*73*	*69*	*66*	*66*	*67*	*64*	*64*	*64*	*64*	*63*	*65*	*67*	*69*	*69*	*70*	*71*
Total Pullets	*25*	*22*	*22*	*23*	*25*	*23*	*23*	*24*	*23*	*23*	*24*	*24*	*27*	*26*	*26*	*28*
Chickens	*4*	*4*	*3*	*3*	*3*	*3*	*4*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*
Broilers	*19*	*23*	*31*	*32*	*32*	*33*	*31*	*31*	*31*	*32*	*31*	*31*	*32*	*32*	*32*	*33*
Turkeys	*10*	*9*	*7*	*7*	*7*	*7*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*
Horses	**9**	**11**	**12**	**12**	**11**	**10**	**10**	**10**	**10**	**10**	**9**	**8**	**8**	**8**	**7**	**7**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

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

Table A-196: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Dairy Cattle	**17.7**	**18.2**	**18.4**	**19.0**	**19.0**	**18.7**	**19.0**	**19.0**	**19.3**	**19.5**	**19.4**	**19.6**	**20.1**	**20.3**	**20.4**	**20.6**
Dairy Cows	*10.6*	*10.7*	*10.5*	*10.8*	*10.8*	*10.7*	*10.8*	*10.7*	*10.9*	*11.1*	*11.1*	*11.2*	*11.4*	*11.5*	*11.6*	*11.8*
Dairy Heifer	*7.1*	*7.5*	*7.8*	*8.2*	*8.2*	*8.0*	*8.1*	*8.3*	*8.4*	*8.5*	*8.3*	*8.4*	*8.7*	*8.8*	*8.8*	*8.8*
Dairy Calves	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Swine	**4.0**	**4.5**	**5.5**	**5.6**	**6.0**	**6.1**	**5.9**	**5.8**	**5.9**	**6.0**	**6.0**	**5.8**	**6.2**	**6.3**	**6.6**	**6.7**
Market Swine	*3.0*	*3.5*	4.6	4.8	5.2	5.3	5.2	5.1	5.2	5.2	5.2	5.0	5.4	5.6	5.7	5.9
Market <50 lbs.	*0.6*	*0.6*	*0.9*	*0.9*	*1.0*	*0.8*	*0.8*	*0.7*	*0.8*	*0.8*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	*0.8*
Market 50-119 lbs.	*0.6*	*0.7*	*0.9*	*0.9*	*1.0*	*1.2*	*1.2*	*1.1*	*1.2*	*1.2*	*1.2*	*1.1*	*1.2*	*1.2*	*1.3*	*1.3*
Market 120-179 lbs.	*0.9*	*1.0*	*1.3*	*1.3*	*1.4*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.6*	*1.6*	*1.7*	*1.7*
Market >180 lbs.	*0.9*	*1.1*	*1.5*	*1.6*	*1.7*	*1.8*	*1.8*	*1.7*	*1.8*	*1.8*	*1.8*	*1.7*	*1.8*	*1.9*	*2.0*	*2.0*
Breeding Swine	*1.0*	*1.1*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
Beef Cattle	**19.8**	**21.8**	**24.0**	**25.7**	**25.6**	**25.1**	**25.1**	**25.3**	**25.9**	**25.8**	**26.0**	**26.0**	**25.8**	**27.2**	**28.7**	**31.0**
Feedlot Steers	*13.4*	*14.4*	*15.5*	*16.7*	*16.7*	*16.5*	*16.5*	*16.6*	*16.9*	*16.7*	*17.0*	*17.3*	*17.3*	*18.4*	*19.3*	*20.8*
Feedlot Heifers	*6.4*	*7.4*	*8.5*	*9.0*	*8.9*	*8.7*	*8.6*	*8.7*	*9.1*	*9.0*	*9.0*	*8.8*	*8.5*	*8.8*	*9.4*	*10.1*
Sheep	**0.4**	**0.7**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**	**1.0**	**1.0**	**1.0**	**1.0**	**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**
Poultry	**4.7**	**5.1**	**5.4**	**5.4**	**5.4**	**5.4**	**5.2**	**5.2**	**5.2**	**5.3**	**5.2**	**5.2**	**5.2**	**5.4**	**5.5**	**5.6**
Hens >1 yr.	*1.0*	*1.0*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.4*	*1.3*	*1.4*	*1.4*	*1.5*
Total Pullets	*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*	*0.4*	*0.4*	*0.5*
Chickens	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Broilers	*2.2*	*2.7*	*3.0*	*2.9*	*2.9*	*2.9*	*2.7*	*2.8*	*2.8*	*2.9*	*2.7*	*2.7*	*2.8*	*2.8*	*2.9*	*2.9*
Turkeys	*1.2*	*1.1*	*0.8*	*0.8*	*0.8*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Horses	**0.3**	**0.4**	**0.5**	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**

Note: American bison are maintained entirely on pasture, range, and paddock. Emissions from manure deposited on pasture are included in the Agricultural Soils Management sector.
+ Does not exceed 0.05 kt.
NA (Not Applicable)

Table A-197: Methane Emissions by State from Livestock Manure Management for 2018 (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	Total
Alabama	0.0196	2.5576	0.6444	0.0109	0.6128	0.2921	10.0158	4.0815	0.0228	0.0091	0.0191	0.1542	0.0124	0.0004	18.4526
Alaska	0.0001	0.0188	0.0081	0.0002	0.0041	0.0015	0.3658	+	0.0227	0.0061	0.0002	0.0031	+	0.0033	0.4341
Arizona	0.7467	1.1143	22.6091	0.2781	2.3077	0.5078	1.2367	+	0.0228	0.0881	0.0221	0.2473	0.0030	0.0003	29.1841
Arkansas	0.0392	3.4272	0.5007	0.0080	0.7011	1.3186	0.6322	3.9664	0.7878	0.0091	0.0134	0.1385	0.0085	0.0005	11.5512
California	1.5783	3.9672	328.8087	1.9650	1.2727	0.2016	3.3533	0.2082	0.2751	0.4017	0.0495	0.2991	0.0064	0.0046	342.3915
Colorado	1.7935	3.1421	16.9646	0.1510	4.0937	2.3794	4.3482	+	0.0227	0.2091	0.0129	0.2081	0.0045	0.0246	33.3542
Connecticut	0.0004	0.0187	2.5977	0.0163	0.0090	0.0032	0.1353	+	0.0227	0.0038	0.0014	0.0223	0.0007	0.0008	2.8325
Delaware	0.0003	0.0087	0.7004	0.0040	0.0267	0.0330	0.1412	0.9543	0.0227	0.0061	0.0004	0.0083	0.0001	0.0003	1.9064
Florida	0.0140	3.2761	16.6941	0.1031	0.0933	0.0564	5.2916	0.2375	0.0228	0.0091	0.0236	0.2778	0.0122	0.0002	26.1118
Georgia	0.0195	1.9065	11.4906	0.0823	0.5867	0.4967	17.5986	4.9449	0.0228	0.0091	0.0262	0.1574	0.0118	0.0004	37.3534
Hawaii	0.0035	0.3072	0.4528	0.0030	0.0613	0.0711	0.5588	+	0.0228	0.0091	0.0063	0.0146	0.0004	0.0003	1.5111
Idaho	0.5057	1.8331	95.7254	0.4702	0.1322	0.0717	1.0558	+	0.0227	0.1104	0.0076	0.1005	0.0023	0.0477	100.0852
Illinois	0.5290	1.0916	11.7615	0.0851	48.5808	11.9133	0.3480	0.2075	0.0227	0.0258	0.0093	0.0867	0.0033	0.0013	74.6660
Indiana	0.2287	0.6166	18.5135	0.1298	43.0970	5.4902	1.1482	0.2075	0.4985	0.0268	0.0104	0.1623	0.0034	0.0013	70.1341
Iowa	2.3875	3.2558	33.7951	0.2167	200.2792	18.6204	1.8780	0.2075	0.2966	0.0775	0.0216	0.1063	0.0027	0.0046	261.1497
Kansas	4.7944	5.5176	31.1294	0.1653	30.6612	4.8948	0.0804	+	0.0227	0.0315	0.0126	0.1076	0.0032	0.0103	77.4308
Kentucky	0.0417	2.6069	5.1627	0.0722	3.2804	0.9555	0.7409	1.0980	0.0227	0.0273	0.0147	0.2522	0.0091	0.0040	14.2883
Louisiana	0.0107	1.6534	1.0919	0.0113	0.0273	0.0251	2.2941	0.2082	0.0228	0.0091	0.0071	0.1329	0.0072	0.0002	5.5013
Maine	0.0009	0.0396	3.3115	0.0249	0.0073	0.0042	0.1276	+	0.0227	0.0038	0.0014	0.0172	0.0003	0.0005	3.5620
Maryland	0.0208	0.1287	5.5858	0.0515	0.1167	0.0487	0.3567	1.0477	0.0227	0.0061	0.0036	0.0601	0.0014	0.0001	7.4505
Massachusetts	0.0004	0.0214	0.4993	0.0119	0.0185	0.0149	0.0156	+	0.0227	0.0038	0.0019	0.0294	0.0008	+	0.6408
Michigan	0.3026	0.4836	64.6288	0.2712	9.8014	2.1039	0.9662	0.2075	0.1321	0.0376	0.0074	0.1302	0.0029	0.0053	79.0809
Minnesota	0.7665	1.3319	49.1167	0.4691	61.8333	9.4514	0.3671	0.2139	1.0469	0.0611	0.0092	0.0941	0.0024	0.0053	124.7690
Mississippi	0.0171	1.7959	0.7059	0.0166	8.2978	1.7405	7.9230	2.7217	0.0228	0.0091	0.0119	0.1210	0.0093	0.0006	23.3933
Missouri	0.2271	5.0513	8.0111	0.0746	37.7611	13.1703	0.4748	1.0611	0.4736	0.0470	0.0179	0.1734	0.0082	0.0019	66.5535
Montana	0.0868	4.4934	1.4994	0.0135	0.9287	0.4212	0.7923	+	0.0227	0.1057	0.0038	0.1641	0.0027	0.0441	8.5784
Nebraska	5.0500	6.3788	11.3436	0.0403	34.2176	9.9592	0.5097	0.2075	0.0227	0.0376	0.0074	0.0995	0.0017	0.0537	67.9295
Nevada	0.0054	0.6449	6.2569	0.0168	0.0831	0.0072	0.0409	+	0.0227	0.0287	0.0029	0.0273	0.0004	+	7.1371
New Hampshire	0.0003	0.0164	1.3330	0.0100	0.0098	0.0035	0.1296	+	0.0227	0.0038	0.0010	0.0145	0.0003	0.0006	1.5457
New Jersey	0.0005	0.0223	0.6203	0.0065	0.0389	0.0099	0.1384	+	0.0227	0.0061	0.0028	0.0493	0.0010	0.0002	0.9189
New Mexico	0.0256	1.4761	38.7860	0.1710	0.0030	0.0052	1.1829	+	0.0227	0.0451	0.0089	0.0918	0.0018	0.0108	41.8308
New York	0.0419	0.4874	88.7044	0.5995	0.2457	0.0621	0.5555	0.2075	0.0227	0.0399	0.0073	0.1408	0.0023	0.0022	91.1191
North Carolina	0.0135	1.4156	5.6674	0.0557	135.4980	32.5530	12.2828	3.1731	0.8128	0.0190	0.0210	0.1582	0.0123	0.0007	191.6834
North Dakota	0.1015	2.4732	2.3584	0.0142	0.6622	0.5100	0.0758	+	0.0227	0.0329	0.0018	0.0575	0.0007	0.0234	6.3342

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	America n Bison	Total
Ohio	0.3124	0.8972	33.1522	0.1943	26.0507	3.9530	1.1444	0.3906	0.1670	0.0559	0.0153	0.2054	0.0058	0.0019	66.5461
Oklahoma	0.6109	5.8725	3.6459	0.0459	28.0251	16.0733	3.5639	0.7148	0.0228	0.0381	0.0368	0.3905	0.0184	0.0059	59.0647
Oregon	0.1866	1.6830	10.0832	0.1121	0.0436	0.0162	0.8844	0.2075	0.0227	0.0775	0.0119	0.1374	0.0030	0.0044	13.4738
Pennsylvania	0.2086	0.7237	48.2122	0.5453	10.8677	2.1249	0.8827	0.7244	0.1745	0.0451	0.0133	0.1797	0.0072	0.0024	64.7116
Rhode Island	0.0001	0.0041	0.0585	0.0009	0.0048	0.0021	0.1357	+	0.0227	0.0038	0.0002	0.0042	0.0001	+	0.2372
South Carolina	0.0043	0.6420	1.8258	0.0191	3.5344	0.3791	4.6319	0.8637	0.0228	0.0091	0.0154	0.1319	0.0068	0.0002	12.0865
South Dakota	0.7887	4.5816	20.7912	0.0718	13.2394	4.6553	0.1688	+	0.1059	0.1175	0.0045	0.1083	0.0015	0.0542	44.6887
Tennessee	0.0464	3.4364	4.0185	0.0633	3.0448	0.6947	0.2542	0.6440	0.0228	0.0324	0.0372	0.2793	0.0207	0.0010	12.5957
Texas	7.0735	19.5728	62.1310	0.5981	15.0207	4.3199	5.3891	2.3736	0.0228	0.5286	0.3110	1.0436	0.0958	0.0236	118.5042
Utah	0.0410	1.0540	9.0198	0.0833	3.6981	1.1829	4.1960	+	0.0227	0.1292	0.0051	0.1133	0.0013	0.0023	19.5489
Vermont	0.0014	0.0715	12.9275	0.0930	0.0071	0.0050	0.0159	+	0.0227	0.0038	0.0024	0.0173	0.0002	0.0003	13.1682
Virginia	0.0466	1.6723	8.5790	0.0669	5.2131	0.1696	0.3711	1.0096	0.4187	0.0352	0.0121	0.1343	0.0058	0.0013	17.7358
Washington	0.4326	0.8841	41.7824	0.2062	0.0663	0.0285	1.2698	0.2075	0.0227	0.0211	0.0075	0.1102	0.0024	0.0022	45.0435
West Virginia	0.0090	0.5323	0.5977	0.0070	0.0062	0.0038	0.1674	0.3016	0.0773	0.0164	0.0060	0.0501	0.0027	0.0002	1.7776
Wisconsin	0.5445	1.1872	135.7794	1.1262	2.0359	0.6093	0.4333	0.2020	0.0227	0.0352	0.0271	0.1515	0.0032	0.0115	142.1690
Wyoming	0.1405	2.1605	0.9219	0.0045	0.1464	0.3340	1.0308	+	0.0227	0.1621	0.0038	0.1147	0.0024	0.0216	5.0659

+ Does not exceed 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-198: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2018(kt)

	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine-Market	Swine-Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	America n Bison	Total
Alabama	0.0042	0.0087	0.0043	0.0037	0.0036	0.0012	0.0704	0.3611	0.0026	0.0049	0.0015	0.0053	0.0004	NA	0.4720
Alaska	+	0.0001	0.0002	0.0002	0.0001	+	0.0060	+	0.0026	0.0016	+	0.0002	+	NA	0.0110
Arizona	0.1962	0.4029	0.3704	0.2486	0.0123	0.0020	0.0065	+	0.0026	0.0138	0.0017	0.0085	0.0001	NA	1.2656
Arkansas	0.0088	0.0180	0.0034	0.0020	0.0051	0.0069	0.0889	0.3509	0.0913	0.0043	0.0011	0.0048	0.0003	NA	0.5858
California	0.3397	0.6979	2.4521	1.5939	0.0084	0.0010	0.0707	0.0184	0.0319	0.0710	0.0039	0.0103	0.0002	NA	5.2994
Colorado	0.7215	1.4810	0.2980	0.2305	0.0540	0.0230	0.0259	+	0.0026	0.0491	0.0015	0.0107	0.0002	NA	2.8981
Connecticut	0.0001	0.0003	0.0203	0.0119	0.0001	+	0.0057	+	0.0026	0.0031	0.0002	0.0011	+	NA	0.0455
Delaware	0.0001	0.0002	0.0051	0.0027	0.0002	0.0002	0.0057	0.0847	0.0026	0.0049	+	0.0004	+	NA	0.1070
Florida	0.0029	0.0058	0.0744	0.0515	0.0005	0.0002	0.0356	0.0210	0.0026	0.0049	0.0019	0.0095	0.0004	NA	0.2113
Georgia	0.0041	0.0083	0.0541	0.0304	0.0039	0.0024	0.1231	0.4375	0.0026	0.0049	0.0021	0.0054	0.0004	NA	0.6792

Hawaii	0.0007	0.0014	0.0030	0.0023	0.0003	0.0003	0.0060	+	0.0026	0.0016	0.0005	0.0005	+	NA	0.0193
Idaho	0.2054	0.4214	0.8671	0.7198	0.0017	0.0007	0.0065	+	0.0026	0.0259	0.0009	0.0052	0.0001	NA	2.2572
Illinois	0.1983	0.4069	0.0927	0.1068	0.4081	0.0736	0.0248	0.0184	0.0026	0.0180	0.0011	0.0045	0.0002	NA	1.3560
Indiana	0.0861	0.1769	0.1940	0.1490	0.3428	0.0322	0.1594	0.0184	0.0580	0.0187	0.0012	0.0084	0.0002	NA	1.2454
Iowa	0.9109	1.8716	0.2324	0.2658	1.9354	0.1326	0.2608	0.0184	0.0345	0.0541	0.0026	0.0055	0.0001	NA	5.7245
Kansas	1.7718	3.6370	0.1623	0.2164	0.1883	0.0222	0.0057	+	0.0026	0.0220	0.0015	0.0055	0.0002	NA	6.0356
Kentucky	0.0139	0.0285	0.0358	0.0237	0.0219	0.0047	0.0315	0.0975	0.0026	0.0221	0.0018	0.0130	0.0005	NA	0.2974
Louisiana	0.0022	0.0045	0.0067	0.0025	0.0002	0.0001	0.0117	0.0184	0.0026	0.0043	0.0006	0.0046	0.0003	NA	0.0587
Maine	0.0003	0.0007	0.0299	0.0178	0.0001	+	0.0057	+	0.0026	0.0031	0.0002	0.0009	+	NA	0.0614
Maryland	0.0070	0.0144	0.0449	0.0349	0.0010	0.0003	0.0149	0.0930	0.0026	0.0049	0.0004	0.0031	0.0001	NA	0.2216
Massachusetts	0.0001	0.0003	0.0099	0.0082	0.0002	0.0001	0.0007	+	0.0026	0.0031	0.0002	0.0015	+	NA	0.0269
Michigan	0.1165	0.2397	0.5359	0.3630	0.0964	0.0152	0.0708	0.0184	0.0154	0.0262	0.0009	0.0067	0.0002	NA	1.5053
Minnesota	0.2957	0.6076	0.4971	0.5853	0.6366	0.0716	0.0510	0.0190	0.1217	0.0426	0.0011	0.0049	0.0001	NA	2.9343
Mississippi	0.0036	0.0075	0.0053	0.0041	0.0471	0.0072	0.0407	0.2403	0.0026	0.0049	0.0010	0.0042	0.0003	NA	0.3689
Missouri	0.0836	0.1716	0.0702	0.0823	0.2425	0.0619	0.0661	0.0942	0.0551	0.0328	0.0021	0.0089	0.0004	NA	0.9719
Montana	0.0356	0.0732	0.0150	0.0197	0.0130	0.0043	0.0051	+	0.0026	0.0248	0.0004	0.0085	0.0001	NA	0.2022
Nebraska	1.9233	3.9501	0.0665	0.0532	0.2593	0.0555	0.0368	0.0184	0.0026	0.0262	0.0009	0.0051	0.0001	NA	6.3981
Nevada	0.0022	0.0044	0.0323	0.0256	0.0006	+	0.0057	+	0.0026	0.0067	0.0003	0.0014	+	NA	0.0819
New Hampshire	0.0001	0.0003	0.0132	0.0073	0.0001	+	0.0057	+	0.0026	0.0031	0.0001	0.0007	+	NA	0.0333
New Jersey	0.0002	0.0003	0.0057	0.0043	0.0003	0.0001	0.0057	+	0.0026	0.0049	0.0003	0.0025	0.0001	NA	0.0271
New Mexico	0.0100	0.0206	0.6190	0.2336	+	+	0.0065	+	0.0026	0.0106	0.0011	0.0047	0.0001	NA	0.9088
New York	0.0150	0.0306	0.6822	0.4204	0.0025	0.0005	0.0241	0.0184	0.0026	0.0324	0.0009	0.0073	0.0001	NA	1.2370
North Carolina	0.0032	0.0066	0.0299	0.0162	0.7439	0.1312	0.0870	0.2807	0.0942	0.0103	0.0017	0.0054	0.0004	NA	1.4107
North Dakota	0.0396	0.0814	0.0168	0.0176	0.0082	0.0046	0.0057	+	0.0026	0.0230	0.0002	0.0030	+	NA	0.2026
Ohio	0.1179	0.2423	0.2625	0.2227	0.2230	0.0249	0.1566	0.0347	0.0194	0.0451	0.0018	0.0106	0.0003	NA	1.3619
Oklahoma	0.2347	0.4813	0.0544	0.0440	0.1442	0.0606	0.0186	0.0632	0.0026	0.0177	0.0029	0.0134	0.0007	NA	1.1383
Oregon	0.0648	0.1330	0.1560	0.1226	0.0004	0.0001	0.0114	0.0184	0.0026	0.0205	0.0014	0.0071	0.0002	NA	0.5386
Pennsylvania	0.0725	0.1487	0.4649	0.3451	0.1041	0.0150	0.1227	0.0643	0.0203	0.0366	0.0016	0.0093	0.0004	NA	1.4055
Rhode Island	+	0.0001	0.0006	0.0005	+	+	0.0057	+	0.0026	0.0031	+	0.0002	+	NA	0.0130
South Carolina	0.0010	0.0020	0.0093	0.0052	0.0206	0.0016	0.0237	0.0764	0.0026	0.0049	0.0012	0.0045	0.0002	NA	0.1534
South Dakota	0.3036	0.6244	0.1247	0.0927	0.1259	0.0325	0.0124	+	0.0123	0.0820	0.0005	0.0056	0.0001	NA	1.4168
Tennessee	0.0112	0.0229	0.0256	0.0223	0.0184	0.0031	0.0105	0.0570	0.0026	0.0175	0.0030	0.0096	0.0007	NA	0.2043
Texas	1.8794	3.8593	0.8937	0.5633	0.0941	0.0199	0.1099	0.2100	0.0026	0.0827	0.0246	0.0359	0.0034	NA	7.7788
Utah	0.0166	0.0342	0.1593	0.1262	0.0450	0.0106	0.0239	+	0.0026	0.0303	0.0006	0.0058	0.0001	NA	0.4553
Vermont	0.0005	0.0010	0.1346	0.0674	0.0001	+	0.0007	+	0.0026	0.0031	0.0003	0.0009	+	NA	0.2112
Virginia	0.0159	0.0328	0.0571	0.0255	0.0317	0.0008	0.0154	0.0896	0.0487	0.0286	0.0014	0.0069	0.0003	NA	0.3549
Washington	0.1495	0.3070	0.3817	0.2364	0.0008	0.0003	0.0300	0.0184	0.0026	0.0056	0.0009	0.0057	0.0001	NA	1.1389
West Virginia	0.0031	0.0064	0.0062	0.0047	0.0001	+	0.0072	0.0268	0.0090	0.0133	0.0007	0.0026	0.0001	NA	0.0803

Wisconsin	0.2102	0.4316	1.4680	1.3704	0.0235	0.0052	0.0319	0.0179	0.0026	0.0246	0.0032	0.0078	0.0002	NA	3.5971
Wyoming	0.0571	0.1172	0.0065	0.0057	0.0027	0.0043	0.0065	+	0.0026	0.0380	0.0004	0.0059	0.0001	NA	0.2472

Note: American bison are maintained entirely on pasture, range, and paddock. Emissions from manure deposited on pasture are included in the Agricultural Soils Management sector.
+ Does not exceed 0.00005 kt.
NA (Not Applicable)

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3.12. Methodologies for Estimating Soil Organic C Stock Changes, Soil N_2O Emissions, and CH_4 Emissions and from Agricultural Lands (Cropland and Grassland)

This annex provides a detailed description of Tier 1, 2, and 3 methods that are used to estimate 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; indirect N_2O emissions associated with volatilization, leaching, and runoff of N from croplands and grasslands; and CH_4 emissions from rice cultivation.

Nitrous oxide (N_2O) is produced in soils through the microbial processes of nitrification and denitrification.[95] 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; Paustian et al. 2016). 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 (Paustian et al. 1997, Paustian et al. 2016). CH_4 emissions from rice cultivation occur under flooded conditions through the process of methanogenesis, and is influenced by water management practices, organic amendments and cultivar choice (Sanchis et al. 2014). This annex provides the underlying methodologies for these three emission sources because there is considerable overlap in the methods with the majority of emissions estimated using the DayCent ecosystem simulation model.

A combination of Tier 1, 2, and 3 approaches are used to estimate soil C stock changes, direct and indirect soil N_2O emissions and CH_4 emissions from rice cultivation in agricultural croplands and grasslands. The methodologies used to estimate soil organic C stock changes include:

1) A Tier 3 method using the DayCent ecosystem simulation model to estimate soil organic C stock changes in mineral soils on non-federal lands that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, 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) 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), are used to produce crops or have land use changes to cropland and grassland (other than the conversions between cropland and grassland that are not simulated with DayCent;
3) Tier 2 methods with country-specific stock change factors for estimating mineral soil organic C stock changes on federal lands;
4) Tier 2 methods with country-specific emission factors for estimating losses of C from organic soils that are drained for agricultural production; and
5) Tier 2 methods for estimating additional changes in mineral soil C stocks due to biosolids (i.e., treated sewage sludge) additions to soils.

The methodologies used to estimate soil N_2O emissions include:

1) A Tier 3 method using the DayCent ecosystem 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, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco 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);

[95] 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) A combination of the Tier 1 and 3 methods to estimate indirect N_2O emissions associated with management of cropland and grassland simulated with DayCent;
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; Pasture/Range/Paddock (PRP) manure N deposited on federal grasslands, and land application of biosolids (i.e., treated sewage sludge) to soils; 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 CH_4 emissions from rice cultivation include:

1) A Tier 3 method using the DayCent ecosystem simulation model to estimate CH_4 emissions from mineral soils that have less than 35 percent coarse fragments by volume and rice grown continuously or in rotation with crops that are simulated with DayCent, including alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat; and
2) A Tier 1 method to estimate CH_4 emissions from all other soils used to produce rice that are not estimated with the Tier 3 method, including rice grown on organic soils (i.e., *Histosols*), mineral soils with very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume), and rice grown in rotation with crops that are not simulated by DayCent.

As described above, the Inventory uses a Tier 3 approach to estimate C stock changes, direct soil N_2O emissions, and CH_4 emissions from rice cultivation for most 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;
4) The legacy effects of past management can be addressed with the Tier 3 approach such as land use change from decades prior to the inventory time period that can have ongoing effects on soil organic C stocks, and the ongoing effects of N fertilization that may continue to stimulate N_2O emissions in years after the application; and
5) Soil N_2O and CH_4 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.

More information is provided about the model structure and evaluation of the Tier 3 method at the end of this Annex (See section titled Tier 3 Method Description and Model Evaluation).

Splicing methods are used to fill gaps at the end of the time series for these emission sources and are not described in this annex. The splicing methods are applied when there are gaps in the activity data at the end of the time series and the Tier 1, 2 and 3 methods cannot be applied. The splicing methods are described in the main chapters, particularly Box 6-6 in the *Cropland Remaining Cropland* section and Box 5-5 in the Agricultural Soil Management section.

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; indirect N_2O emissions from volatilization, leaching, and runoff from croplands and grasslands; and CH_4

emissions from rice cultivation. First, the activity data are compiled 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, and CH_4 emissions are estimated using Tier 1, 2 and 3 methods. In the fifth step, total emissions are calculated by summing all components for soil organic C stock changes, N_2O emissions and CH_4 emissions. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

This step describes how the activity data are derived to estimate soil organic C stock changes, direct and indirect N_2O emissions, and CH_4 emissions from rice cultivation. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates and timing,[96] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) cover crop management, (7) planting and harvesting dates for crops, (8) irrigation data, (9) Enhanced Vegetation Index (EVI), (10) daily weather data, and (1) edaphic characteristics.[97]

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

The U.S. Department of Agriculture's 2015 National Resources Inventory (NRI) (USDA-NRCS 2018a) 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.*[98] In 1998, the NRI program began collecting annual data, and data are currently available through 2015 (USDA-NRCS 2018a). The time series will be extended as new data are released by the USDA NRI program.

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 locations are selected according to a restricted randomization procedure. Each sample location 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 survey location. The NRI uses a sampling approach, and therefore there is some uncertainty associated with scaling the survey location data to a region or the country using the expansion factors. In general, those uncertainties decline at larger scales because of a larger sample size, such as states compared to smaller county units. An extensive amount of soils, land-use, and land management data have been collected through the survey (Nusser et al. 1998).[99] Primary sources for data include aerial photography as well as field visits and county office records.

The NRI survey provides crop data for most years between 1979 and 2015, 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 survey 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 survey locations are included in the land base for the agricultural soil C and N2O emissions inventories if they are identified as cropland or grassland[100] between 1990 and 2015 (See Section 6.1 Representation of the U.S. Land Base for more information about areas in each land use and land use change category).[101] NRI survey locations on federal lands are not sampled by the USDA NRI program. The land use at the survey locations in federal lands is determined from the

[96] 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, such as application of enhanced efficiency fertilizers.

[97] Edaphic characteristics include such factors as soil texture and pH.

[98] Note that the Inventory does not include estimates of 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.

[99] In the current Inventory, NRI data only provide land use and management statistics through 2015. More recent data will be incorporated in the future to extend the time series of activity data.

[100] 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).

[101] Land use for 2016 to 2018 is not compiled, but will be updated with a new release of the NRI data (i.e., USDA-NRCS 2015).

National Land Cover Dataset (NLCD) (Yang et al. 2018), and included in the agricultural land base if the land uses are cropland and/or grassland. The NRI data are harmonized with the Forest Inventory and Analysis Dataset, and in this process, the land use and land use change data are modified to account for differences in *Forest Land Remaining Forest Land*, *Land Converted to Forest Land* and Forest Land converted to other land uses between the two national surveys (See Section 6.1 for more information on the U.S. land representation). Through this process, 524,991 survey locations in this NRI are designated as agricultural land in the conterminous United States and Hawaii.

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 crop management in a specific year are classified as *Cropland Remaining Cropland* if the parcel has been used as cropland for at least 20 years.[102] 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 *2006 IPCC Guidelines*. Lands converted into Cropland and Grassland are further subdivided into the specific land use conversions (e.g., *Forest Land Converted to Cropland)*.

The Tier 3 method using the DayCent model is applied to estimate soil C stock changes, CH_4 and N_2O emissions for 349,464 NRI survey locations that occur on mineral soils. The actual crop and grassland histories are simulated with the DayCent model when applying the Tier 3 methods. 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[103] and CH_4 emissions from rice cultivation (Table A-199).

The land base for the Tier 1 and 2 methods includes 175,527 survey locations, and is comprised of (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest or settlements 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 and perennial/horticultural crops, 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., lettuce), 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-199: Total Cropland and Grassland Area Estimated with Tier 1/2 and 3 Inventory Approaches (Million Hectares)

	Land Areas (million ha)				
	Mineral			Organic	
Year	**Tier 1/2**	**Tier 3**	**Total**	**Tier 1/2**	**Total[104]**
1990	152.22	307.63	459.85	1.39	**461.24**
1991	151.49	307.89	459.37	1.38	**460.75**
1992	150.83	308.07	458.90	1.38	**460.28**
1993	149.84	308.47	458.31	1.38	**459.69**
1994	149.04	308.87	457.91	1.38	**459.29**
1995	147.92	309.28	457.20	1.37	**458.57**
1996	146.90	309.75	456.65	1.36	**458.01**

[102] NRI points are classified according to land-use history records starting in 1979 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 1998.

[103] 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 the Tier 1 method is only dependent on the amount of N input to mineral soils and not the actual land area.

[104] The current Inventory includes estimation of greenhouse gas emissions and removals from all privately-owned and federal grasslands and croplands in the conterminous United States and Hawaii, but does not include the croplands and grasslands in Alaska. This leads to a discrepancy between the total area in this table, which is included in the estimation, compared to the total managed land area in Section 6.1 Representation of the U.S. Land Base. See Planned Improvement sections in *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland* for more information about filling these gaps in the future so that emissions and removals will be estimated for all managed land.

1997	145.69	310.19	455.88	1.35	**457.23**
1998	144.67	310.63	455.31	1.35	**456.65**
1999	143.71	311.10	454.81	1.35	**456.16**
2000	142.98	311.38	454.36	1.35	**455.71**
2001	142.49	311.82	454.31	1.34	**455.66**
2002	141.78	312.09	453.87	1.35	**455.22**
2003	141.15	312.00	453.16	1.32	**454.48**
2004	140.65	311.92	452.57	1.34	**453.90**
2005	140.12	311.81	451.93	1.34	**453.27**
2006	139.57	311.77	451.34	1.33	**452.68**
2007	139.04	311.74	450.78	1.32	**452.10**
2008	138.71	311.60	450.31	1.32	**451.63**
2009	138.36	311.54	449.89	1.32	**451.21**
2010	138.05	311.43	449.48	1.32	**450.80**
2011	137.65	311.41	449.06	1.32	**450.38**
2012	137.28	311.33	448.61	1.32	**449.93**
2013	137.28	311.33	448.61	1.32	**449.93**
2014	137.28	311.33	448.61	1.32	**449.93**
2015	137.28	311.33	448.61	1.32	**449.93**

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series of the land use data.

NRI survey locations on mineral soils are classified into specific crop categories, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis for soil C (Table A-200). NRI locations are assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). For croplands on federal lands, information on specific crop systems is not available, so all croplands are assumed to be medium input. In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and interseeding of legumes. Grasslands on federal lands (as identified with the NLCD) are classified according to rangeland condition (nominal, moderately degraded and severely degraded) in areas where information is available. For lands managed for livestock grazing by the Bureau of Land Management (BLM), IPCC rangeland condition classes are interpreted at the state-level from the Rangeland Inventory, *Monitoring and Evaluation Report* (BLM 2014). In order to estimate uncertainties, probability distribution functions (PDFs) for the NRI land-use data are based on replicate weights that allow for proper variance estimates that correctly account for the complex sampling design. In particular, the variance estimates and resulting PDFs correctly account for spatial or temporal dependencies. For example, 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 an area of some land use/management categories increase, the area of other land use/management categories will decline.

Table A-200: Total Land Areas by Land-Use and Management System for the Tier 2 Mineral Soil Organic C Approach (Million Hectares)

	Land Areas (million hectares)												
Land-Use/Management System	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Cropland Systems	**33.47**	**33.18**	**32.87**	**32.36**	**31.86**	**31.39**	**30.96**	**30.49**	**29.69**	**29.17**	**28.78**	**28.44**	**28.13**
Conservation Reserve Program	2.74	3.15	3.08	2.91	2.67	2.59	2.46	2.45	1.96	2.12	1.86	1.99	1.73
High Input Cropping Systems, Full Tillage	2.41	2.21	2.20	2.11	2.28	2.26	2.10	1.99	1.94	1.93	1.97	1.78	1.58
High Input Cropping Systems, Reduced Tillage	0.57	0.50	0.50	0.50	0.54	0.52	0.50	0.48	0.49	0.49	0.50	0.49	0.45
High Input Cropping Systems, No Tillage	0.41	0.37	0.37	0.37	0.38	0.36	0.45	0.43	0.44	0.45	0.45	0.52	0.51

High Input Cropping Systems with Manure, Full Tillage	0.67	0.64	0.61	0.59	0.55	0.52	0.51	0.49	0.47	0.43	0.40	0.34	0.32
High Input Cropping Systems with Manure, Reduced Tillage	0.18	0.17	0.16	0.16	0.16	0.15	0.14	0.14	0.13	0.13	0.12	0.12	0.11
High Input Cropping Systems with Manure, No Tillage	0.22	0.20	0.19	0.19	0.19	0.18	0.17	0.16	0.15	0.15	0.14	0.17	0.17
Medium Input Cropping Systems, Full Tillage	7.03	7.02	6.78	6.57	6.49	6.26	6.32	5.97	5.65	5.47	5.54	4.29	4.03
Medium Input Cropping Systems, Reduced Tillage	1.71	1.66	1.62	1.58	1.58	1.53	1.53	1.49	1.40	1.37	1.42	1.68	1.69
Medium Input Cropping Systems, No Tillage	1.85	1.71	1.68	1.63	1.62	1.60	1.58	1.52	1.45	1.41	1.44	2.33	2.35
Low Input Cropping Systems, Full Tillage	9.46	9.31	9.31	9.34	9.30	9.40	9.14	9.17	9.30	9.13	9.08	8.21	8.25
Low Input Cropping Systems, Reduced Tillage	1.06	1.04	1.04	1.05	1.05	1.07	1.08	1.07	1.11	1.05	1.04	1.11	1.11
Low Input Cropping Systems, No Tillage	0.68	0.73	0.73	0.74	0.73	0.72	0.90	0.90	0.92	0.86	0.89	1.53	1.52
Hay with Legumes or Irrigation	1.67	1.67	1.69	1.64	1.50	1.44	1.35	1.38	1.31	1.25	1.14	1.04	1.20
Hay with Legumes or Irrigation and Manure	0.50	0.49	0.50	0.51	0.48	0.45	0.43	0.47	0.46	0.44	0.41	0.42	0.54
Hay, Unimproved	0.01	0.01	0.02	0.02	0.02	0.02	0.00	0.01	0.07	0.05	0.01	0.03	0.04
Pasture with Legumes or Irrigation in Rotation	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.04	0.03	0.01	0.02	0.02
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rice	0.04	0.05	0.04	0.04	0.05	0.06	0.05	0.05	0.05	0.05	0.06	0.07	0.08
Perennials	2.24	2.24	2.31	2.36	2.28	2.25	2.24	2.32	2.38	2.37	2.31	2.28	2.42
Grassland Systems	**118.68**	**118.22**	**117.88**	**117.40**	**117.11**	**116.46**	**115.87**	**115.14**	**114.93**	**114.47**	**114.13**	**113.98**	**113.57**
Pasture with Legumes or Irrigation	3.62	3.47	3.28	3.25	3.27	3.14	2.83	2.41	2.51	2.46	2.26	2.17	2.08
Pasture with Legumes or Irrigation and Manure	0.17	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.12	0.11	0.11
Rangelands and Unimproved Pasture	82.27	81.87	81.82	81.68	81.42	80.82	79.85	79.64	78.94	78.42	78.83	78.54	79.53
Rangelands and Unimproved Pasture, Moderately Degraded	23.62	23.78	23.91	23.79	23.84	23.95	24.43	24.30	25.08	25.11	24.46	24.70	23.63
Rangelands and Unimproved Pasture, Severely Degraded	9.01	8.93	8.72	8.53	8.43	8.41	8.60	8.65	8.25	8.34	8.46	8.46	8.22
Total	**152.15**	**151.40**	**150.75**	**149.76**	**148.97**	**147.85**	**146.83**	**145.63**	**144.61**	**143.64**	**142.91**	**142.42**	**141.70**

Land-Use/Management System	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Systems	**27.88**	**27.55**	**27.39**	**27.16**	**26.99**	**26.83**	**26.62**	**26.51**	**26.33**	**26.29**	**26.24**	**26.16**	**25.96**
Conservation Reserve Program	1.60	1.50	1.52	1.42	1.38	1.30	1.35	1.26	1.89	0.92	1.43	0.90	0.73
High Input Cropping Systems, Full Tillage	1.59	1.59	1.60	1.37	1.34	1.37	1.42	1.44	1.30	1.24	1.18	1.14	1.06
High Input Cropping Systems, Reduced Tillage	0.47	0.47	0.47	0.49	0.49	0.52	0.53	0.53	0.57	0.55	0.52	0.52	0.50
High Input Cropping Systems, No Tillage	0.48	0.50	0.50	0.59	0.61	0.63	0.65	0.63	0.72	0.73	0.71	0.71	0.67
High Input Cropping Systems with Manure, Full Tillage	0.30	0.29	0.29	0.24	0.26	0.27	0.26	0.27	0.25	0.26	0.28	0.27	0.26
High Input Cropping Systems with Manure, Reduced Tillage	0.11	0.11	0.11	0.13	0.14	0.13	0.14	0.14	0.17	0.18	0.19	0.18	0.18
High Input Cropping Systems with Manure, No Tillage	0.18	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20
Medium Input Cropping Systems, Full Tillage	3.98	3.99	3.82	3.50	3.58	3.55	3.49	3.49	3.16	3.39	3.19	3.41	3.26
Medium Input Cropping Systems, Reduced Tillage	1.72	1.75	1.71	1.83	1.85	1.85	1.78	1.78	1.87	2.04	1.93	2.10	2.07
Medium Input Cropping Systems, No Tillage	2.41	2.40	2.39	2.53	2.57	2.58	2.49	2.49	2.39	2.77	2.49	2.83	2.79
Low Input Cropping Systems, Full Tillage	8.26	8.11	8.13	7.93	7.83	7.78	7.75	7.72	7.46	7.54	7.52	7.46	7.60
Low Input Cropping Systems, Reduced Tillage	1.06	1.01	1.01	1.08	1.02	1.00	1.00	1.01	1.00	1.04	1.04	0.97	1.01
Low Input Cropping Systems, No Tillage	1.45	1.36	1.38	1.67	1.59	1.56	1.54	1.55	1.39	1.45	1.45	1.34	1.42
Hay with Legumes or Irrigation	1.18	1.16	1.18	1.16	1.14	1.11	1.06	1.02	0.98	0.99	1.02	1.02	1.02
Hay with Legumes or Irrigation and Manure	0.52	0.54	0.50	0.49	0.48	0.47	0.46	0.45	0.43	0.43	0.47	0.47	0.48
Hay, Unimproved	0.04	0.05	0.04	0.02	0.03	0.01	0.02	0.02	0.03	0.02	0.01	0.00	0.00
Pasture with Legumes or Irrigation in Rotation	0.03	0.03	0.03	0.01	0.02	0.02	0.03	0.02	0.01	0.01	0.01	0.00	0.00
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rice	0.06	0.06	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03
Perennials	2.43	2.46	2.49	2.46	2.44	2.46	2.44	2.47	2.50	2.53	2.55	2.59	2.65
Grassland Systems	**113.20**	**113.04**	**112.67**	**112.34**	**111.96**	**111.80**	**111.65**	**111.45**	**111.22**	**110.90**	**110.66**	**110.50**	**110.29**
Pasture with Legumes or Irrigation	2.01	2.05	1.97	1.91	1.86	1.84	1.85	1.80	1.79	1.71	1.61	1.64	1.59

Pasture with Legumes or Irrigation and Manure	0.11	0.11	0.11	0.10	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07
Rangelands and Unimproved Pasture	79.60	78.73	78.47	78.36	78.00	77.90	77.74	77.75	77.73	77.46	77.40	77.04	77.37
Rangelands and Unimproved Pasture, Moderately Degraded	23.19	23.22	23.25	23.15	23.25	23.24	23.25	23.17	23.06	22.89	22.80	22.61	22.51
Rangelands and Unimproved Pasture, Severely Degraded	8.28	8.93	8.87	8.82	8.76	8.74	8.71	8.65	8.57	8.77	8.79	9.14	8.74
Total	**141.08**	**140.59**	**140.05**	**139.50**	**138.95**	**138.63**	**138.27**	**137.96**	**137.55**	**137.19**	**136.90**	**136.66**	**136.25**

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series for the land use and management data.

Organic soils are categorized into land-use systems based on drainage (IPCC 2006) (Table A-201). 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.

Table A-201: 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)	0.59	0.58	0.59	0.59	0.59	0.59	0.59	0.60	0.60	0.60	0.59	0.59	0.59	0.59
Managed Pasture (low drainage)	0.34	0.34	0.35	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35
Undrained	0.04	0.05	0.04	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.02
Total	**0.97**	**0.97**	**0.98**	**0.98**	**0.98**	**0.98**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.96**	**0.96**
	Warm Temperate													
Cultivated Cropland (high drainage)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.16
Managed Pasture (low drainage)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Undrained	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00
Total	**0.25**	**0.25**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.25**	**0.25**	**0.25**	**0.25**
	Sub-Tropical													
Cultivated Cropland (high drainage)	0.24	0.24	0.24	0.25	0.25	0.25	0.26	0.26	0.26	0.17	0.17	0.29	0.28	0.28
Managed Pasture (low drainage)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.11	0.10	0.10	0.09
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.00	0.01	0.00
Total	**0.37**	**0.37**	**0.37**	**0.37**	**0.37**	**0.38**	**0.38**	**0.38**	**0.38**	**0.38**	**0.38**	**0.39**	**0.39**	**0.37**

IPCC Land-Use Category for Organic Soils	Land Areas (million ha)											
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
	Cold Temperate											
Cultivated Cropland (high drainage)	0.59	0.59	0.59	0.59	0.59	0.58	0.58	0.58	0.59	0.60	0.60	0.60
Managed Pasture (low drainage)	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38

Undrained	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01
Total	**0.98**	**0.98**	**0.98**	**0.98**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**1.00**
Warm Temperate												
Cultivated Cropland (high drainage)	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Managed Pasture (low drainage)	0.09	0.10	0.09	0.10	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10
Undrained	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.27**	**0.27**	**0.27**	**0.28**	**0.28**	**0.28**
Sub-Tropical												
Cultivated Cropland (high drainage)	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.24	0.26	0.25
Managed Pasture (low drainage)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Undrained	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.03	0.01	0.01
Total	**0.37**	**0.37**	**0.37**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.35**	**0.36**	**0.35**

Note: In the current Inventory, NRI data only provide land use and management statistics through 2012. Additional data will be incorporated in the future to extend the time series for the land use and management data.

The harvested area for rice cultivation is estimated from the NRI based on survey locations classified as flooded rice (Table A-202). Ratoon crops occur in the Southeast with a second season of rice during the year. Ratoon cropping also occurs in Louisiana (LSU 2015 for years 2000 through 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crops (45 percent), but ratoon cropping is uncommon in Arkansas occurring on relatively small fraction of fields estimated at about 1 percent. No data are available on ratoon crops in Missouri or Mississippi, and so the amount of ratooning is assumed similar to Arkansas. Ratoon rice crops are not grown in California.

Table A-202: Total Rice Harvested Area Estimated with Tier 1 and 3 Inventory Approaches (Million Hectares)

	Land Areas (Million Hectares)		
Year	**Tier 1**	**Tier 3**	**Total**
1990	0.21	1.50	1.71
1991	0.21	1.54	1.74
1992	0.22	1.65	1.87
1993	0.22	1.58	1.80
1994	0.23	1.51	1.74
1995	0.21	1.53	1.74
1996	0.22	1.52	1.74
1997	0.20	1.47	1.67
1998	0.25	1.46	1.70
1999	0.38	1.43	1.81
2000	0.42	1.48	1.90
2001	0.24	1.39	1.63
2002	0.23	1.57	1.80
2003	0.21	1.42	1.63
2004	0.21	1.50	1.71
2005	0.21	1.58	1.79
2006	0.17	1.27	1.44
2007	0.18	1.38	1.56
2008	0.15	1.28	1.44
2009	0.21	1.52	1.73
2010	0.20	1.57	1.77
2011	0.17	1.24	1.41
2012	0.22	1.18	1.40

2013	0.16	1.26	1.42
2014	0.24	1.39	1.63
2015	0.17	1.45	1.62

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015.
Additional data will be incorporated in the future to extend the time series of the land use and management data.

Step 1b: Obtain Management Activity Data to estimate Soil C Stock Changes, N_2O and CH_4 Emissions from Mineral Soils

The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. Respondents provide detailed information about management practices at the NRI survey locations, such as time of planting and harvest; amount, type and time of fertilization; implement type and timing of soil cultivation events; and type and timing of cover crop planting and termination practices.

These data are combined with other datasets in an imputation analysis that extends the time series from 1980 to 2015. The imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994); and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method that is adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. The final imputation product includes six complete imputations of the management activity data in order to adequately capture the uncertainty in management activity. The sections below provide additional information for each of the management practices.

Synthetic and Manure N Fertilizer Applications: Data on synthetic mineral N fertilizer rates are imputed based on crop-specific fertilizer rates in the USDA-NRCS CEAP product and USDA–Economic Research Service (ERS) data. The ERS crop management data had been collected as part of Cropping Practices Surveys through 1995 (USDA-ERS 1997), and are now compiled as part of Agricultural Resource Management Surveys (ARMS) starting in 1996 (USDA-ERS 2018).[105] In these surveys, data on inorganic N fertilization rates are collected for crops in the high production states and for a subset of low production states. Additional data on fertilization practices are compiled from other sources, particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). These data are used to build a time series of mineral fertilizer application rates for specific crops and states for 1980 to 2015, to the extent that data are available. These data are then used to inform the imputation product in combination with the USDA CEAP survey, as described previously. The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both mineral and manure amendment rates. This approach captures the relationship between mineral fertilization and manure amendment practices for US croplands based directly on the observed patterns in the CEAP survey data.

Fertilizer sales data are used to check and adjust synthetic mineral fertilizer amounts that are simulated with DayCent. The total amount of synthetic fertilizer used on-farms (cropland and grazing land application) has been estimated by the USGS from 1990 through 2012 on a county scale from fertilizer sales data (Brakebill and Gronberg 2017). For 2013 through 2015, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales

[105] Available online: <http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/arms-data.aspx>.

(AAPFCO 2013 through 2017).[106] The resulting data are used to check the simulated synthetic fertilizer inputs in the DayCent simulations at the state scale. Specifically, the simulated amounts of mineral fertilizer application for each state and year are compared to the sales data. If the simulated amounts exceed the sales data in a year, then the simulated N_2O emissions are reduced based on the amount of simulated fertilizer that exceeded the sales data relative to the total application of fertilizer in the DayCent simulations for the state. See Step 2A for the approach that is used to disaggregate N_2O emissions from DayCent into the sources of N inputs (e.g., mineral fertilizer inputs). For example, if the simulated amount exceeded the sales data by 3 percent, then the emissions associated with synthetic mineral fertilization is reduced by 3 percent (the same adjustments are also made for leaching and volatilization losses of N that are used to estimate indirect N_2O emissions). This method ensures that the simulated amount of mineral fertilization using bottom-up data from the ARMS and CEAP surveys are adjusted so that they do not exceed the sales data. The bottom-up data from CEAP and ARMS will be further investigated in the future to evaluate the discrepancies with the sales data, and potentially improve these datasets to attain greater consistency.

Similar to synthetic mineral fertilization in DayCent, total amount of manure available for application to soils is used to check and adjust the simulated amounts of manure application to soils in the DayCent simulations. The available manure is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10), and it is assumed that all available manure is applied to soils in cropland and grazing lands. If the amount of manure amendments in DayCent simulations exceeded the available manure for application to soils, the amount of N_2O emissions is reduced based on the amount of over-application in the simulations. For example, if the simulated amount exceeded the available amount by 2 percent, then the emissions associated with manure N inputs are reduced by 2 percent (the same adjustments is also made for leaching and volatilization losses of N that are used to estimate indirect N_2O emissions). This method ensures that the simulated amount of manure amendments using bottom-up data from the CEAP survey are adjusted so that they do not exceed the amount of manure available for application to soils. The bottom-up data from CEAP will be further investigated in the future to evaluate the discrepancies with the manure availability data, and potentially improve these datasets to attain greater consistency.

The resulting amounts of synthetic and manure fertilizer application data are found in Table A-203.

Simulations are also conducted for the time period prior to 1980 in order to initialize the DayCent model (see Step 2a), and crop-specific regional fertilizer rates prior to 1980 are based largely on extrapolation/interpolation of mineral fertilizer and manure amendment 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 fertilization rates (e.g., no data are available for the State of Alabama during the 1970s for corn fertilization rates; therefore, mean values from the southeastern United States are used to simulate fertilization to corn fields in this state).

PRP Manure N: Another key source of N for grasslands is PRP manure N (i.e., manure deposited by grazing livestock on pasture, range or paddock). The total amount of PRP manure N is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10). Nitrogen from PRP animal waste deposited on non-federal grasslands in a county is 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 are 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-203.

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, which are not harvested or burned (the DayCent

[106] The fertilizer consumption data in AAPFCO 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).

simulations assumed that 3 percent of non-harvested above ground residues for crops are burned),[107] are provided in Table A-203.

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 the IPCC (2006). The simulated N input from residues, soil organic matter mineralization and asymbiotic N fixation are provided in Table A-203.

Tillage Practices: Tillage practices are grouped into three 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 practices are estimated for each cropping system based on data from the Conservation Technology Information Center for 1980 through 2004 (CTIC 2004), USDA-NRCS CEAP survey for 2000 through 2005 (USDA-NRCS 2018b), and USDA ARMS surveys for 2002 through 2015 (Claasen et al. 2018). CTIC compiles data on cropland area under tillage management classes by major crop species and year for each county. The CTIC and ARMS surveys involve aggregate area, and therefore 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. These estimates include a relatively high proportion of "intermittent" no-till, where no-till in one year may be followed by tillage in a subsequent year, leading to no-till practices that 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 data are further processed to impute a tillage management system for each NRI survey location over the time series from 1980 to 2015. First, we impute a tillage management system for every NRI survey location in the "base block" of 2001-2005 by forming imputation classes consisting of all NRI survey locations within the same CEAP region, crop group, and soil texture class. Within one imputation class, NRI locations with missing tillage systems are assigned the tillage system of a randomly-selected CEAP donor. Once the base block is imputed, tillage systems for remaining five-year time blocks are imputed forward and backward in time using trending information obtained from CTIC and ARMS, described above. The trending information from one time block to the next is reflected in the imputations by first constructing the 3x3 transition probability matrix, **M**, between the two blocks. Let **a** denote the vector of proportions in the current time block (already imputed) and let **b** denote the vector of desired proportions---from the trending information---in the target time block (to be imputed). The rows of **M** correspond to the tillage type (no-till, reduced till, or conventional till) in the target time block and the columns of **M** correspond to the tillage type in the current time block. The elements of **M** are constrained so that (a) each column is a probability distribution (all elements between 0 and 1 and column sums to 1); (b) **Ma**=**b**; and (c) the diagonal elements of **M** are as large as possible. (The last constraint implies as much temporal continuity as possible at a location, subject to overall trends.) The solution for **M** is obtained by a mathematical optimization technique known as linear programming. Once **M** is obtained, it is used for imputing the tillage system as follows: determine the column that corresponds to the tillage system (imputed or real) of the current block, and use the probabilities in that column to randomly select the tillage system for the target block. Repeat the construction of **M** and the imputation block by block forward in time and backward in time.

Cover Crops: Cover crop data are based on USDA CEAP data (USDA-NRCS 2018b) and information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover cropping was minimal prior to 1990 and the rates increased over the decade to the levels of cover crop management derived from the CEAP survey. Cover crops in the "base block" of 2001-2005 are determined from the imputation for planting date (cover crops are assigned based on recipients with donor that had a cover crop in the USDA CEAP survey). Going back in time, for 1996-2000 we

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

randomly remove cover crop from locations so that remaining cover crop area is about one-half of the 2001-2005 cover crop area. For 1991-1995, we randomly remove half the remaining area. For 1990 and before, we remove all cover crops. Going forward in time, for the blocks 2006-2010, 2011-2015, and 2016-2020, we add (or possibly delete, if cover crops declined in a region) cover crops at random, to respect trending information from USDA Census of Agriculture (USDA-NASS 2012, 2017).

Irrigation: NRI (USDA-NRCS 2018a) 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 water is applied to the level of field capacity with intervals between irrigation events occurring each time that soils drain to 60 percent of field capacity.

Daily Weather Data: Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the PRISM Climate Group (2018). It is necessary to use computer-generated weather data because weather station data do not exist near all NRI points. The PRISM product uses this information with interpolation algorithms to derive weather patterns for areas between these stations (Daly et al. 1998). PRISM weather data are available for the United States from 1981 through 2015 at a 4 km resolution. Each NRI survey location is assigned the PRISM weather data for the grid cell containing the survey location.

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.[108]

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 survey location. 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 do not meet a 90 percent purity level for any crop are eliminated from the dataset. CDL does not provide full coverage for crop maps across 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 survey location based on a 10 km buffer surrounding the survey location. EVI data are not assigned to a survey location if there are no pixels with at least 90 percent purity within the 10 km buffer. In these cases, production is simulated with a single value for the maximum daily NPP, which is reduced if there is water, temperature or nutrient stress affecting plant growth.

Water Management for Rice Cultivation: Rice crop production in the United States is mostly managed with continuous flooding, but does include a minor amount of land with mid-season drainage or alternate wet-dry periods (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). However, continuous flooding is applied to all rice cultivation areas in the inventory because water management data are not available. Winter flooding is another key practice associated with water management in rice fields. Winter flooding occurs on 34 percent of rice fields in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of winter flooding is assumed to be relatively constant over the Inventory time period.

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

Organic Amendments for Rice Cultivation: Rice straw is not typically harvested from fields in the United States. The C input from rice straw is simulated directly within the DayCent model for the Tier 3 method. For the Tier 1 method, residues are assumed to be left on the field for more than 30 days prior to cultivation and flooding for the next crop, with the exception of ratoon crops, which are assumed to have residues on the field for less than 30 days prior to the second crop in the season. To estimate the amount of rice straw, crop yield data (except rice in Florida) are compiled from USDA NASS QuickStats (USDA 2015). Rice yield data are not collected by USDA for the state of Florida, and so are derived based on NRI crop areas and average primary and ratoon rice yields from Deren (2002). Relative proportions of ratoon crops are derived from information in several publications (Schueneman 1997, 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004, 2006; Cantens 2004, 2005; Gonzalez 2007 through 2014). The yields are multiplied by residue: crop product ratios from Strehler and Stützle (1987), to estimate rice straw input amounts for the Tier 1 method.

Soil Properties: Soil texture and drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as inputs 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.[109] Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from being fully aerobic to completely anaerobic, varying over the year. Decomposition rates are modified according to a linear function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in DayCent).[110] 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 2019). The data are based on field measurements collected as part of soil survey and mapping. Each NRI survey location 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 synthetic fertilizer used on-farms has been estimated using USGS and AAPFCO datasets, as discussed in Step 1b (Brakebill and Gronberg 2017; AAPFCO 2013 through 2017). 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 that is used on farms after subtracting the amount applied to crops and non-federal grasslands simulated by DayCent. The differences are aggregated to the national 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-203.

Managed Livestock Manure and Other Organic Fertilizers: Managed 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. The total amount of manure available for application to soils has been estimated with methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10). Managed manure N applied to croplands for the Tier 1 method is calculated using a process of elimination approach. Specifically, the amount of managed manure N that is amended to soils in the DayCent model simulations is subtracted from total managed manure N available for application to soils. The difference is assumed to be applied to croplands that are not included in the DayCent model simulations. The fate of manure available for application to soils is summarized in Table A-203.

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

[110] Hydric soils are primarily subject to anaerobic conditions outside the plant growing season, such as late winter or early spring prior to planting. Soils that are flooded during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the DayCent model.

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 2017).[111] Commercial organic fertilizers include dried blood, tankage, compost, and other organic materials, which are recorded in mass units of fertilizer, and 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). Dried manure and biosolids (i.e., treated sewage sludge) that are used as commercial fertilizer are subtracted from totals to avoid double counting because dried manure is counted with the manure available for application to soils, and biosolids are assumed to be applied to grasslands. 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-203.

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 3.10. PRP N deposited on federal grasslands is calculated using a process of elimination approach. Specifically, the amount of PRP N generated by DayCent model simulations of non-federal grasslands is subtracted from total PRP N. This difference was assumed to be deposited on federal grasslands. The total PRP manure N added to soils is found in Table A-203.

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment works and are typically used as a soil amendment, or are sent to waste disposal facilities, such as landfills. In this Inventory, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands. Estimates of the amounts of biosolids N applied to agricultural lands are derived from national data on biosolids generation, disposition, and N content. Total biosolids generation data for 1990 through 2004, in dry mass units, are obtained from AAPFCO (1995 through 2004). Values for 2005 through 2018 are not available so a "least squares line" statistical extrapolation using the previous 16 years of data to impute 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 disposal methods. The resulting estimates of biosolids N applied to agricultural land are used to estimate N_2O emissions from agricultural soil management; the estimates of biosolids 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). Biosolids disposal data are provided in Table A-203.

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-NASS 2019). Total production for each crop is converted to tons of dry matter product using the residue dry matter fractions. 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 is 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 residue N inputs are presented in Table A-203.

Table A-203: Sources of Soil Nitrogen (kt N)

N Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1. Synthetic Fertilizer N: Cropland	9,892	10,285	10,274	10,110	11,126	10,300	10,871	10,852	10,815	10,970
2. Synthetic Fertilizer N: Grassland	13	12	24	56	42	12	10	19	78	19
3. Managed Manure N: Cropland	2,463	2,495	2,505	2,491	2,553	2,587	2,578	2,605	2,635	2,644

[111] Similar to the data for synthetic fertilizers described above, the organic 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).

4. Managed Manure N: Grassland	-	1	1	2	1	-	-	2	1	1
5. Pasture, Range, & Paddock Manure N	4,097	4,104	4,265	4,354	4,427	4,529	4,495	4,384	4,331	4,259
6. N from Crop Residue Decomposition[a]	6,875	7,091	6,693	7,047	6,789	7,255	6,977	6,842	6,881	7,739
7. N from Grass Residue Decomposition[a]	12,374	12,298	12,623	12,757	12,217	12,937	12,551	12,644	11,960	13,366
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	11,344	10,931	10,686	12,089	10,722	11,596	11,000	11,219	12,605	11,296
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	16,445	17,261	17,389	17,205	16,020	17,028	16,820	17,824	17,363	16,807
10. Treated Sewage Sludge N: Grassland	52	55	58	62	65	68	72	75	78	81
11. Other Organic Amendments: Cropland[c]	4	8	6	5	8	10	13	14	12	11
Total	**63,559**	**64,541**	**64,524**	**66,178**	**63,970**	**66,321**	**65,385**	**66,479**	**66,758**	**67,193**

N Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1. Synthetic Fertilizer N: Cropland	10,792	10,105	10,542	10,602	11,324	10,723	10,454	11,493	10,932	10,215
2. Synthetic Fertilizer N: Grassland	24	30	27	24	44	18	19	15	22	18
3. Managed Manure N: Cropland	2,685	2,679	2,720	2,737	2,660	2,703	2,786	2,815	2,792	2,777
4. Managed Manure N: Grassland	1	2	-	1	-	1	1	-	1	-
5. Pasture, Range, & Paddock Manure N	4,155	4,142	4,140	4,138	4,087	4,131	4,175	4,059	4,015	3,975
6. N from Crop Residue Decomposition[a]	7,428	7,336	7,262	7,504	7,171	7,337	7,375	7,141	7,255	7,442
7. N from Grass Residue Decomposition[a]	12,532	12,936	12,677	13,040	12,243	13,092	12,689	13,178	13,034	12,571
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	11,414	11,821	11,284	11,433	12,839	11,494	11,346	11,961	12,054	12,484
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	15,687	16,599	16,475	16,991	19,099	17,701	16,934	18,549	17,474	18,120
10. Treated Sewage Sludge N: Grassland	84	86	89	91	94	98	101	104	107	110
11. Other Organic Amendments: Cropland[c]	9	7	8	8	9	10	12	15	12	10
Total	**64,810**	**65,744**	**65,223**	**66,569**	**69,570**	**67,307**	**65,892**	**69,330**	**67,699**	**67,721**

N Source	2010	2011	2012	2013	2014	2015	2016	2017	2018
1. Synthetic Fertilizer N: Cropland	10,784	11,261	11,906	11,905	11,706	11,480	11,306	11,234	11,454
2. Synthetic Fertilizer N: Grassland	11	12	13	11	12	14	13	13	13
3. Managed Manure N: Cropland	2,771	2,802	2,836	2,820	2,822	2,870	2,876	2,856	2,858
4. Managed Manure N: Grassland	-	1	1	1	-	-	-	-	-
5. Pasture, Range, & Paddock Manure N	3,920	3,815	3,720	3,676	3,627	3,683	3,558	3,530	3,569
6. N from Crop Residue Decomposition[a]	7,887	7,676	7,448	7,359	7,621	7,231	7,004	6,989	7,176
7. N from Grass Residue Decomposition[a]	12,910	12,499	13,091	12,107	12,211	11,769	11,092	10,991	11,120
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	13,366	11,272	10,216	12,694	13,536	14,311	13,705	13,737	14,168
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	18,527	16,127	15,341	18,472	18,501	19,041	17,947	17,785	17,994
10. Treated Sewage Sludge N: Grassland	113	116	119	122	124	127	130	133	136
11. Other Organic Amendments: Cropland[c]	10	12	13	13	11	12	13	12	11
Total	**70,299**	**65,592**	**64,704**	**69,179**	**70,171**	**70,538**	**67,643**	**67,279**	**68,498**

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

NE (Not Estimated)

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

[b] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[c] Includes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

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

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment facilities and are typically used as a soil amendment or is sent for waste disposal to landfills. In this Inventory, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands. See section on biosolids in Step 1c for more information about the methods used to derive biosolid N estimates. The total amount of biosolid N is given in Table A-203. Biosolid 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. In this Inventory, all biosolids are applied to grasslands so these rates may not be fully representative of amendments of a biosolids, but there are no data available on N amendments that are specific to grasslands (Future Inventories will incorporate new information when it is available). This capacity varies from year to year, because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total biosolid N available for application is divided by the assimilative capacity to estimate the total land area over which biosolids had been applied. The resulting estimates are used for the estimation of soil C stock change.

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.

Step 1e: Additional Activity Data for Indirect N_2O Emissions

A portion of the N that is applied as synthetic fertilizer, livestock manure, biosolids (i.e., treated sewage sludge), and other organic amendments volatilizes as NH_3 and NO_x. In turn, the volatilized N is eventually 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 regions in the Western United States, 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, biosolids 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-203.

Using the DayCent model, volatilization and leaching/surface run-off of N from soils is estimated in the simulations 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[112], which are addressed in the Tier 1 methodology. Similarly, the N available for producing indirect emissions resulting from grassland management as well as PRP manure is also estimated by DayCent. However, indirect emissions are not estimated for leaching and runoff of N if precipitation plus irrigation does 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. Uncertainty in the estimates is derived from the measure of variability in the fertilizer and organic amendment activity data (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, biosolids applications, and PRP manure on federal grasslands, which are not simulated by DayCent. To estimate volatilized N losses, the amount of synthetic fertilizers, manure, biosolids, 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

[112] The amount of volatilization and leaching are reduced if the simulated amount of synthetic mineral fertilization in DayCent exceeds the amount mineral fertilizer sales, or the simulated amount of manure application in DayCent exceeds the manure available for applications to soils. See subsection on Synthetic and Manure N Fertilizer Applications in Step 1b for more information.

N are estimated by summing the N additions from synthetic and other organic fertilizers, manure, biosolids, 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, consistent with the Tier 3 method. 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 GHG Emissions and Stocks Changes for Mineral Soils: Soil Organic C Stock Changes, Direct N_2O Emissions, and CH_4 Emissions from Rice Cultivation

In this step, soil organic C stock changes, N_2O emissions, and CH_4 emissions from rice cultivation are estimated for cropland and non-federal grasslands. Three methods are used to estimate soil organic C stock changes, direct N_2O emissions from mineral soils, and CH_4 emissions from rice cultivation. 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 types, grasslands (i.e., federal grasslands) and soil types that are 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, PRP manure N deposition on federal grasslands, and CH_4 emissions from rice cultivation.

Step 2a: Estimate Soil Organic C Stock Changes, Soil N_2O Emissions, and CH_4 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, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, which combined represent approximately 85 percent of total cropland in the United States. The DayCent simulations also include all non-federal grasslands in the United States.

The methodology description is divided into two sub-steps. First, the DayCent model is used to establish the initial conditions and C stocks for 1979, which is the first year of the NRI survey. In the second sub-step, DayCent is used to simulate changes in soil organic C stocks, direct soil N_2O emissions, leaching and volatilization losses of N contributing to indirect N_2O emissions, and CH_4 emissions from rice cultivation based on the land-use and management histories recorded in the NRI (USDA-NRCS 2018a).

Simulate Initial Conditions (Pre-NRI Conditions): The purpose of the DayCent model initialization is to estimate 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 subdivided by the pools 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 PRISM product (1981 through 2010), and the soil characteristics for the NRI survey locations. 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 2015. The simulations address the influence of soil management on direct soil 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 PRISM 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, cover crop usage, and EVI data (See Step 1b for description of the inputs). There are six DayCent simulations for each NRI survey location based on the imputation product in order to capture the uncertainty in the management activity data derived by combining data from CEAP, ARMS, Census of Agriculture and CTIC surveys. See Step 1b for more information. The simulation system incorporates a dedicated MySQL database server and a parallel processing computer cluster. Input/output operations are managed by a set of run executive programs.

Evaluating uncertainty is an integral part of the analysis and includes three components: (1) uncertainty in the management activity data inputs (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 the first component, the uncertainty is based on the six imputations underlying the data product combining CEAP, ARMS, Census of Agriculture and CTIC survey data. See Step 1b for discussion about the imputation product. 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 72 long-term experiment sites and 142 NRI soil monitoring network sites (Spencer et al. 2011), with 948 observations across all of the sites that represent a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, and manure amendments). There are 41 experimental sites available with over 200 treatment observations to evaluate structural uncertainty in the N_2O emission predictions from DayCent (Del Grosso et al. 2010). There are 17 long-term experiments with data on CH_4 emissions from rice cultivation, representing 238 combinations of management treatments. 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). However, additional uncertainty is introduced with the measurements from the NRI soil monitoring network because the management data are represented by the six imputations. Therefore, we statistically analyzed the results and quantified uncertainty for each imputation separately for soil organic C.

The empirical relationship between field measurements and modeled soil organic C stocks, soil N_2O emissions and CH_4 emissions are statistically analyzed using linear-mixed effect modeling techniques. The modeled stocks and emissions are treated as a fixed effect in the statistical model. The resulting relationship is used to make an adjustment to modeled values if there are biases due to significant mismatches between the modeled and measured values. Several other variables are tested in these models including soil characteristics, geographic location (i.e., state), and management practices (e.g., tillage practices, fertilizer rates, rice production with and without winter flooding). Random effects are included in all of these models 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. See Section, Tier 3 Method Description and Model Evaluation, for more information about model evaluation, including graphs illustrating the relationships between modeled and measured values.

The third element is the uncertainty associated with scaling the DayCent results for each NRI survey location to the entire land base, using the expansion factors and replicate weights provided with the NRI dataset. The expansion factors represent the number of hectares associated with the land-use and management history for a particular survey point. The scaling uncertainty is due to the complex sampling design that selects the locations for NRI, and this uncertainty is properly reflected in the replicate weights for the expansion factor. Briefly, each set of replicate weights is used to compute one weighted estimate. The empirical variation across the weighted estimates from all replicates is an estimate of the theoretical scaling uncertainty due to the complex sampling design.

A Monte Carlo approach is used to propagate uncertainty from the three components through the analysis with 1000 iterations for each NRI survey location. In each iteration, there is a random selection of management activity data from the imputation product; a random draw of parameter values for the uncertainty estimator (Ogle et al. 2010); and a random draw of a set of replicate weights to scale the emissions and stock changes from the individual NRI survey locations to the entire domain of the inventory analysis. Note that parameter values for the statistical equation (i.e., fixed effects) are selected from their joint probability distribution, as well as random error associated with the time series and data collected from the same site, and the residual/unexplained error. The randomly selected parameter value for soil organic C, N_2O and CH_4 emissions and associated management information is then used as input into the linear mixed-effect model, and adjusted values are computed for each C stock change, N_2O and CH_4 emissions estimate. After completing the Monte Carlo stochastic simulation, the median of the final distribution from the 1000 replicates is used as the estimate of total emissions or soil C stock changes, and a 95 percent confidence interval is based on 2.5 and 97.5 percentile values.

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. For example, if 70 percent of the mineral N made available in the soil is due to synthetic mineral fertilization, then 70 percent of the N_2O emissions are assigned to this practice.

A portion 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. Mineralization of soil organic matter is significant source of N, but is typically less than half of the amount of N made available in 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. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Accounting for the influence of “other N inputs” is necessary because the processes leading to these inputs of N are influenced by management.

This attribution of N_2O emissions to the individual N inputs to the soils is need for reporting emissions in a manner consistent with UNFCCC reporting guidelines. However, 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. 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.

For the land base that is simulated with the DayCent model, direct soil N_2O emissions are provided Table A-207 and Table A-208, soil organic C stock changes are provided in Table A-209, and rice cultivation CH_4 emissions in Table A-211.

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).[113] Uncertainties in the emission factor and fertilizer additions are combined with uncertainty in the equations used to

[113] 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 biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

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 biosolids (i.e., treated 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. 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).

The results for direct soil N_2O emissions using the Tier 1 method are provided in Table A-207 and Table A-208.

Step 2c: Soil CH_4 Emissions from Agricultural Lands Approximated with the Tier 1 Approach

To estimate CH_4 emissions from rice cultivation for the Tier 1 method, an adjusted daily emission factor is calculated using the default baseline emission factor of 1.30 kg CH_4 ha^{-1} d^{-1} (ranging 0.8-2.2 kg CH_4 ha^{-1} d^{-1}) multiplied by a scaling factor for the cultivation water regime, pre-cultivation water regime and a scaling factor for organic amendments (IPCC 2006). The water regime during cultivation is continuously flooded for rice production in the United States and so the scaling factor is always 1 (ranging from 0.79 to 1.26). The pre-season water regime varies based on the proportion of land with winter flooding; land that does not have winter flooding is assigned a value of 0.68 (ranging from 0.58 to 0.80) and areas with winter flooding are assigned a value of 1 (ranging from 0.88 to 1.14). Organic amendments are estimated based on the amount of rice straw and multiplied by 1 (ranging 0.97 to 1.04) for straw incorporated greater than 30 days before cultivation, and by 0.29 (0.2 to 0.4) for straw incorporated greater than 30 days before cultivation. The adjusted daily emission factor is multiplied by the cultivation period and harvested area to estimate the total CH_4 emissions. The uncertainty is propagated through the calculation using an Approach 2 method with a Monte Carlo analysis (IPCC 2006), combining uncertainties associated with the adjusted daily emission factor and the harvested areas derived from the USDA NRI survey data.

The results for rice CH_4 emissions using the Tier 1 method are provided in Table A-211.

Step 2d: 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 from 1990 through 2015, 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 quantity in the inventory calculations has uncertainty that is quantified in PDFs, including the land use and management activity data based on the six imputations in the data product combining CEAP, ARMS, Census of Agriculture, and CTIC data (See Step 1b for more information); reference C stocks and stock change factors; and the replicated weights form the NRI survey. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on random selection of values from each of these sources of uncertainty. Input values are randomly selected from PDFs in an iterative process to estimate SOC change for 1,000 times.

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). Seven of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001). Climate zones are classified using mean annual precipitation and temperature (1950-2000) data from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008; Zomer et al. 2007).

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-204). 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-204: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

		Reference Carbon Stock in Climate Regions					
IPCC Inventory Soil Categories	**USDA Taxonomic Soil Orders**	**Cold Temperate, Dry**	**Cold Temperate, Moist**	**Warm Temperate, Dry**	**Warm Temperate, Moist**	**Sub-Tropical, Dry**	**Sub-Tropical, Moist**
High Clay Activity Mineral Soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols	42 (n = 133)	65 (n = 526)	37 (n = 203)	51 (n = 424)	42 (n = 26)	57 (n = 12)
Low Clay Activity Mineral Soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (n = 37)	52 (n = 113)	25 (n = 86)	40 (n = 300)	39 (n = 13)	47 (n = 7)
Sandy Soils	Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols)	24 (n = 5)	40 (n = 43)	16 (n = 19)	30 (n = 102)	33 (n = 186)	50 (n = 18)
Volcanic Soils	Andisols	124 (n = 12)	114 (n = 2)	124 (n = 12)	124 (n = 12)	124 (n = 12)	128 (n = 9)
Spodic Soils	Spodosols	86 (n=20)	74 (n = 13)	86 (n=20)	107 (n = 7)	86 (n=20)	86 (n=20)
Aquic Soils	Soils with Aquic suborder	86 (n = 4)	89 (n = 161)	48 (n = 26)	51 (n = 300)	63 (n = 503)	48 (n = 12)
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 stock change factors for land use, management and input, 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 models, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, climate, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data 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-205). 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.[114] 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

[114] Improved grasslands are identified in the NRI as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

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.

Table A-205: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

		U.S. Factor			
	IPCC default	Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Change Factors					
Cultivated[a]	1	1	1	1	1
General Uncult[a,b] (n=251)	1.4	1.42±0.06	1.37±0.05	1.24±0.06	1.20±0.06
Set-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

[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.
Note: The "n" values refer to sample size.

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-206). 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 standard deviation are used to construct a PDF with a normal density (Table A-206).

Table A-206: Rate and standard deviation 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.[115] For this analysis, stocks are estimated for each year and difference between years is the stock change. From the final distribution of 1,000 values, the median is used as the estimate of soil organic C stock change and a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution.

Soil organic C stock changes using the Tier 2 method are provided in Table A-209 and Table A-211.

Step 2e: Estimate Additional Changes in Soil Organic C Stocks Due to Biosolids (i.e., Treated Sewage Sludge) Amendments

There are two additional land use and management activities occurring on mineral soils of U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves the application of biosolids to agricultural lands. Minimal data exist on where and how much biosolids are applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving biosolids can be approximated based on biosolids N production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). In this Inventory, it is assumed that biosolids for agricultural land application to soils is only used as an amendment in grassland. 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, by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions are that the reference C stock is 50 metric tonnes C/ha, which represents a mid-range value of reference C stocks for the cropland soils in the United States,[116] 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 × 1.4 × 1.11 – 50 × 1.4] / 20 = 0.38). A ±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 biosolids amendments.

The influence of biosolids (i.e., treated sewage sludge) on soil organic C stocks is provided in Table A-211.

Table A-207: Direct Soil N_2O Emissions from Mineral Soils in Cropland (MMT CO_2 Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Mineral Soil Emission	**182.1**	**173.5**	**169.7**	**187.5**	**182.1**	**179.9**	**187.6**	**178.8**	**176.5**	**178.6**
Tier 3 Cropland	165.0	157.4	152.7	170.7	163.8	161.5	168.9	160.2	158.5	160.6
Inorganic N Fertilizer Application	58.5	57.4	57.1	59.2	63.2	56.7	63.3	59.7	56.8	58.7
Managed Manure Additions	5.2	5.1	5.0	5.2	5.1	4.7	5.2	4.8	4.5	4.6
Crop Residue N	34.2	33.9	31.2	35.4	33.1	35.0	35.3	32.7	30.8	36.4
Min. SOM / Asymbiotic N-Fixation[a]	67.1	61.0	59.4	70.8	62.4	65.1	65.1	62.9	66.4	61.0
Tier 1 Cropland	17.1	16.1	16.9	16.8	18.3	18.4	18.7	18.7	18.0	18.0
Inorganic N Fertilizer Application	4.6	3.9	4.3	4.6	5.3	5.4	5.9	5.7	4.8	4.8
Managed Manure Additions	7.4	7.4	7.5	7.5	7.9	8.2	7.9	8.2	8.3	8.4
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Crop Residue N	5.1	4.8	5.1	4.7	5.1	4.7	4.8	4.8	4.9	4.7
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.013	0.012	0.012	0.013	0.012	0.012	0.013	0.012	0.011	0.012

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Mineral Soil Emission	**173.3**	**182.7**	**183.0**	**184.1**	**183.8**	**180.3**	**175.8**	**181.7**	**179.6**	**181.0**
Tier 3 Cropland	155.2	164.6	164.1	164.3	163.2	160.9	156.4	162.1	159.9	163.2
Inorganic N Fertilizer Application	56.8	57.2	59.2	58.2	57.5	58.0	55.8	60.6	57.2	55.5
Managed Manure Additions	4.5	4.5	4.7	4.5	4.4	4.5	4.5	4.6	4.5	4.7
Crop Residue N	33.8	36.0	36.0	37.0	32.8	35.1	34.7	33.0	33.6	35.1
Min. SOM / Asymbiotic N-Fixation[a]	60.1	66.9	64.2	64.6	68.5	63.3	61.3	63.9	64.6	67.9
Tier 1 Cropland	18.1	18.1	18.9	19.9	20.7	19.4	19.5	19.6	19.6	17.8
Inorganic N Fertilizer Application	4.7	4.7	5.6	6.2	7.2	5.9	5.8	5.8	5.8	4.2

[115] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.
[116] Reference C stocks are based on cropland soils for the Tier 2 method applied in this Inventory.

Managed Manure Additions	8.6	8.8	8.9	9.1	8.6	8.9	9.1	9.1	9.2	9.0
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
Crop Residue N	4.7	4.5	4.3	4.5	4.8	4.6	4.5	4.6	4.6	4.6
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.011	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Cropland Mineral Soil Emission	**182.8**	**180.9**	**173.3**	**194.4**	**204.2**	**196.8**	**188.2**	**187.9**	**192.6**
Tier 3 Cropland	163.4	161.3	154.5	174.1	184.1	171.8	164.5	164.9	170.1
Inorganic N Fertilizer Application	54.8	58.8	61.1	62.9	64.2	54.7	52.4	52.5	54.1
Managed Manure Additions	4.5	5.0	5.0	5.3	5.2	4.0	3.8	3.8	3.9
Crop Residue N	35.5	36.6	34.5	35.5	37.7	34.3	32.8	32.9	33.9
Min. SOM / Asymbiotic N-Fixation[a]	68.7	61.0	53.9	70.5	77.1	78.9	75.5	75.7	78.1
Tier 1 Cropland	19.3	19.6	18.8	20.3	20.0	25.0	23.6	23.0	22.5
Inorganic N Fertilizer Application	5.8	6.4	5.6	7.0	6.3	10.1	8.5	8.0	7.7
Managed Manure Additions	8.9	8.8	8.9	8.7	9.0	10.1	10.2	10.1	10.0
Other Organic Amendments[b]	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Crop Residue N	4.6	4.3	4.3	4.5	4.7	4.7	4.9	4.8	4.8
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.011	0.012	0.011	0.012	0.012	0.012	NE	NE	NE

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.
NE – Not Estimated
[a] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.
[b] Includes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.
[c] The Annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied; The Implied Emission Factor is not calculated for 2016 – 2018 due to lack of activity data for most sources.

Table A-208: Direct Soil N_2O Emissions from Mineral Soils in Grassland (MMT CO_2 Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Mineral Soil Emission	**84.1**	**84.2**	**83.3**	**84.5**	**80.5**	**83.4**	**85.5**	**86.2**	**87.2**	**81.8**
Tier 3 Grassland	77.1	77.4	76.3	77.6	73.6	76.7	79.1	80.2	81.2	76.2
Inorganic N Fertilizer Application	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition[a]	7.8	7.7	7.8	8.2	8.5	8.5	8.9	8.4	8.9	8.0
Grass Residue N	29.7	29.0	28.8	29.5	28.1	29.5	30.0	29.8	29.4	30.2
Min. SOM / Asymbiotic N-Fixation[b]	39.5	40.7	39.6	39.8	36.9	38.8	40.1	41.9	42.7	37.9
Tier 1 Grassland	7.0	6.8	7.0	6.9	6.9	6.7	6.5	6.1	6.0	5.7
Pasture, Range, & Paddock N Deposition	6.8	6.5	6.7	6.6	6.6	6.4	6.1	5.7	5.6	5.3
Treated Sewage Sludge Additions	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Implied Emission Factor for Grassland[c] (kt N_2O-N/kt N)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.005

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Mineral Soil Emission	**76.5**	**82.6**	**83.2**	**82.7**	**91.0**	**85.7**	**84.1**	**86.2**	**83.6**	**87.2**
Tier 3 Grassland	71.0	77.4	78.1	77.7	86.0	80.8	79.4	81.8	79.2	83.0
Inorganic N Fertilizer Application	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition[a]	7.9	8.4	8.6	8.3	8.6	8.3	8.5	8.2	8.1	8.5
Grass Residue N	28.0	30.2	30.2	30.1	30.2	30.8	30.3	30.6	30.3	30.5
Min. SOM / Asymbiotic N-Fixation[b]	35.0	38.7	39.3	39.2	47.1	41.7	40.5	43.0	40.7	43.9
Tier 1 Grassland	5.5	5.3	5.1	5.0	4.9	4.9	4.8	4.4	4.4	4.3
Pasture, Range, & Paddock N Deposition	5.1	4.9	4.7	4.5	4.5	4.4	4.3	4.0	3.9	3.8

Treated Sewage Sludge Additions	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Implied Emission Factor for Grassland[c] (kt N_2O-N/kt N)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005

Land Use Change Category	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Total Grassland Mineral Soil Emission	**89.4**	**79.8**	**75.1**	**90.9**	**92.1**	**91.8**	**86.9**	**86.2**	**87.2**
Tier 3 Grassland	85.2	75.7	71.1	87.0	88.2	88.0	83.1	82.4	83.3
Inorganic N Fertilizer Application	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition[a]	8.4	8.0	7.3	8.1	8.2	8.4	8.1	8.0	8.1
Grass Residue N	31.5	29.6	29.4	31.2	31.8	30.4	28.6	28.4	28.7
Min. SOM / Asymbiotic N-Fixation[b]	45.2	38.1	34.4	47.6	48.2	49.2	46.3	45.9	46.5
Tier 1 Grassland	4.3	4.1	4.0	4.0	3.9	3.8	3.8	3.8	3.9
Pasture, Range, & Paddock N Deposition	3.7	3.6	3.5	3.4	3.3	3.2	3.2	3.2	3.2
Treated Sewage Sludge Additions	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Implied Emission Factor for Grassland[c] (kt N_2O-N/kt N)	0.005	0.005	0.005	0.006	0.006	0.006	NE	NE	NE

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.
NE – Not Estimated
[a]For the years 1997-2018 there are differences in the PRP manure N data used in Agricultural Soil Management and Manure Management. EPA is assessing this issue and will update in subsequent Inventory reports.
[b] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.
[c] The annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied; The Implied Emission Factor is not calculated for 2016 – 2018 due to lack of activity data for most sources.

Table A-209: Annual Change in Soil Organic Carbon Stocks in Croplands (MMT CO_2 Eq./yr)

Land Use Change Category	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Total Cropland SOC Stock Change	**-55.8**	**-60.3**	**-56.4**	**-43.4**	**-51.0**	**-39.6**	**-55.9**	**-44.5**	**-38.6**	**-40.9**
Cropland Remaining Cropland (CRC)	-58.2	-63.3	-60.0	-45.8	-53.5	-46.1	-61.4	-53.1	-43.5	-46.0
Tier 2	-0.6	-1.5	-1.6	-1.4	-0.4	-0.6	-0.5	-1.8	-0.7	-1.9
Tier 3	-57.6	-61.7	-58.4	-44.4	-53.1	-45.5	-60.8	-51.3	-42.9	-44.1
Grassland Converted to Cropland (GCC)	4.1	4.9	5.8	4.7	4.8	8.9	8.0	11.3	7.6	7.9
Tier 2	3.9	4.2	4.0	4.0	4.3	4.7	5.0	5.0	5.1	5.0
Tier 3	0.2	0.7	1.8	0.7	0.6	4.2	2.9	6.3	2.5	2.9
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-2.3	-2.4	-2.5	-2.7	-2.9	-2.9	-3.0	-3.1	-3.1	-3.2
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Land Use Change Category	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Total Cropland SOC Stock Change	**-47.0**	**-56.6**	**-63.6**	**-55.8**	**-58.6**	**-61.1**	**-58.3**	**-61.3**	**-52.7**	**-43.0**
Cropland Remaining Cropland (CRC)	-51.6	-60.7	-65.4	-57.8	-59.9	-62.4	-58.5	-61.8	-55.4	-46.2
Tier 2	-0.9	-3.9	-5.6	-5.1	-4.9	-5.0	-4.5	-4.9	-4.7	-5.1
Tier 3	-50.7	-56.8	-59.8	-52.7	-55.0	-57.4	-53.9	-56.9	-50.7	-41.1
Grassland Converted to Cropland (GCC)	7.8	7.4	4.9	4.8	4.0	4.0	2.8	2.9	5.0	5.3
Tier 2	5.2	5.2	5.0	4.6	4.8	4.8	4.7	4.7	4.5	4.5
Tier 3	2.6	2.2	-0.1	0.2	-0.7	-0.8	-1.9	-1.8	0.4	0.8
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-3.6	-3.6	-3.4	-3.2	-3.1	-2.9	-2.9	-2.7	-2.5	-2.4
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Cropland SOC Stock Change	**-46.5**	**-62.7**	**-56.2**	**-43.5**	**-40.3**	**-39.9**	**-51.0**	**-51.7**	**-46.3**
Cropland Remaining Cropland (CRC)	-51.0	-64.1	-58.7	-46.6	-44.7	-44.9	-54.3	-55.1	-49.4
Tier 2	-4.6	-5.2	-3.6	-5.6	-5.5	-6.2	-5.7	-5.4	-5.9
Tier 3	-46.4	-58.9	-55.1	-41.0	-39.2	-38.8	-48.6	-49.6	-43.5
Grassland Converted to Cropland (GCC)	6.7	3.7	4.5	5.2	6.2	6.9	5.2	5.4	5.1
Tier 2	4.5	4.6	4.7	4.4	4.3	4.2	4.2	4.3	4.3
Tier 3	2.2	-0.9	-0.1	0.8	1.9	2.7	1.0	1.1	0.9
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-2.4	-2.4	-2.3	-2.3	-2.0	-2.0	-2.1	-2.2	-2.2
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2

Table A-210: Annual Change in Soil Organic Carbon Stocks in Grasslands (MMT CO_2 Eq./yr)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland SOC Stock Change	**-25.6**	**-25.4**	**-23.5**	**-23.9**	**-42.7**	**-37.0**	**-41.7**	**-39.4**	**-52.0**	**-52.0**
Grassland Remaining Grassland (GRG)	-2.2	-2.1	-0.5	2.3	-10.7	-2.5	-3.5	0.5	-5.5	-1.3
Tier 2	-0.2	-0.5	-1.1	-1.4	-1.5	-1.4	-0.7	-0.7	-1.5	-1.3
Tier 3	-1.4	-0.9	1.3	4.4	-8.5	-0.4	-2.0	2.1	-3.1	0.9
Treated Sewage Sludge Additions	-0.6	-0.6	-0.7	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9	-0.9
Cropland Converted to Grassland (CCG)	-18.9	-18.7	-18.3	-18.5	-19.8	-19.8	-20.5	-20.1	-24.0	-24.7
Tier 2	-4.0	-3.9	-3.9	-4.3	-4.9	-4.8	-4.8	-4.8	-5.6	-5.9
Tier 3	-15.0	-14.8	-14.4	-14.2	-15.0	-14.9	-15.7	-15.3	-18.3	-18.8
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-4.2	-4.3	-4.5	-7.2	-11.4	-14.0	-16.7	-18.8	-21.4	-24.7
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.2	-0.2	-0.2	-0.3	-0.5	-0.7	-0.8	-0.9	-1.0	-1.2
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland SOC Stock Change	**-69.9**	**-61.9**	**-63.7**	**-64.8**	**-58.7**	**-57.4**	**-71.2**	**-55.9**	**-59.9**	**-58.6**
Grassland Remaining Grassland (GRG)	-13.9	-2.5	-4.0	-5.7	0.0	0.8	-12.0	2.2	-5.0	-3.9
Tier 2	-1.4	-1.5	-2.6	-2.6	-0.9	-1.1	-1.3	-1.4	-1.4	-1.6
Tier 3	-11.5	0.0	-0.4	-2.0	1.9	3.0	-9.6	4.8	-2.3	-1.0
Treated Sewage Sludge Additions	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1	-1.2	-1.2	-1.2	-1.3
Cropland Converted to Grassland (CCG)	-26.4	-26.4	-26.8	-26.1	-25.7	-25.0	-26.0	-24.9	-21.7	-21.5
Tier 2	-6.1	-6.3	-6.2	-5.9	-5.8	-5.6	-5.4	-5.2	-5.0	-4.7
Tier 3	-20.3	-20.2	-20.6	-20.1	-19.9	-19.4	-20.6	-19.8	-16.7	-16.8
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-28.3	-31.4	-31.4	-31.6	-31.5	-31.7	-31.6	-31.7	-31.7	-31.8
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-1.3	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Grassland SOC Stock Change	**-43.0**	**-45.0**	**-58.1**	**-41.8**	**-32.5**	**-36.8**	**-42.3**	**-41.1**	**-40.4**
Grassland Remaining Grassland (GRG)	10.6	7.9	-6.3	6.4	10.0	4.0	0.1	1.5	1.8
Tier 2	-1.6	-1.5	-0.6	-0.2	1.1	0.1	-0.8	-0.9	-0.9
Tier 3	13.5	10.8	-4.3	8.0	10.3	5.4	2.3	2.5	2.9
Treated Sewage Sludge Additions	-1.3	-1.3	-1.4	-1.4	-1.4	-1.5	-1.5	-0.2	-0.2
Cropland Converted to Grassland (CCG)	-20.3	-19.4	-18.3	-17.5	-15.9	-16.9	-19.1	-19.4	-19.3
Tier 2	-4.6	-4.6	-4.5	-4.1	-3.5	-3.4	-3.5	-3.6	-3.7
Tier 3	-15.7	-14.8	-13.8	-13.3	-12.4	-13.4	-15.6	-15.8	-15.6
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-31.8	-32.1	-32.0	-29.5	-25.6	-22.9	-22.3	-22.2	-21.9
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-1.4	-1.4	-1.4	-1.3	-1.1	-1.0	-0.9	-1.0	-0.9
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-211: Methane Emissions from Rice Cultivation (MMT CO_2 Eq.)

Approach	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Rice Methane Emission	**16.0**	**16.1**	**16.1**	**17.1**	**15.7**	**16.5**	**16.7**	**15.4**	**17.1**	**17.7**
Tier 1	2.2	2.3	2.4	2.4	2.5	2.3	2.4	2.3	2.7	4.2
Tier 3	13.8	13.9	13.8	14.7	13.2	14.2	14.3	13.1	14.4	13.5

Approach	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Rice Methane Emission	**19.0**	**15.4**	**17.7**	**14.7**	**15.6**	**18.0**	**14.7**	**15.9**	**14.1**	**16.2**
Tier 1	4.4	2.8	2.5	2.4	2.4	2.2	1.9	2.2	1.8	2.5
Tier 3	14.6	12.6	15.2	12.3	13.2	15.8	12.8	13.8	12.2	13.7

Approach	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Rice Methane Emission	**18.9**	**15.3**	**15.2**	**13.8**	**15.4**	**16.2**	**13.5**	**12.8**	**13.3**
Tier 1	2.4	2.1	2.8	2.1	3.4	2.4	2.4	2.5	2.5
Tier 3	16.5	13.2	12.4	11.7	12.0	13.8	11.1	10.3	10.8

Note: Estimates after 2015 are based on a data splicing method (See the *Rice Cultivation* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

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). Table A-212 lists the direct N_2O emissions associated with drainage of organic soils in cropland and grassland.

Table A-212: Direct Soil N_2O Emissions from Drainage of Organic Soils (MMT CO_2 Eq.)

Land Use	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Organic Soil Emissions	**6.3**	**6.2**	**6.2**	**6.3**	**6.3**	**6.3**	**6.3**	**6.2**	**6.2**	**6.2**
Cropland	3.8	3.8	3.7	3.7	3.7	3.8	3.8	3.7	3.7	3.7
Grassland	2.5	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.5	2.5

Land Use	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Organic Soil Emission	**6.2**	**6.2**	**6.2**	**6.1**	**6.1**	**6.1**	**6.1**	**6.0**	**6.0**	**6.0**
Cropland	3.7	3.8	3.8	3.7	3.7	3.7	3.7	3.6	3.6	3.5
Grassland	2.5	2.4	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.5

Land Use	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Organic Soil Emission	**6.0**	**6.0**	**6.0**	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**
Cropland	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4
Grassland	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

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 2015, based on the land-use and management activity data in conjunction with appropriate emission factors. The activity data are based on annual data from 1990 through 2015 from the NRI. 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-213). 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 1,000 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-214 for croplands and Table A-215 for grasslands.

Table A-213: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

	Cropland		Grassland	
Region	IPCC	U.S. Revised	IPCC	U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2±2.5	0.25	2.8±0.5[a]
Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8[a]
Sub-Tropical, Dry & Sub-Tropical, Moist	1	14.3±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-214: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Cropland (MMT CO_2 Eq)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland SOC Stock Change	**38.6**	**38.0**	**38.1**	**38.3**	**38.5**	**38.6**	**38.5**	**38.5**	**38.5**	**32.9**
Cropland Remaining Cropland (CRC)	35.0	34.2	34.5	34.2	34.2	34.1	33.9	34.0	33.6	28.0
Grassland Converted to Cropland (GCC)	2.7	2.8	2.8	3.1	3.2	3.5	3.5	3.4	3.8	3.8
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC)	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.6	0.6	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.9

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland SOC Stock Change	**32.5**	**39.0**	**38.8**	**38.6**	**38.1**	**37.7**	**37.5**	**36.7**	**36.4**	**36.0**
Cropland Remaining Cropland (CRC)	27.9	33.5	33.5	33.7	33.8	33.4	33.2	32.6	32.4	32.2
Grassland Converted to Cropland (GCC)	3.6	4.5	4.5	4.1	3.6	3.5	3.5	3.3	3.4	3.1
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
Other Lands Converted to Cropland (OCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.7	0.7	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.5

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Cropland SOC Stock Change	**36.1**	**36.1**	**36.2**	**35.3**	**36.3**	**35.8**	**35.2**	**36.5**	**36.5**
Cropland Remaining Cropland (CRC)	32.3	32.4	32.3	31.3	32.5	32.1	31.6	32.8	32.8
Grassland Converted to Cropland (GCC)	3.1	3.1	3.4	3.5	3.4	3.3	3.3	3.3	3.3
Forest Converted to Cropland (FCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Lands Converted to Cropland (OCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.6	0.6	0.5	0.5	0.3	0.3	0.3	0.3	0.4

Table A-215: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Grasslands (MMT CO_2 Eq)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland SOC Stock Change	**7.1**	**7.0**	**7.1**	**7.1**	**7.2**	**7.1**	**7.0**	**7.0**	**7.0**	**7.1**
Grassland Remaining Grassland (GRG)	6.3	6.2	6.2	6.1	6.1	6.0	6.0	5.9	5.7	5.7
Cropland Converted to Grassland (CCG)	0.6	0.6	0.7	0.8	0.9	0.9	0.8	0.8	1.0	1.0
Forest Converted to Grassland (FCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Other Lands Converted to Grassland (OCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

Total Grassland SOC Stock Change	**7.1**	**7.0**	**7.1**	**6.9**	**7.1**	**7.1**	**7.1**	**7.1**	**7.1**	**7.3**
Grassland Remaining Grassland (GRG)	5.6	5.3	5.3	5.2	5.2	5.2	5.2	5.2	5.3	5.3
Cropland Converted to Grassland (CCG)	1.1	1.2	1.4	1.3	1.5	1.5	1.4	1.4	1.3	1.5
Forest Converted to Grassland (FCG)	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland (OCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Grassland SOC Stock Change	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.2**
Grassland Remaining Grassland (GRG)	5.3	5.3	5.3	5.3	5.5	5.4	5.4	5.4	5.4
Cropland Converted to Grassland (CCG)	1.5	1.4	1.4	1.4	1.3	1.4	1.4	1.4	1.3
Forest Converted to Grassland (FCG)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland (OCG)	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.2	0.2

Step 4: Estimate Indirect Soil N_2O Emissions for Croplands and Grasslands

In this step, soil 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 volatilized 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 indirect soil 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 implied emission factors are provided in Table A-207 for cropland and in Table A-208 for grassland.

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

The amounts 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 water flows are used to calculate indirect emissions from leaching of mineral N from soils and losses in runoff 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 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).The emission estimates are provided in Table A-216 and Table A-217 including the implied Tier 3 emission factors.

Table A-216: Indirect Soil N_2O Emissions for Cropland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Indirect Emissions	**34.2**	**31.5**	**33.7**	**37.9**	**29.3**	**34.1**	**33.7**	**32.2**	**36.3**	**32.7**
Volatilization & Atmospheric Deposition	6.5	6.3	6.1	6.4	6.6	6.7	6.7	6.7	6.9	6.9
Leaching & Runoff	27.7	25.3	27.7	31.5	22.7	27.4	27.0	25.5	29.4	25.9
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Indirect Emissions	**30.2**	**35.1**	**32.2**	**33.4**	**36.8**	**31.8**	**33.2**	**35.2**	**36.7**	**36.0**
Volatilization & Atmospheric Deposition	7.1	7.1	7.3	7.3	7.5	7.3	7.3	7.3	7.3	7.2
Leaching & Runoff	23.1	28.0	24.9	26.2	29.3	24.4	25.9	27.9	29.4	28.8
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Cropland Indirect Emissions	**36.3**	**35.5**	**28.8**	**38.1**	**37.9**	**43.0**	**39.2**	**37.8**	**42.8**
Volatilization & Atmospheric Deposition	7.7	7.4	7.0	7.8	8.2	8.6	8.3	8.1	8.2
Leaching & Runoff	28.6	28.1	21.8	30.3	29.7	34.4	30.9	29.7	34.6
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	NE	NE	NE	NE	NE	NE
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	NE	NE	NE	NE	NE	NE

Note: Estimates after 2015 are based on a data splicing method (See the *Agricultural Soil Management* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.
NE (Not Estimated)

Table A-217: Indirect Soil N_2O Emissions for Grassland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Indirect Emissions	**9.2**	**9.1**	**9.4**	**9.7**	**9.0**	**9.3**	**9.1**	**9.4**	**10.4**	**9.2**
Volatilization & Atmospheric Deposition	3.6	3.5	3.6	3.5	3.5	3.5	3.6	3.6	3.6	3.4
Leaching & Runoff	5.6	5.5	5.8	6.3	5.6	5.8	5.5	5.9	6.8	5.8
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Indirect Emissions	**8.1**	**9.7**	**9.4**	**8.9**	**10.3**	**9.1**	**9.0**	**9.9**	**9.7**	**10.0**
Volatilization & Atmospheric Deposition	3.1	3.4	3.5	3.4	3.7	3.6	3.5	3.5	3.4	3.4
Leaching & Runoff	5.0	6.4	5.9	5.4	6.6	5.5	5.5	6.4	6.3	6.6
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total Grassland Indirect Emissions	**9.6**	**9.3**	**8.6**	**10.0**	**9.1**	**10.6**	**9.6**	**9.6**	**9.7**
Volatilization & Atmospheric Deposition	3.5	3.1	3.1	3.6	3.6	3.5	3.4	3.4	3.4
Leaching & Runoff	6.1	6.1	5.5	6.4	5.5	7.1	6.3	6.2	6.3
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	NE	NE	NE	NE		NE
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	NE	NE	NE	NE		NE

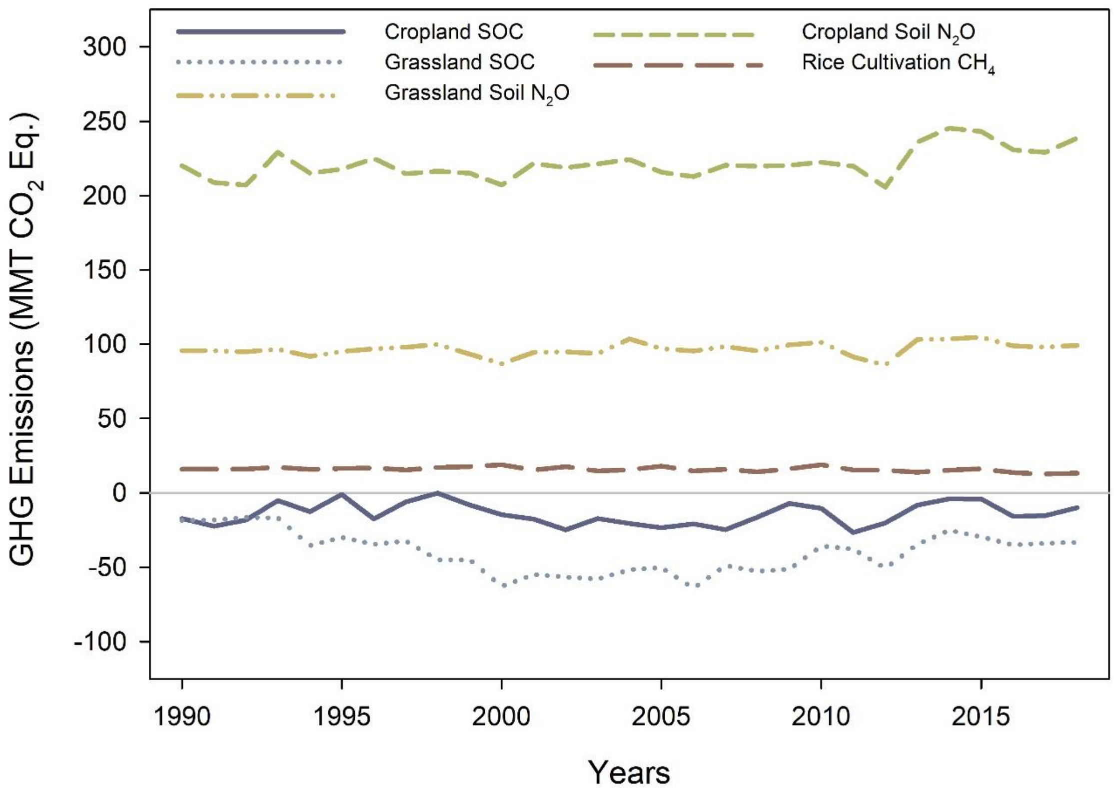
Note: Estimates after 2015 are based on a data splicing method (See the *Agricultural Soil Management* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.
NE (Not Estimated)

Step 5: Estimate Total Emissions for U.S. Agricultural Soils

Total N_2O emissions are estimated by summing total direct and indirect emissions for croplands and grasslands (both organic and mineral soils). Total soil organic C stock changes for cropland (*Cropland Remaining Cropland* and *Land Converted to Cropland*) and grassland (*Grassland Remaining Grassland* and *Land Converted to Grassland*) are summed to determine the total change in soil organic C stocks (both organic and mineral soils). Total rice CH_4 emissions are estimated by summing results from the Tier 1 and 3 methods. The results are provided in Figure A-7. In general, N_2O

emissions from agricultural soil management have been increasing slightly from 1990 to 2018, while CH_4 emissions from rice cultivation have been relatively stable. Agricultural soil organic C stocks have increased for most years in croplands and grasslands leading to sequestration of C in soils, with larger increases in grassland soils.

Figure A-7: GHG Emissions and Removals for Cropland & Grassland (MMT CO_2 Eq.)



Direct and indirect simulated emissions of soil N_2O vary regionally in croplands and grasslands as a function of N input, other management practices, weather, and soil type. The highest total N_2O emissions for 2015[117] occur in Iowa, Illinois, Kansas, Minnesota, Missouri, Montana, Nebraska, South Dakota, and Texas (Table A-218). These areas are used to grow corn or have extensive areas of grazing with large amounts of PRP manure N inputs. 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 states with largest increases in soil organic C stocks in 2015 include Illinois, Iowa, Missouri, Nebraska, North Dakota (Table A-218). These states tend to have larger amounts of land conversion to grassland and/or more conservation practices such as enrollment in Conservation Reserve Program or adoption of conservation tillage. For rice cultivation, the states with highest CH_4 emissions are Arkansas, California, Louisiana and Texas (Table A-218). These states also have the largest areas of rice cultivation, and Louisiana and Texas have a relatively large proportion of fields with a second ratoon crop each year. Ratoon crops extend the period of flooding, and with the residues left from the initial rice crop, there are additional CH_4 emissions compared to non-ratoon rice management systems.

[117] The emissions data at the state scale is available for 1990 to 2015, but data splicing methods have been applied at national scales to estimate emissions for most emission sub-source categories for 2016 to 2018. Therefore, the final year of emissions data at the state scale is 2015.

Table A-218: Total Soil N_2O Emissions (Direct and Indirect), Soil Organic C Stock Changes and Rice CH_4 Emissions from Agricultural Lands by State in 2015 (MMT CO_2 Eq.)

	N_2O Emissions[a]		Soil C Stock Change		Rice	Total
State	Croplands	Grasslands	Croplands	Grasslands	CH_4	Emissions
AL	1.34	1.15	-0.39	-1.00	0.00	1.10
AR	5.30	1.37	-0.65	-0.72	6.39	11.69
AZ	0.24	3.82	0.16	-0.27	0.00	3.95
CA	1.08	2.07	0.45	-3.57	4.14	4.17
CO	3.38	4.37	0.06	-2.24	0.00	5.57
CT	0.06	0.02	-0.05	-0.05	0.00	-0.02
DE	0.17	0.02	-0.04	-0.03	0.00	0.12
FL	0.25	1.68	11.88	0.16	0.00	13.97
GA	1.83	0.82	0.35	-0.55	0.00	2.45
HI[b]	NE	NE	0.29	0.53	0.00	0.82
IA	21.23	2.14	-3.83	-1.15	0.00	18.39
ID	2.04	1.01	-0.25	-2.05	0.00	0.76
IL	18.43	0.93	-6.23	-0.65	0.00	12.48
IN	9.02	0.61	0.51	-0.52	0.00	9.63
KS	16.28	4.98	-0.77	-1.30	0.00	19.19
KY	3.66	2.28	-0.30	-0.76	0.00	4.88
LA	3.32	0.92	-0.85	-0.55	2.57	5.41
MA	0.08	0.03	0.21	-0.02	0.00	0.30
MD	0.73	0.16	-0.04	-0.11	0.00	0.74
ME	0.16	0.07	-0.12	0.02	0.00	0.13
MI	3.73	0.70	2.50	-0.25	0.00	6.68
MN	13.26	1.39	5.75	1.18	0.01	21.60
MO	10.71	3.48	-2.93	-0.85	0.00	10.41
MS	3.50	0.84	-1.04	-0.73	1.00	3.57
MT	6.43	6.74	-1.52	1.27	0.00	12.91
NC	2.09	0.60	1.95	-0.63	0.00	4.01
ND	7.80	2.04	-3.12	-1.70	0.00	5.02
NE	13.18	4.94	-2.87	-1.15	0.00	14.10
NH	0.06	0.03	-0.04	0.01	0.00	0.05
NJ	0.14	0.04	-0.01	-0.07	0.00	0.11
NM	0.55	6.63	0.02	2.95	0.00	10.16
NV	0.20	1.10	-0.03	-1.37	0.00	-0.10
NY	2.27	1.04	-0.91	-0.13	0.00	2.28
OH	7.25	0.72	-1.79	-0.84	0.00	5.34
OK	4.56	5.26	0.55	-1.39	0.00	8.98
OR	0.96	1.11	-0.07	-1.65	0.00	0.35
PA	2.70	0.67	-1.33	-0.77	0.00	1.27
RI	0.01	0.01	0.02	-0.01	0.00	0.03
SC	1.09	0.37	-0.18	-0.37	0.00	0.90
SD	10.84	4.66	-1.99	-0.89	0.00	12.62
TN	2.60	1.67	-0.63	-0.60	0.00	3.04
TX	13.66	16.72	2.10	-1.11	1.43	32.80
UT	0.60	1.26	0.22	-3.72	0.00	-1.65
VA	1.43	1.26	-0.73	-0.42	0.00	1.54
VT	0.35	0.16	-0.11	0.01	0.00	0.42
WA	1.69	0.70	-0.03	0.01	0.00	2.37
WI	5.98	1.18	2.18	0.24	0.00	9.58
WV	0.24	0.48	-0.30	-0.29	0.00	0.12
WY	0.77	3.79	-0.22	0.03	0.00	4.38

[a] This table only includes N_2O emissions estimated by DayCent using the Tier 3 method.
[b] N_2O emissions are not reported for Hawaii except from cropland organic soils, which are estimated with the Tier 1 method and therefore not included in this table.

Tier 3 Method Description and Model Evaluation

The DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil. The model provides a more complete estimation of soil C stock changes, CH_4 and N_2O emissions than IPCC Tier 1 or 2 methods by accounting for a broader suite of environmental drivers that influence emissions and C stock changes. These drivers 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 three source categories (i.e., agricultural soil C, rice CH_4 and soil 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, and ensuring conservation of mass. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth, along with residue management, determines C inputs to soils and influences C stock changes. Removal of soil mineral N by microbial organisms influences the amount of production and C inputs, while plant uptake of N influence availability of N for microbial processes of nitrification and denitrification that generate N_2O emissions. 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.

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 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), 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; Cheng et al. 2014), and CH_4 emissions (Cheng et al. 2013).
2) The model is designed to simulate management practices that influence soil C dynamics, CH_4 emissions 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 to estimate soil organic C stock changes and IPCC Tier 1 method is used to estimate CH_4 and N_2O emissions. The model can also be used to estimate the amount of N leaching and runoff, as well as volatilization of N, which is subject to indirect N_2O emissions.
3) Much of the data needed for the model is available from existing national databases. The exceptions are management of federal grasslands and biosolids (i.e., treated 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.

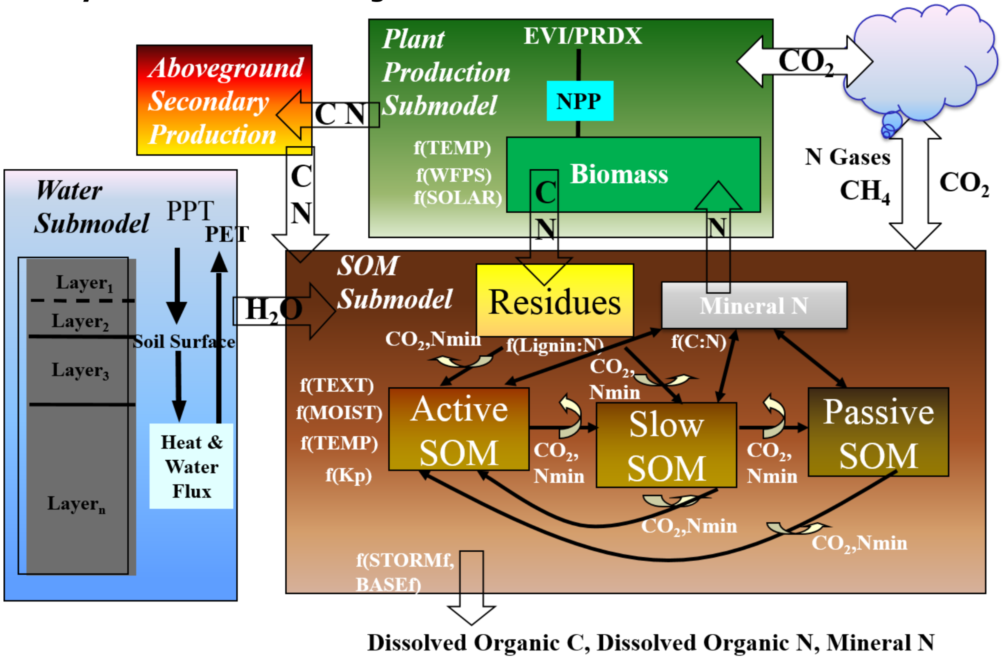
DayCent Model Description

Key processes simulated by DayCent include (1) plant growth; (2) organic matter formation and decomposition; (3) soil water and temperature regimes by layer; (4) nitrification and denitrification processes; and (5) methanogenesis (Figure A-8). Each submodel is described 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. The NASA-CASA production algorithm is only used

for the following major crops: corn, soybeans, sorghum, cotton and wheat.[118] 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 by 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-9.

Figure A-8: DayCent Model Flow Diagram

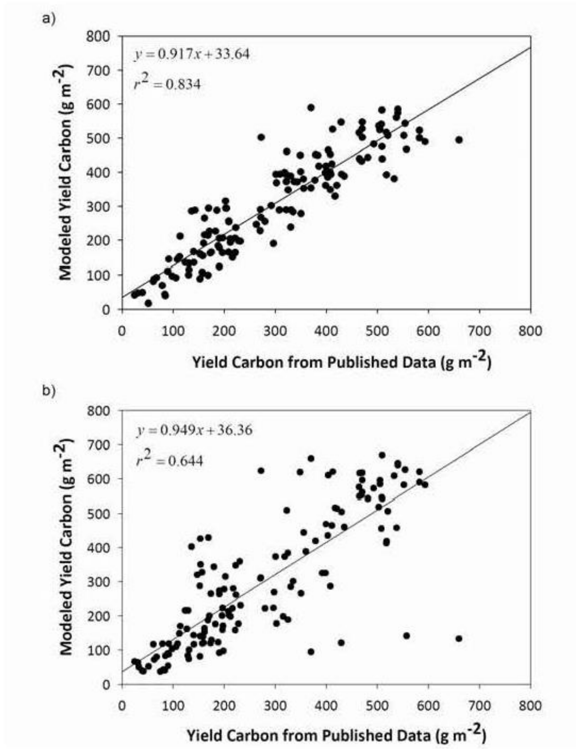


2) Dynamics of soil organic C and N (Figure A-8) are simulated for the surface and belowground litter pools and soil organic matter in the top 30 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N stocks are represented by two plant litter pools (metabolic 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 be influenced the most by land use and management activity. 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.

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

3) The soil-water submodel simulates water flows and changes in soil water availability, which influences both plant growth, decomposition and nutrient cycling. 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.

Figure A-9: 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%).

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. Soil 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 A-2 for more information).
5) Methanogenesis is modeled under anaerobic conditions and is controlled by carbon substrate availability, temperature, and redox potential (Cheng et al. 2013). Carbon substrate supply is determined by decomposition of residues and soil organic matter, in addition to root exudation. The transport of CH_4 to the atmosphere occurs through the rice plant and via ebullition (i.e., bubbles). CH_4 can be oxidized (methanotrophy) as it moves through a flooded soil and the oxidation rates are higher as the plants mature and in soils with more clay (Sass et al. 1994).

The model allows for a variety of management options to be simulated, including different crop types, crop sequences (e.g., rotation), cover crops, tillage practices, fertilization, organic matter addition (e.g., manure amendments), harvest events (with variable residue removal), drainage, flooding, 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. 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), Cheng et al. (2013) and Metherell et al. (1993), and archived copies of the model source code are available.

Box A-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/m2/day)
NH4+	=	the model-derived soil ammonium concentration (g N/m^2)
Kmax	=	the maximum fraction of NH4+ nitrified (Kmax = 0.10/day)
F(t)	=	the effect of soil temperature on nitrification (Figure A-10a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A-10b)
F(pH)	=	the effect of soil pH on nitrification (Figure A-10c)

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:

$$Den = \min[F(CO_2), F(NO3)] \times F(WFPS)$$

where,

Den	=	the soil denitrification rate (μg N/g soil/day)
$F(NO_3)$	=	a function relating N gas flux to nitrate levels Figure A-11a)
$F(CO_2)$	=	a function relating N gas flux to soil respiration (Figure A-11b)
F(WFPS)	=	a dimensionless multiplier (Figure A-11c)

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-10b). 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.

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

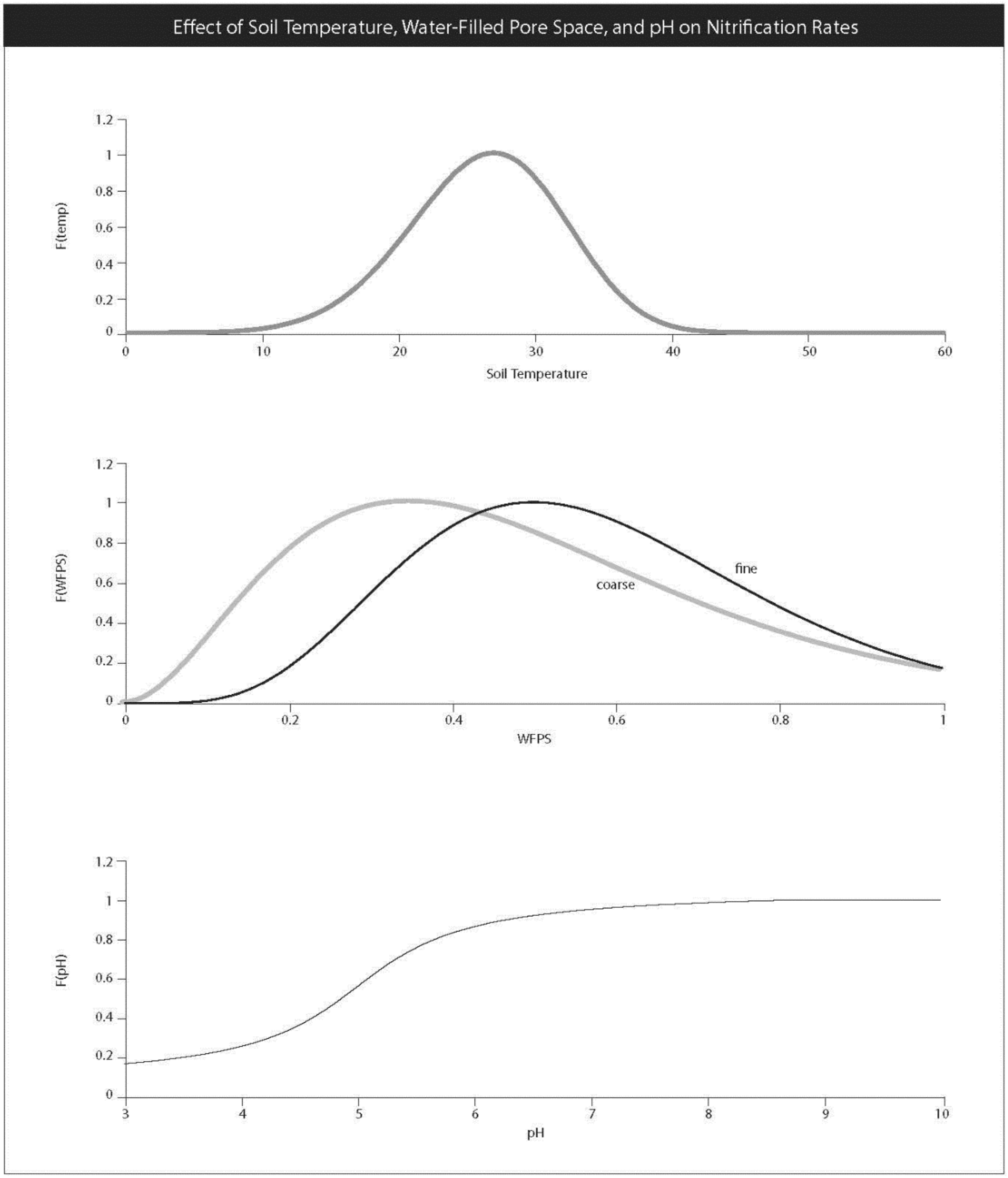
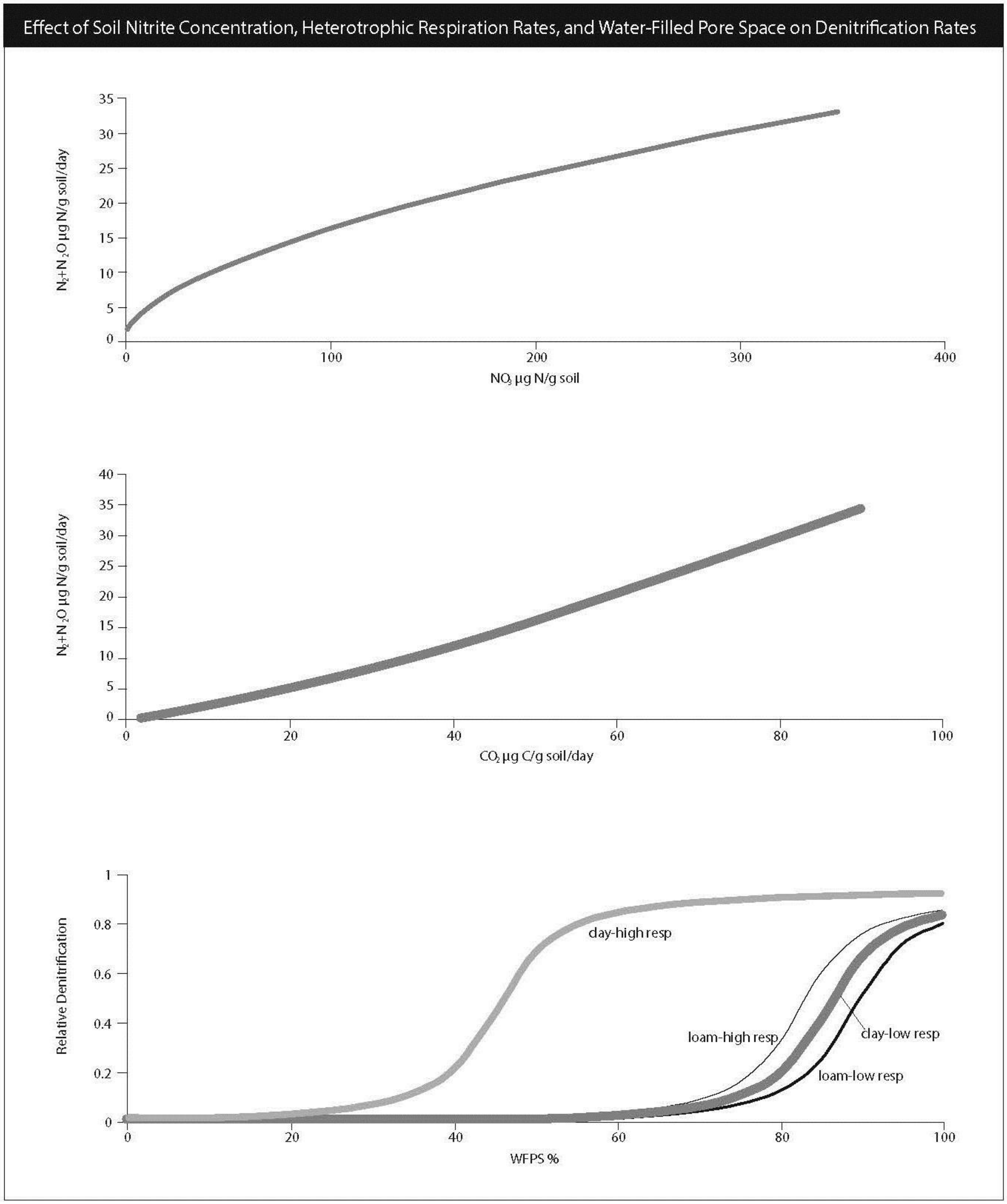


Figure A-11: Effect of Soil Nitrite Concentration (a), Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



Hot moments, or pulses, of N_2O emissions can occur during freeze-thaw events in soils of cold climates, and these events can contribute a substantial portion of annual emissions in northern temperate and boreal regions (Butterbach-Bahl et al. 2017). A recent analysis suggests that not accounting for these events could lead to under-estimation of global agricultural N_2O emissions by 17-28 percent (Wagner-Riddle et al. 2017). The mechanisms responsible for this phenomenon are not entirely understood but the general hypotheses include accumulation of substrates while the soil is frozen that drives denitrification as the soil thaws; impacts on soil gas diffusivity and O_2 availability in pores during freeze-thaw events that influence denitrification rates; and differing temperature sensitives of the enzymatic processes that control the amounts of N_2 and N_2O gases released during denitrification (Congreves et al. 2018). The denitrification routine in DayCent was amended so that periods of thawing of frozen soils in the 2-5 cm layer during the late winter/spring will trigger a hot moment or pulse of N_2O emissions. Specifically, the soil water content and microbial respiration controls on denitrification are relaxed for approximately 3 days upon melting and N_2O from denitrification is amplified by an amount proportional to cumulative freezing degree days during the winter season. DayCent was evaluated using annual high frequency N_2O data collected at research sites in eastern and western Canada (Wagner-Riddle et al. 2017). The results showed less bias with a better match to observed patterns of late winter/spring emissions than the previous version of the DayCent model (Del Grosso et al. 2020).

DayCent Model Evaluation

Comparison of model results and plot level data show that DayCent simulates soil organic matter levels with reasonable accuracy (Ogle et al. 2007). The model was tested and shown to capture the general trends in C storage across 948 observations from 72 long-term experiment sites and 142 NRI soil monitoring network sites (Spencer et al. 2011) (Figure A-12). Some bias 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-13).

Figure A-12: Comparisons of Results from DayCent Model and Measurements of Soil Organic C Stocks

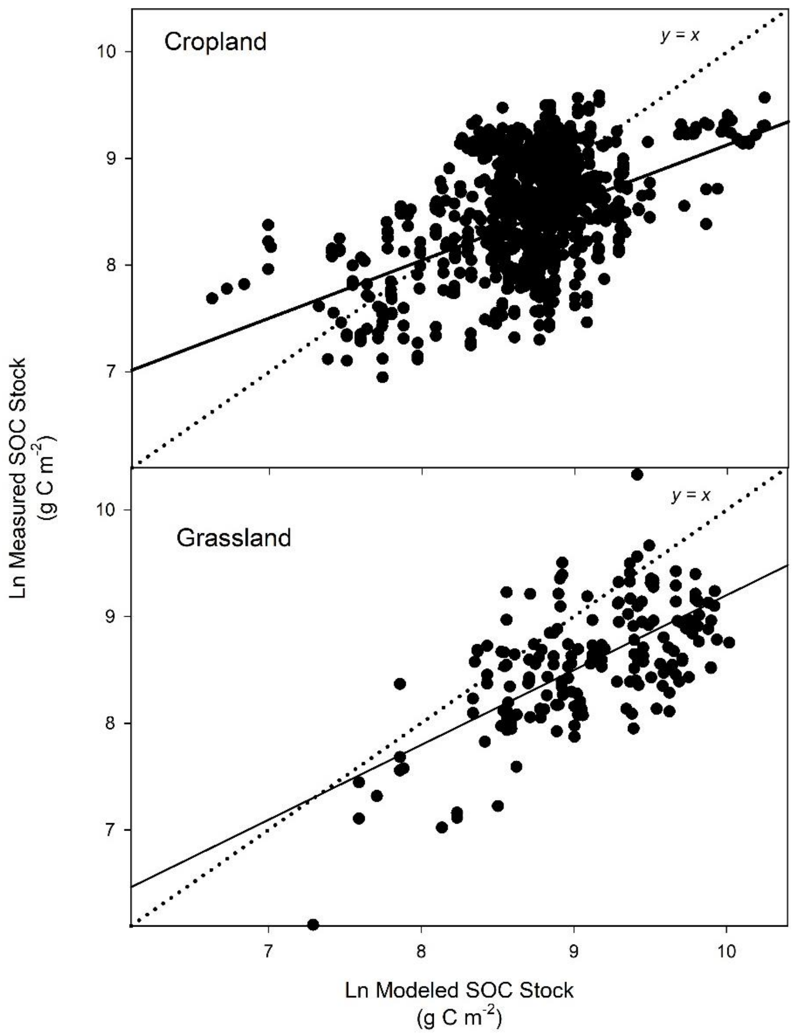
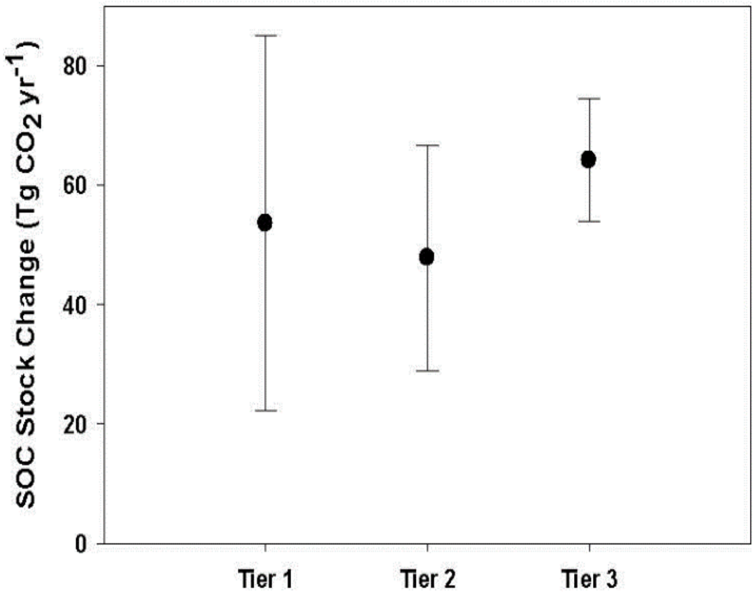


Figure A-13: Comparison of Estimated Soil Organic C Stock Changes and Uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 Methods



Similarly, DayCent model results have been compared to trace gas N_2O fluxes for a number of native and managed systems from 41 experimental sites with over 200 treatment observations (Del Grosso et al. 2001, 2005, 2010) (Figure A-14). 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) with higher r^2 values and a fitted line closer to a perfect 1:1 relationship between measured and modeled N_2O emissions (Del Grosso et al. 2005, 2008). This is not surprising, since DayCent includes site-specific factors (climate, soil properties, and previous management) that influence N_2O emissions. Furthermore, DayCent also simulated NO_3- leaching (root mean square error = 20 percent) more accurately than IPCC Tier 1 methodology (root mean square error = 69 percent) (Del Grosso et al. 2005). 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.

DayCent predictions of soil CH_4 emissions have also been compared to experimental measurements from sites in California, Texas, Arkansas, and Louisiana (Figure A-15). There are 17 long-term experiments with data on CH_4 emissions from rice cultivation, representing 238 treatment observations. In general, the model estimates CH_4 emissions with no apparent bias, but there is a lack of precision, which is addressed in the uncertainty analysis.

Figure A-14: Comparisons of Results from DayCent Model and Measurements of Soil Nitrous Oxide Emissions

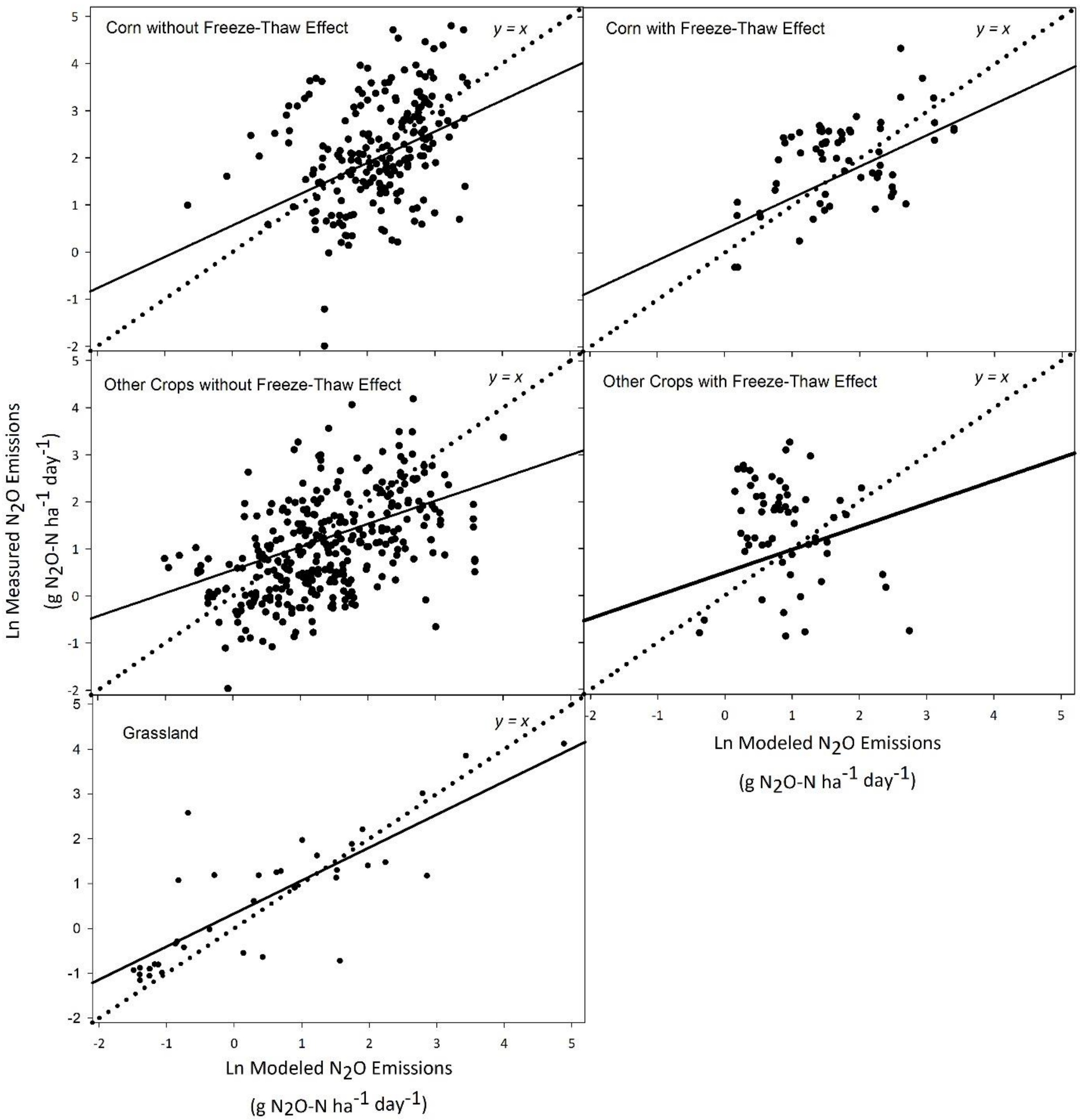
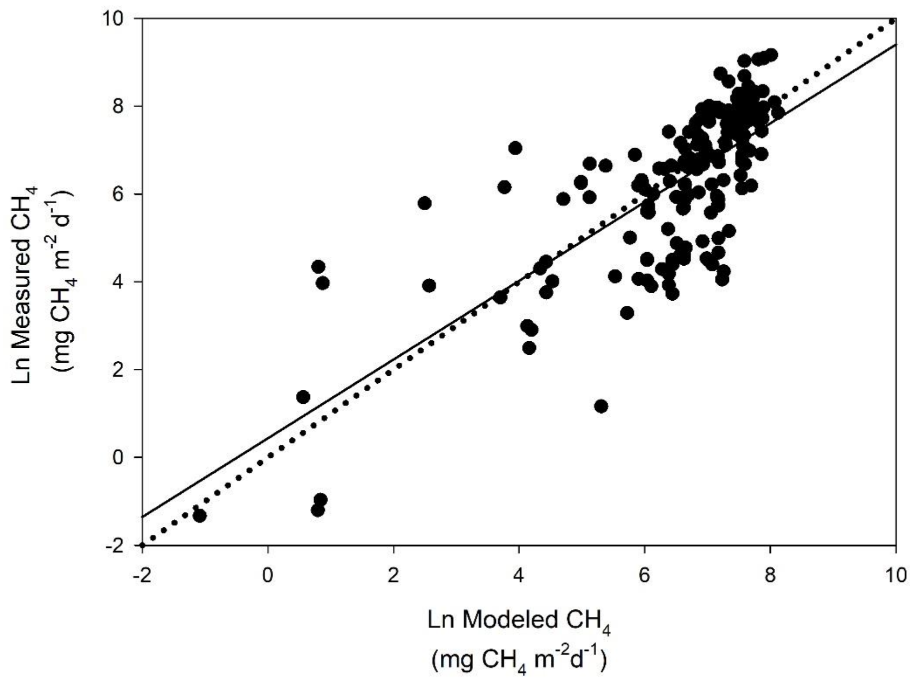


Figure A-15: Comparisons of Results from DayCent Model and Measurements of Soil Methane Emissions



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3.13. Methodology for Estimating Net Carbon Stock Changes in Forest Ecosystems and Harvested Wood Products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as well as Non-CO_2 Emissions from Forest Fires.

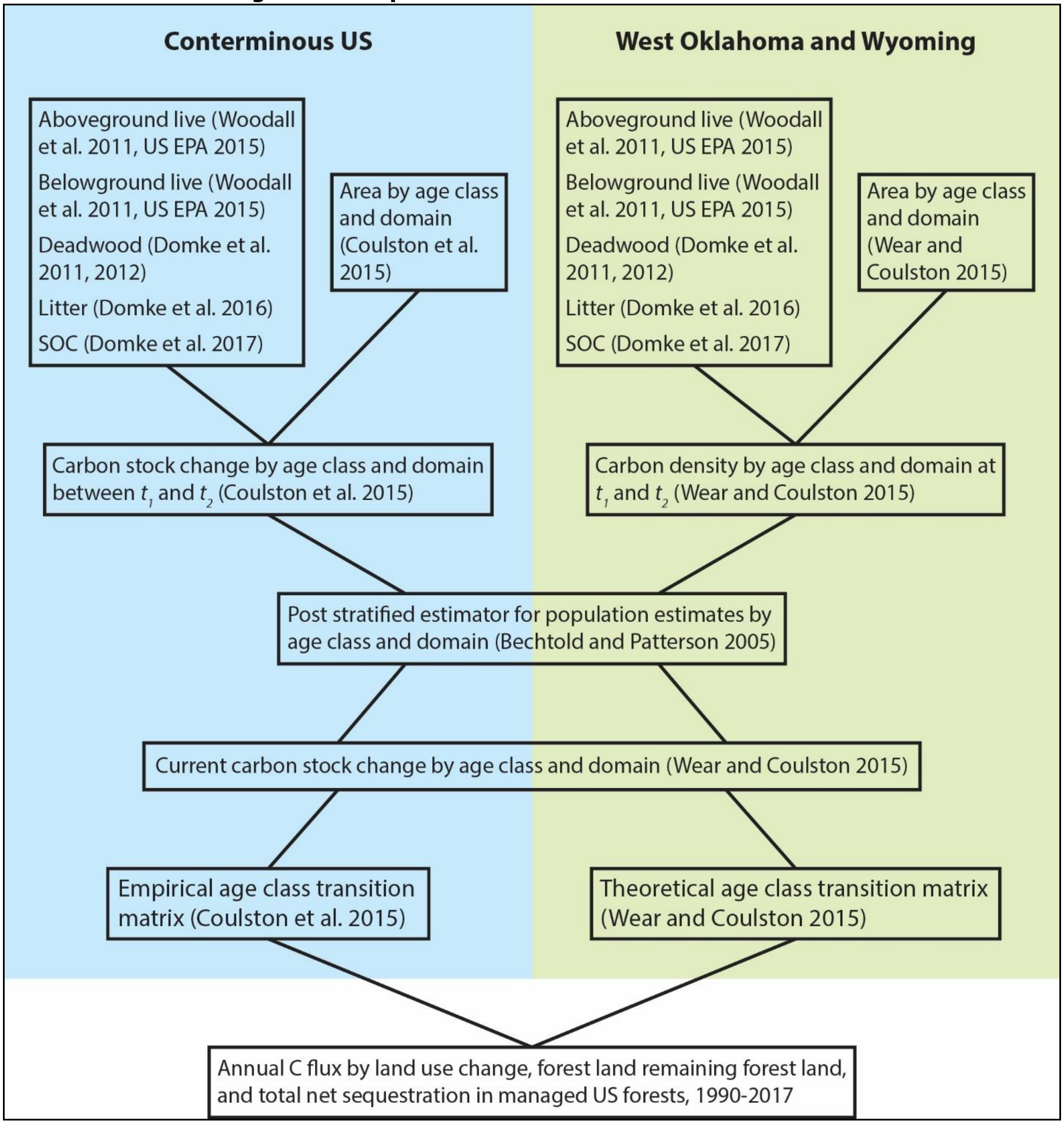
This sub-annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as well as non-CO_2 emissions from forest fires. Full details of the C conversion factors and procedures may be found in the cited references. For details on the methods used to estimate changes in mineral soil C stocks in the *Land Converted to Forest Land* section please refer to Annex 3.12.

Carbon stocks and net stock change in forest ecosystems

The inventory-based methodologies for estimating forest C stocks are based on a combination of approaches (Woodall et al 2015a) and are consistent with the IPCC (2003, 2006) stock-difference (used for the conterminous United States (U.S.)) and gain-loss (used for Alaska) methods. Estimates of ecosystem C are based on data from the network of annual national forest inventory (NFI) plots established and measured by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service; either direct measurements or variables from the NFI are the basis for estimating metric tons of C per hectare in forest ecosystem C pools (i.e., above- and belowground biomass, dead wood, litter, and soil carbon). For the conterminous U.S., plot-level estimates are used to inform land area (by use) and stand age transition matrices across time which can be summed annually for an estimate of forest C stock change for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. A general description of the land use and stand age transition matrices that are informed by the annual NFI of the U.S. and were used in the estimation framework to compile estimates for the conterminous U.S. in this Inventory are described in Coulston et al. (2015). The annual NFI data in the conterminous U.S. allows for empirical estimation of net change in forest ecosystem carbon stocks within the estimation framework. In contrast, Wyoming and West Oklahoma have no remeasurement data so theoretical age transition matrices were developed (Figure A-16). The incorporation of all managed forest land in Alaska was facilitated by an analysis to determine the managed land base in Alaska (Ogle et al. 2018), the expansion of the NFI into interior Alaska beginning in 2014, and a myriad of publicly available data products that provided information necessary for prediction of C stocks and fluxes on plots that have yet to be measured as part of the NFI.

The following subsections of this annex describe the estimation system used this year (Figure A-16) including the methods for estimating individual pools of forest ecosystem C in addition to the approaches to informing land use and stand age transitions.

Figure A-16: Flowchart of the inputs necessary in the estimation framework, including the methods for estimating individual pools of forest C in the conterminous United States



Note: An empirical age class transition matrix was used in every state in the conterminous United States with the exception of west Oklahoma and Wyoming where a theoretical age class transition matrix was used due to a lack of remeasurements in the annual NFI.

Forest Land Definition

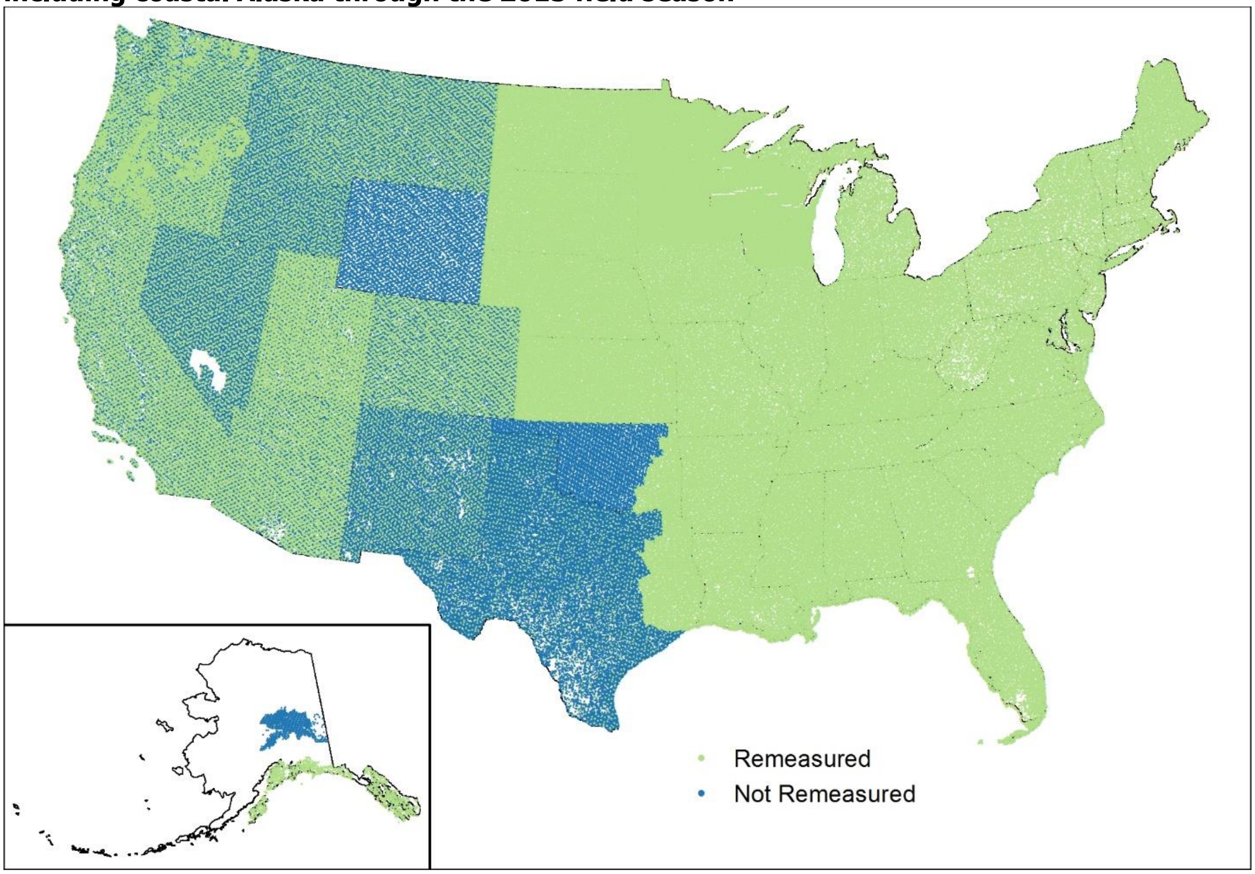
The definition of forest land within the United States and used for this Inventory is defined in Oswalt et al. (2014) as "Land at least 120 feet (37 meters) wide and at least 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly 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 (36.6 meters) wide or an acre (0.4 hectare) 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 C incorporated into harvested wood products. Productivity for timberland 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).

Forest Inventory Data

The estimates of forest C stocks are based on data from the annual NFI. NFI data were obtained from the USDA Forest Service, FIA Program (Frayer and Furnival 1999; USDA Forest Service 2018a; USDA Forest Service 2018b). NFI data include remote sensing information and a collection of measurements in the field at sample locations called plots. Tree measurements include diameter at breast height, tree height, species, and variables describing tree form and condition. On a subset of plots, additional measurements or samples are taken on downed dead wood, litter, and soil variables. The technical advances needed to estimate C stocks from these data are ongoing (Woodall et al. 2015a) with the latest research incorporated on an annual basis (see Domke et al. 2016, Domke et. al. 2017). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2018c). Bechtold and Patterson (2005) provide the estimation procedures for standard NFI results. The data are freely available for download at USDA Forest Service (2011b) as the FIA Database (FIADB) Version 8.0 (USDA Forest Service 2018b; USDA Forest Service 2018c); these are the primary sources of NFI data used to estimate forest C stocks. In addition to the field sampling component, fine-scale remotely sensed imagery (National Agriculture Imagery Program; NAIP 2015; Woodall et al. 2015b) is used to assign the land use at each sample location which has a nominal spatial resolution (raster cell size) of 1 m^2. Prior to field measurement of each year's collection of annual plots due for measurement (i.e., panel), each sample location in the panel (i.e., systematic distribution of plots within each state each year) is photo-interpreted manually to classify the land use. Annual NFI data are available for the temperate oceanic ecoregion of Alaska (southeast and south central) from 2004 to present as well as for interior Alaska from a pilot inventory in 2014 which became operational in 2016. Agroforestry systems are 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.

A national plot design and annualized sampling (USDA Forest Service 2015a) were introduced by FIA with most new annual NFIs beginning after 1998. These are the only NFIs used in the compilation of estimates for this Inventory. These NFIs involve the sampling of all forest land including reserved and lower productivity lands. All states with the exception of Hawaii have annualized NFI data available with substantial remeasurement (with the exception of Wyoming and West Oklahoma) in the conterminous U.S. (Figure A-17). Annualized sampling means that a spatially representative 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 U.S. 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 within the state, but with higher sampling uncertainty 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 three or four cycles of the annualized NFI, and most western states are on their 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 annual inventory data can affect trend estimates of C stocks and stock changes (e.g., estimates based on 60 percent of an inventory cycle will be different than estimates with a complete (100 percent) cycle). In general, the C stock and stock change estimates use annual NFI summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update (i.e., 2018) is the exception because it is included in stock change calculations in order to include the most recent available data for each state. The specific inventories used in this report are listed in Table A-219 and this list can be compared with the full set of summaries available for download (USDA Forest Service 2018b).

Figure A-17: Annual FIA plots (remeasured and not remeasured) across the United States including coastal Alaska through the 2015 field season



Note: Due to the vast number of plots (where land use is measured even if no forest is present) they appear as spatially contiguous when displayed at the scale and resolution presented in this figure.

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) this will require that 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 represent C stocks and stock change on managed forest lands (IPCC 2006, see Section 6.1 Representation of the U.S. Land Base), which is how all forest lands are classified. In some cases there are NFI plots that do not meet the height component of the definition of forest land (Coulston et al. 2016). These plots are identified as "woodlands" (i.e., not forest land use) and were removed from the forest estimates and classified as grassland.[119] Note that minor differences (approximately 2 percent less forest land area in the CONUS) in identifying and classifying woodland as "forest" versus "woodland" exist between the current Resources Planning Act Assessment (RPA) data (Oswalt et al. 2014) and the FIADB (USDA Forest Service 2015b) due to a refined modelling approach developed specifically for Inventory reporting (Coulston et al. 2016). Plots in the coastal region of the conterminous U.S. were also evaluated using the National Land Cover Database and the Coastal Change Analysis Program data products to ensure that land areas were completely accounted for in this region and also that they were not included in both the Wetlands

[119] See the *Grassland Remaining Grassland* and *Land Converted to Grassland* sections for details.

category and the Forest Land category. This resulted in several NFI plots or subplots being removed from the Forest Land compilation.

Table A-219: Specific annual forest inventories by state used in development of forest C stock and stock change estimate

Remeasured Annual Plots			Split Annual Cycle Plots		
State	Time 1 Year Range	Time 2 Year Range	State	Time 1 Year Range	Time 2 Year Range
Alabama	2001 - 2012	2011 - 2018	Oklahoma (West)	2010 - 2012	2013 - 2016
Arizona	2001 - 2007	2011 - 2017	Wyoming	2000	2011 - 2017
Arkansas	2006 - 2013	2013 - 2018			
California	2001 - 2006	2011 - 2016	Alaska (Coastal)[1]	2004 - 2017	
Colorado	2002 - 2007	2012 - 2017	Alaska (Interior)[1]	2014, 2016 - 2017	
Connecticut	2006 - 2011	2011 - 2017			
Delaware	2006 - 2011	2011 - 2017			
Florida	2002 - 2011	2012 - 2016			
Georgia	2005 - 2012	2013 - 2017			
Idaho	2004 - 2007	2014 - 2017			
Indiana	2007 - 2012	2012 - 2018			
Iowa	2007 - 2012	2012 - 2018			
Kansas	2006 - 2011	2011 - 2017			
Kentucky	2005 - 2011	2011 - 2016			
Louisiana	2001 - 2010	2009 - 2016			
Maine	2008 - 2012	2013 - 2017			
Maryland	2006 - 2011	2011 - 2017			
Massachusetts	2006 - 2011	2011 - 2017			
Michigan	2007 - 2012	2012 - 2018			
Minnesota	2009 - 2013	2014 - 2018			
Mississippi	2006 - 2012	2009 - 2017			
Missouri	2007 - 2012	2012 - 2018			
Montana	2003 - 2007	2013 - 2017			
Nebraska	2007 - 2012	2012 - 2018			
Nevada	2004 - 2007	2014 - 2017			
New Hampshire	2005 - 2011	2011 - 2017			
New Jersey	2007 - 2012	2012 - 2017			
New Mexico	2005 - 2007	2015 - 2017			
New York	2005 - 2011	2011 - 2017			
North Carolina	2003 - 2013	2009 - 2018			
North Dakota	2007 - 2012	2012 - 2018			
Ohio	2005 - 2011	2011 - 2017			
Oklahoma (East)	2008 - 2012	2012 - 2016			
Oregon	2001 - 2006	2011 - 2016			
Pennsylvania	2006 - 2011	2011 - 2017			
Rhode Island	2007 - 2011	2011 - 2017			
South Carolina	2007 - 2014	2013 - 2017			
South Dakota	2007 - 2012	2012 - 2018			
Tennessee	2005 - 2011	2010 - 2015			
Texas (East)	2004 - 2012	2009 - 2017			
Texas (West)	2004 - 2007	2014 - 2015			

Utah	2000 - 2007	2010 - 2017
Vermont	2006 - 2011	2011 - 2017
Virginia	2008 - 2014	2013 - 2017
Washington	2002 - 2006	2012 - 2016
West Virginia	2006 - 2011	2011 - 2017
Wisconsin	2007 - 2012	2012 - 2018

Note: Remeasured annual plots represent a complete inventory cycle between measurements of the same plots while spilt annual cycle plots represent a single inventory cycle of plots that are split where remeasurements have yet to occur.
[1]Plots in Alaska have not been split but are included in this column to conserve space in the Table.

Estimating Forest Inventory Plot-Level C-Density

For each inventory plot in each state, field data from the FIA program are used alone or in combination with auxiliary information (e.g., climate, surficial geology, elevation) to predict C density for each forest ecosystem C pool (i.e., aboveground and belowground biomass, dead wood, litter, SOC). In the past, 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 extension of the forest C simulation model FORCARB (Heath et al. 2010). The conversion factors and model coefficients were usually categorized by region and forest type. Thus, region and type are specifically defined for each set of estimates. More recently, the coarse approaches of the past have been updated with empirical information regarding C variables for individual forest C pools such as dead wood and litter (e.g., Domke et al. 2013 and Domke et al. 2016). Factors are applied to the forest inventory data at the scale of NFI plots which are a systematic sample of all forest attributes and land uses within each state. The results are estimates of C density (T per hectare) for each forest ecosystem C pool. Carbon density for live trees, standing dead trees, understory vegetation, downed dead wood, litter, and soil organic matter are estimated. All non-soil C pools except litter and downed dead wood can be separated into aboveground and belowground components. The live tree and understory C pools are combined into the aboveground and belowground biomass pools 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* and *Land Converted to Forest Land* are reported in forest ecosystem C 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 fraction of 0.5 because biomass is 50 percent of dry weight (USDA Forest Service 2018d). Further discussion and example calculations are provided in Woodall et al. (2011) and Domke et al. (2012).

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 2.54 cm 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:

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density}))} \qquad (1)$$

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-220. 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:

$$\text{Understory (T C/ha)} = (\text{live tree C density}) \times e^{(0.855 - 1.03 \times \ln(\text{tree C density}))} \qquad (2)$$

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-220) are set to coefficient A, which is a C density (T C/ha) for these types only.

Table A-220: Coefficients for Estimating the Ratio of C Density of Understory Vegetation (above- and belowground, T C/ha) by Region and Forest Type[a]

Region[b]	Forest Type[b]	A	B	Maximum ratio[c]
NE	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
	Oak-Hickory	0.842	1.053	2.057
	Oak-Pine	1.960	1.235	4.203
	Other Pine	2.149	1.268	4.191
	Spruce-Fir	0.825	1.121	2.140
	White-Red-Jack Pine	1.000	1.116	2.098
	Nonstocked	2.020	2.020	2.060
NLS	Aspen-Birch	0.777	1.018	2.023
	Lowland Hardwood	0.650	0.997	2.037
	Maple-Beech-Birch	0.863	1.120	2.129
	Oak-Hickory	0.965	1.091	2.072
	Pine	0.740	1.014	2.046
	Spruce-Fir	1.656	1.318	2.136
	Nonstocked	1.928	1.928	2.117
NPS	Conifer	1.189	1.190	2.114
	Lowland Hardwood	1.370	1.177	2.055
	Maple-Beech-Birch	1.126	1.201	2.130
	Oak-Hickory	1.139	1.138	2.072
	Oak-Pine	2.014	1.215	4.185
	Nonstocked	2.052	2.052	2.072
PSW	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
	Other Conifer	4.032	1.785	4.768
	Pinyon-Juniper	4.430	4.430	4.820
	Redwood	2.513	1.312	4.698
	Nonstocked	4.431	4.431	4.626
PWE	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
	Lodgepole Pine	1.790	1.257	4.823

	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	1.768	1.213	4.768
	Nonstocked	4.315	4.315	4.626
PWW	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
	Other Hardwoods	2.157	1.220	4.745
	Red Alder	2.094	1.230	4.745
	Western Hemlock	2.081	1.218	4.693
	Nonstocked	4.401	4.401	4.589
RMN	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
	Lodgepole Pine	2.571	1.500	4.773
	Other Conifer	2.614	1.518	4.821
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	2.099	1.344	4.776
	Nonstocked	4.430	4.430	4.773
RMS	Douglas-fir	5.145	2.232	4.829
	Fir-Spruce	2.861	1.568	4.822
	Hardwoods	1.858	1.110	4.745
	Lodgepole Pine	3.305	1.737	4.797
	Other Conifer	2.134	1.382	4.821
	Pinyon-Juniper	2.757	2.757	4.820
	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
SC	Bottomland Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
	Oak-Pine	1.903	1.190	4.173
	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
SE	Bottomland Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
	Oak-Pine	1.642	1.117	4.195
	Planted Pine	1.470	1.036	4.141
	Upland Hardwood	1.903	1.191	4.182
	Nonstocked	4.033	4.033	4.182

[a] Prediction of ratio of understory C to live tree C is based on the 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. Note that this ratio is multiplied by tree C density on each plot to produce understory vegetation.
[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 substantially affect C mass are decay, which affects density and thus specific C fraction (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). A C fraction of 0.5 is used for standing dead trees (USDA forest Service 2018d).

Downed dead wood, inclusive of logging residue, are sampled on a subset of NFI 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-221. 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-222. 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-221 (SC, Natural Pine)

C density = $82.99 \times 0.068 = 5.67$ (T C/ha)

Second, an average logging residue from age and Table A-221 (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 = $(5.67 + 1.37) \times 0.886 = 6.24$ (T C/ha)

Table A-221: Ratio for Estimating Downed Dead Wood by Region and Forest Type

Region[a]	Forest type[a]	Ratio[b]
NE	Aspen-Birch	0.078
	MBB/Other Hardwood	0.071
	Oak-Hickory	0.068
	Oak-Pine	0.061
	Other Pine	0.065
	Spruce-Fir	0.092
	White-Red-Jack Pine	0.055
	Nonstocked	0.019
NLS	Aspen-Birch	0.081
	Lowland Hardwood	0.061
	Maple-Beech-Birch	0.076
	Oak-Hickory	0.077
	Pine	0.072
	Spruce-Fir	0.087
	Nonstocked	0.027
NPS	Conifer	0.073
	Lowland Hardwood	0.069
	Maple-Beech-Birch	0.063
	Oak-Hickory	0.068
	Oak-Pine	0.069
	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
PWW	Douglas-fir	0.100
	Fir-Spruce	0.090
	Other Conifer	0.073
	Other Hardwoods	0.062
	Red Alder	0.095
	Western Hemlock	0.099
	Nonstocked	0.020
RMN	Douglas-fir	0.062
	Fir-Spruce	0.100
	Hardwoods	0.112
	Lodgepole Pine	0.058
	Other Conifer	0.060
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.087
	Nonstocked	0.018
RMS	Douglas-fir	0.077
	Fir-Spruce	0.079
	Hardwoods	0.064
	Lodgepole Pine	0.098
	Other Conifer	0.060
	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).

[b] The ratio is multiplied by the live tree C density on a plot to produce downed dead wood C density (T C/ha).

Table A-222: 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 NFI 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 NFI plots, a model (3) was developed to predict C density based on plot/site variables for plots that lacked litter information (Domke et al. 2016):

$$P(FFCFull) = f(lat, lon, elev, fortypgrp, above, ppt, tmax, gmi) + u \quad (3)$$

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.

Due to data limitations in certain regions and inventory periods a series of reduced non-parametric models, which did not include climate variables, were used rather than replacing missing variables with imputation techniques. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied. Litter C predictions are expressed as density (T ha^{-1}).

Soil organic carbon

This section provides a summary of the methodology used to predict SOC for this report. A complete description of the approach is in Domke et al. (2017). The data used to develop the modeling framework to predict SOC on forest land came from the NFI and the International Soil Carbon Network. Since 2001, the FIA program has collected soil samples on every 16th base intensity plot (approximately every 2428 ha) distributed approximately every 38,848 ha, where at least one forested condition exists (Woodall et al. 2010). On fully forested plots, mineral and organic soils were sampled adjacent to subplots 2 by taking a single core at each location from two layers: 0 to 10.16 cm and 10.16 to 20.32 cm. The texture of each soil layer was estimated in the field, and physical and chemical properties were determined in the laboratory (U.S. Forest Service 2011). For this analysis, estimates of SOC from the NFI were calculated following O'Neill et al. (2005):

$$\sum SOC_{FIA\_TOTAL} = C_i \cdot BD_i \cdot t_i \cdot ucf \quad (4)$$

Where $\sum SOC_{FIA\_TOTAL}$ = total mass (Mg C ha-1) of the mineral and organic soil C over all *i*th layers, C_i = percent organic C in the *i*th layer, BD_i = bulk density calculated as weight per unit volume of soil (g·cm-3) at the *i*th soil layer, t_i= thickness (cm) of the *i*th soil layer (either 0 to 10.16 cm or 10.16 to 20.32 cm), and *ucf* = unit conversion factor (100).

The SOC_{FIA_TOTAL} estimates from each plot were assigned by forest condition on each plot, resulting in 3,667 profiles with SOC layer observations at 0 to 10.16 and 10.16 to 20.32 cm depths. Since the United States has historically reported SOC estimates to a depth of 100 cm (Heath et al. 2011, USEPA 2015), International Soil Carbon Monitoring Network (ISCN) data from forests in the United States were harmonized with the FIA soil layer observations to develop model functions of SOC by soil order to a depth of 100 cm. All observations used from the ISCN were contributed by the Natural Resources Conservation Service. A total of 16,504 soil layers from 2,037 profiles were used from ISCN land uses defined as deciduous, evergreen, or mixed forest. The FIA-ISCN harmonized dataset used for model selection and prediction included a total of 5,704 profiles with 23,838 layer observations at depths ranging from 0 to 1,148 cm.

The modeling framework developed to predict SOC for this report was built around strategic-level forest and soil inventory information and auxiliary variables available for all FIA plots in the United States. The first phase of the new estimation approach involved fitting models using the midpoint of each soil layer from the harmonized dataset and SOC estimates at those midpoints. Several linear and nonlinear models were evaluated, and a log-log model provided the optimal fit to the harmonized data:

$$\log_{10} SOC_i = I + \log_{10} Depth \quad (5)$$

Where $\log_{10} SOC_i$ = SOC density (Mg C ha-1 cm depth-1) at the midpoint depth, I = intercept, $\log_{10} Depth$ = profile midpoint depth (cm).

The model was validated by partitioning the complete harmonized dataset multiple times into training and testing groups and then repeating this step for each soil order to evaluate model performance by soil order. Extra sum of squares F tests were used to evaluate whether there were statistically significant differences between the model coefficients from the model fit to the complete harmonized dataset and models fit to subsets of the data by soil order. Model coefficients for each soil order were used to predict SOC for the 20.32 to 100 cm layer for all FIA plots with soil profile observations. Next, the SOC layer observations from the FIA and predictions over the 100 cm profile for each FIA plot were summed:

$$SOC_{100} = SOC_{FIA\_TOTAL} + SOC_{20-100} \quad (6)$$

Where SOC_{100} = total estimated SOC density from 0-100 cm for each forest condition with a soil sample in the FIA database, SOC_{FIA_TOTAL} as previously defined in model (4), SOC_{20-100} = predicted SOC from 20.32 to 100 cm from model (5).

In the second phase of the modeling framework, SOC_{100} estimates for FIA plots were used to predict SOC for plots lacking SOC_{100} estimates using a non-parametric model, this particular machine learning tool used bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breimen 2001). It also relies on random variable selection to develop a forest of uncorrelated regression trees. These trees recognize the relationship between a dependent variable, in this case SOC_{100}, and a set of predictor variables. All relevant predictor variables—those that may influence the formation, accumulation, and loss of SOC—from annual inventories collected on all base intensity plots and auxiliary climate, soil, and topographic variables obtained from the PRISM climate group (Northwest Alliance 2015), Natural Resources Conservation Service (NRCS 2015), and U.S. Geological Survey (Danielson and Gesch 2011), respectively, were included in the analysis. Due to regional differences in sampling protocols, many of the predictor variables included in the variable selection process were not available for all base intensity plots. To avoid problems with data limitations, pruning was used to reduce the models to the minimum number of relevant predictors (including both continuous and categorical variables) without substantial loss in explanatory power or increase in root mean squared error (RMSE). The general form of the full non-parametric models were:

$$P(SOC) = f(lat, lon, elev, fortypgrp, ppt, t\max, gmi, order, surfgeo) \qquad (7)$$

Where lat = latitude, lon = longitude, $elev$ = elevation, $fortypgrp$ = forest type group, ppt = mean annual precipitation, $t\max$ = average maximum temperature, gmi = the ratio of precipitation to potential evapotranspiration, $order$ = soil order, $surfgeo$ = surficial geological description.

Compilation of population estimates using NFI plot data

Methods for the conterminous United States

The estimation framework is fundamentally driven by the annual NFI. Unfortunately, the annual NFI does not extend to 1990 and the periodic data from the NFI are not consistent (e.g., different plot design) with the annual NFI necessitating the adoption of a system to predict the annual C parameters back to 1990. To facilitate the C prediction parameters, the estimation framework is comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (i.e., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (e.g., Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and nonforest observations in the NFI database (U.S. Forest Service 2018a-c). Model predictions for before or after the annual NFI period are constructed from the estimation framework using only the annual observations. This modeling framework includes opportunities for user-defined scenarios to evaluate the impacts of land use change and disturbance rates on future C stocks and stock changes. As annual NFIs have largely completed at least one cycle and been remeasured, age and area transition matrices can be empirically informed. In contrast, as annual inventories in west Oklahoma and Wyoming are still undergoing their first complete cycle they are still in the process of being remeasured, and as a result theoretical transition matrices need to be developed.

Wear and Coulston (2015) and Coulston et al. (2015) provide the framework for the model. The overall objective is to estimate unmeasured historical changes and future changes in forest C parameters consistent with annual NFI estimates. For most regions, forest conditions are observed at time t_0 and at a subsequent time t_1=t_0+s, where s is the time step (time measured in years) and is indexed by discrete (5 year) forest age classes. The inventory from t_0 is then predicted back to the year 1990 and projected from t_1 to 2019. This prediction approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class. For all states in the conterminous U.S. (except for Wyoming and west Oklahoma) age class transition matrices are estimated from observed changes in age classes between t_0 and t_1. In west Oklahoma and Wyoming only one inventory was available (t_0) so transition matrices were obtained from theory but informed by the condition of the observed inventory to predict from t_0 to 1990 and predict from t_0 to 2019.

Theoretical Age Transition Matrices

Without any mortality-inducing disturbance, a projection of forest conditions would proceed by increasing all forest ages by the length of the time step until all forest resided in a terminal age class where the forest is retained indefinitely (this is by assumption, where forest C per unit area reaches a stable maximum). For the most basic case, disturbances (e.g., wildfire or timber harvesting) can reset some of the forest to the first age class. Disturbance can also alter the age class in more subtle ways. If a portion of trees in a multiple-age forest dies, the trees comprising the average age calculation change, thereby shifting the average age higher or lower (generally by one age class).

With *n* age classes**,** the age transition matrix (**T)** is an n x n matrix, and each element defines the proportion of forest area in class *q* transitioning to class *r* during the time step (*s*). The values of the elements of **T** depend on a number of factors, including forest disturbances such as harvests, fire, storms, and the value of s, especially relative to the span of the age classes. For example, holding area fixed, allowing for no mortality, defining the time step *s* equivalent to the span of age classes, and defining five age classes results in:

$$\boldsymbol{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \tag{8}$$

where all forest area progresses to the next age class and forests within the terminal age class are retained forever. With this version of **T**, after five time steps all forests would be in the terminal age class. Relaxing these assumptions changes the structure of **T**. If all disturbances, including harvesting and fire, that result in stand regeneration are accounted for and stochastic elements in forest aging are allowed, **T** defines a traditional Lefkovitch matrix population model (e.g., Caswell 2001) and becomes:

$$\boldsymbol{T} = \begin{pmatrix} 1-t_1-d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1-t_2-d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1-t_3-d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1-t_4-d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1-d_5 \end{pmatrix} \tag{9}$$

Where is the proportion of forest of age class q transitioning to age class *q*+1, is the proportion of age class *q* that experiences a stand-replacing disturbance, and (is the proportion retained within age class *q* ().

Projections and Backcast for West Oklahoma and Wyoming

Projections of forest C in west Oklahoma and Wyoming are based on a life stage model:

$$\Delta \mathrm{C_t} = \mathrm{C_{t+m}} - \mathrm{C_t} = (\mathbf{F_t T} - \mathbf{F_t}) \cdot \mathbf{Den} + \mathbf{L_t} \cdot \mathbf{Den} \tag{10}$$

In this framework **T** is an age transition matrix that shifts the age distribution of the forest **F**. The difference in forest area by age class between time *t* and *t+s* is **F**t**T**-**F**t. This quantity is multiplied by C density by age class (**Den**) to estimate C stock change of forest remaining forest between *t* and *t+s*. Land use change is accounted for by the addition of **L**t·**Den,** where **L**t identifies the age distribution of net land shifts into or out of forests. A query of the forest inventory databases provides estimates of **F** and **Den**, while inventory observations and modeling assumptions are used to estimate **T**. By expanding **Den** to a matrix of C contained in all the constituent pools of forest carbon, projections for all pools are generated.

Land use change is incorporated as a 1 x n vector **L,** with positive entries indicating increased forest area and negative entries indicating loss of forest area, which provides insights of net change only. Implementing a forest area change requires some information and assumptions about the distribution of the change across age classes (the n dimension of **L**). In the eastern states, projections are based on the projection of observed gross area changes by age class. In western states, total forest area changes are applied using rules. When net gains are positive, the area is added to the youngest forest age class; when negative, area is subtracted from all age classes in proportion to the area in each age class category.

Backcasting forest C inventories generally involve the same concepts as forecasting. An initial age class distribution is shifted at regular time steps backwards through time, using a transition matrix (B):

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t \cdot \boldsymbol{B} \quad (11)$$

B is constructed based on similar logic used for creating **T**. The matrix cannot simply be derived as the inverse of **T** () because of the accumulating final age class (i.e., **T** does not contain enough information to determine the proportion of the final age class derived from the n-1 age class and the proportion that is retained in age class n from the previous time step).120 However, **B** can be constructed using observed changes from the inventory and assumptions about transition/accumulation including nonstationary elements of the transition model:

$$\boldsymbol{B} = \begin{pmatrix} 1-\sum_q d_q & \mathrm{b}_2 & 0 & 0 & 0 \\ d_1 & 1-b_2 & \mathrm{b}_3 & 0 & 0 \\ d_2 & 0 & 1-b_3 & \mathrm{b}_4 & 0 \\ d_3 & 0 & 0 & 1-b_4 & \mathrm{b}_r \\ d_4 & 0 & 0 & 0 & 1-\mathrm{b}_r \end{pmatrix} \quad (12)$$

Forest area changes need to be accounted for in the backcasts as well:

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t\boldsymbol{B} - \boldsymbol{L}_t \quad (13)$$

Where **Lt** is the forest area change between t_1 and t_0 as previously defined.

In west Oklahoma and Wyoming the theoretical life-stage models described by matrices (9) and (10) were applied. The disturbance factors (d) in both **T** and **B** are obtained from the current NFI by assuming that the area of forest in age class 1 resulted from disturbance in the previous period, the area in age class 2 resulted from disturbance in the period before that, and so on. The source of disturbed forest was assumed to be proportional to the area of forest in each age class. For projections (**T**), the average of implied disturbance for the previous two periods was applied. For the backcast (**B**), the disturbance frequencies implied by the age class distribution for each time step are moved. For areas with empirical transition matrices, change in forest area (**L**t) was backcasted/projected using the change in forest area observed for the period t_0 to t_1.

Projections and Backcast for CONUS (excluding west Oklahoma and Wyoming)

For all states in the conterminous United States (with the exception of west Oklahoma and Wyoming) remeasured plots were available. When remeasured data are available, the previously described approach is extended to estimate change more directly; in this case ΔCt=Ft·δC, where ΔC is net stock change by pool within the analysis area, F is as previously defined, and δC is an *n* x cp matrix of per unit area forest C stock change per year by pool (cp) arrayed by forest age class. Inter-period forest C dynamics are previously described, and the age transition matrix (T) is estimated from the observed data directly. Forest C change at the end of the next period is defined as: ΔCt+s = Ft·T·δC. Land use change and disturbances such as cutting, fire, weather, insects, and diseases were incorporated by generalizing to account for the change vectors and undisturbed forest remaining as undisturbed forest:

$$\Delta C_{t+s} = \sum_{d \in L} (A_{td} \cdot T_d \cdot \delta C_d) \quad (14)$$

Where A_{td} = area by age class of each mutually exclusive land category in L which includes d disturbances at time t.

[120] Simulation experiments show that a population that evolves as a function of **T** can be precisely predicted using $\mathbf{T}^{-1}$. However, applying the inverse to a population that is not consistent with the long-run outcomes of the transition model can result in predictions of negative areas within some stage age classes.

L = (FF, NFF, FNF, Fcut, Ffire, Fweather, Fid) where FF=undisturbed forest remaining as undisturbed forest, NFF=nonforest to forest conversion, FNF=forest to nonforest conversion, Fcut=cut forest remaining as forest, Ffire=forest remaining as forest disturbed by fire, Fweather=forest remaining as forest disturbed by weather, and Fid=forest remaining as forest disturbed by insects and diseases. In the case of land transfers (FNF and NFF), T_d is an n x n identity matrix and *δCd* is a C stock transfer rate by age. Paired measurements for all plots in the inventory provide direct estimates of all elements of matrices.

Predictions are developed by specifying either Ft+s or At+sd for either a future or a past state. To move the system forward, T is specified so that the age transition probabilities are set up as the probability between a time 0 and a time 1 transition. To move the system backward, T is replaced by B so that the age transition probabilities are for transitions from time 1 to time 0. Forecasts were developed by assuming the observed land use transitions and disturbance rates would continue for the next 5 years. Prediction moving back in time were developed using a Markov Chain process for land use transitions, observed disturbance rates for fire, weather, and insects. Historical forest cutting was incorporated by using the relationship between the area of forest cutting estimated from the inventory plots and the volume of roundwood production from the Timber Products Output program (U.S. Forest Service 2018d). This relationship allowed for the modification of Fcut such that it followed trends described by Oswalt et al. (2014).

Methods for Alaska

Inventory and sampling

The NFI has been measuring plots in southeast and southcentral coastal Alaska as part of the annual NFI since 2004. In 2014, a pilot inventory was established in the Tanana Valley State Forest and Tetlin National Wildlife Refuge in Interior Alaska. This pilot inventory was a collaboration between the USDA Forest Service, FIA program, the National Aeronautical and Space Administration, and many other federal, state, and local partners. This effort resulted in the establishment of 98 field plots which were measured during the summer of 2014 and integrated with NASA's Goddard LiDAR/Hyperspectral/Thermal (G-LiHT) imaging system. Given the remote nature of Interior Alaska forest, the NFI plots in the pilot campaign were sampled at a lower intensity than base NFI plots (1 plot per 2403 ha) in the CONUS and coastal Alaska. Several plot-level protocols were also adapted to accommodate the unique conditions of forests in this region (see Pattison et al. 2018 for details on plot design and sampling protocols). The pilot field campaign became operational in 2016 and plots measured on a 1/5 intensity (1 plot per 12013 ha) from 2014, 2016, and 2017 from the Interior Alaska NFI were used (n = 446) with base-intensity annual NFI plots from coastal AK (n = 2748) in this analysis.

A spatially balanced sampling design was used to identify field sample locations across all of Alaska following standard FIA procedures with a tessellation of hexagons and one sample plot selected per hexagon – 1/5 intensity in interior Alaska and base-intensity in coastal Alaska (Bechtold and Patterson 2005). The sampling locations were classified as forest or non-forest using the NLCD from 2001 and 2011. It is important to note that this is different from how NFI plots are classified into land cover and land use categories in the CONUS where high resolution areal imagery is used. Since the fine-scale remotely sensed imagery (National Agriculture Imagery Program; NAIP 2015) used in the conterminous U.S. were not available for AK and given that the NLCD has been used to classify land use categories in Alaska in the *Representation of the U.S. Land Base* in this Inventory, the NLCD was the most consistent and credible option for classification. Next, the forest land was further classified as managed or unmanaged following the definition in the *Representation of the U.S. Land Base* and using similar procedures (see Ogle et al. 2018 for details on the managed land layer for the U.S.).

While only a subset of the total NFI sample was available at the time of this Inventory, all NFI plot locations within the sampling frame were used in this analysis. Auxiliary climate, soil, structural, disturbance, and topographic variables were harmonized with each plot location and year of occurrence (if relevant and available) over the entire time series (1990 to 2018).

Prediction

The harmonized data were used to predict plot-level parameters using non-parametric random forests (RF) for regression, a machine learning tool that uses bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breiman 2001). Random forests also relies on random variable selection to develop a forest of uncorrelated regression trees. These trees uncover the relationship between a dependent variable (e.g., live aboveground biomass carbon) and a set of predictor variables. The RF analysis included predictor variables (n > 100) that may influence carbon stocks within each forest ecosystem pool at each plot location over the entire time series. To avoid problems with data limitations over the time series, variable pruning was used to reduce the RF models to the minimum number of relevant predictors without substantial loss in explanatory power or increase in root mean squared error (RMSE; see Domke et al. 2017, Domke et al. In prep for more information). The harmonized dataset used to develop the RF models for each plot-level parameter were partitioned 10 times into training (70 percent) and testing (30 percent) groups and the results were evaluated graphically and with a variety of statistical metrics including Spearman's rank correlation, equivalence tests (Wellek 2003), as well as RMSE. All analyses were conducted using R statistical software (R Core Team 2018).

The RF predictions of carbon stocks for the year 2016 were used as a baseline for plots that have not yet been measured. Next, simple linear regression was used to predict average annual gains/losses by forest ecosystem carbon pool using the chronosequence of plot measurements available at the time of this Inventory. These predicted gains/losses were applied over the time series from the year of measurement or the 2016 base year in the case of plots that have not yet been measured. Since the RF predictions of carbon stocks and the predicted gains/losses were obtained from empirical measurements on NFI plots that may have been disturbed at some point over the time series, the predictions inherently incorporate gains/losses associated with natural disturbance and harvesting. That said, there was no evidence of fire disturbance on the plots that have been measured to date. To account for carbon losses associated with fire, carbon stock predictions for plots that have not been measured but were within a fire perimeter during the Inventory period were adjusted to account for area burned (see Table A-233) and the IPCC (Table 2.6, IPCC 2006) default combustion factor for boreal forests was applied to all live, dead, and litter biomass carbon stocks in the year of the disturbance. The plot-level predictions in each year were then multiplied by the area they represent within the sampling frame to compile population estimates over the time series for this Inventory.

Forest Land Remaining Forest Land Area Estimates

Forest land area estimates in section 6.2 *Forest Land Remaining Forest Land* (CRF Category 4A1) of this Inventory are compiled using NFI data. Forest Land area estimates obtained from these data are also used as part of section 6.1 Representation of the U.S. Land Base (CRF Category 4.1). The Forest Land area estimates in section 6.2 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. The National Land Cover Dataset is used in addition to NFI estimates in section 6.2 Representation of the U.S. Land Base and Forest Lands in Hawaii are included in that section. This results in small differences in the managed Forest Land area between sections 6.1 and 6.2 of this Inventory (Table A-231). There are also other factors contributing to the small differences such as harmonization of aspatial and spatial data across all land use categories in section 6.1 over the entire Inventory time series.

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 and the U.S. forest products module (Ince et al. 2011). 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-223). 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-221. 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. The sum of these variables yield estimates for HWP contribution under the production accounting approach.

Table A-223: Harvested Wood Products from Wood Harvested in the United States—Annual Additions of C to Stocks and Total Stocks under the Production Approach

Year	Net C additions per year (MMT C per year)			Total C stocks (MMT C)		
	Total	Products in use	Products in SWDS			
		Total	Total	Total	Products in use	Products in SWDS
1990	(33.8)	(14.9)	(18.8)	1895	1249	646
1991	(33.8)	(16.3)	(17.4)	1929	1264	665
1992	(32.9)	(15.0)	(17.9)	1963	1280	683
1993	(33.4)	(15.9)	(17.5)	1996	1295	701
1994	(32.3)	(15.1)	(17.2)	2029	1311	718
1995	(30.6)	(14.1)	(16.5)	2061	1326	735
1996	(32.0)	(14.7)	(17.3)	2092	1340	752
1997	(31.1)	(13.4)	(17.7)	2124	1355	769
1998	(32.5)	(14.1)	(18.4)	2155	1368	787
1999	(30.8)	(12.8)	(18.0)	2188	1382	805
2000	(25.5)	(8.7)	(16.8)	2218	1395	823
2001	(26.8)	(9.6)	(17.2)	2244	1404	840
2002	(25.6)	(9.4)	(16.2)	2271	1413	857
2003	(28.4)	(12.1)	(16.3)	2296	1423	873
2004	(28.7)	(12.4)	(16.4)	2325	1435	890
2005	(28.9)	(11.6)	(17.3)	2353	1447	906
2006	(27.3)	(10.0)	(17.4)	2382	1459	923
2007	(20.8)	(3.7)	(17.1)	2410	1469	941
2008	(14.9)	1.8	(16.7)	2430	1473	958
2009	(16.6)	(0.0)	(16.6)	2445	1471	974
2010	(18.8)	(2.0)	(16.8)	2462	1471	991
2011	(19.4)	(2.4)	(17.0)	2481	1473	1008
2012	(20.9)	(3.7)	(17.1)	2500	1475	1025
2013	(22.5)	(5.3)	(17.3)	2521	1479	1042
2014	(23.4)	(6.1)	(17.4)	2543	1484	1059
2015	(24.2)	(6.7)	(17.5)	2567	1490	1076

2016	(25.2)	(7.6)	(17.6)	2591	1497	1094
2017	(26.1)	(8.3)	(17.9)	2616	1505	1112
2018	(26.9)	(8.6)	(18.3)	2642	1513	1129

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-224: Comparison of Net Annual Change in Harvested Wood Products C Stocks Using Alternative Accounting Approaches (kt CO_2 Eq./year)

	HWP Contribution to LULUCF Emissions/ Removals (MMT CO_2 Eq.)		
Inventory Year	Stock-Change Approach	Atmospheric Flow Approach	Production Approach
1990	(116.6)	(131.4)	(123.8)
1991	(120.2)	(131.6)	(123.8)
1992	(127.1)	(127.8)	(120.7)
1993	(130.3)	(129.9)	(122.5)
1994	(126.0)	(128.0)	(118.4)
1995	(122.3)	(122.5)	(112.2)
1996	(131.3)	(127.4)	(117.3)
1997	(137.2)	(122.8)	(114.2)
1998	(147.1)	(127.2)	(119.0)
1999	(141.2)	(120.2)	(112.9)
2000	(125.0)	(100.3)	(93.4)
2001	(130.7)	(103.3)	(98.2)
2002	(125.8)	(98.5)	(93.7)
2003	(143.2)	(107.9)	(104.1)
2004	(142.1)	(109.7)	(105.4)
2005	(136.6)	(112.0)	(106.0)
2006	(113.6)	(109.8)	(100.3)
2007	(72.6)	(88.1)	(76.1)
2008	(41.8)	(70.0)	(54.5)
2009	(48.2)	(79.8)	(60.8)
2010	(51.4)	(92.2)	(69.1)
2011	(59.0)	(95.2)	(71.0)
2012	(72.4)	(102.9)	(76.5)
2013	(85.7)	(109.4)	(82.6)
2014	(92.8)	(113.2)	(86.0)
2015	(99.4)	(116.2)	(88.7)
2016	(103.2)	(120.1)	(92.4)
2017	(132.1)	(119.9)	(95.7)
2018	(135.0)	(125.5)	(98.8)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-225: Harvested Wood Products Sectoral Background Data for LULUCF—United States

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
	ΔCHWP IU DC	ΔCHWP SWDS DC	ΔC HWP IU DH	ΔCHWP SWDS DH	PIM	PEX	H	↑CHWP DC	↑CHWP DH	
									MMT C/yr	MMT CO_2/yr
1990	13.2	18.6	14.9	18.8	11.6	15.6	144.4	108.6	110.7	(123.8)
1991	15.8	17.0	16.3	17.4	12.9	16.0	139.4	103.5	105.6	(123.8)
1992	17.0	17.6	15.0	17.9	14.5	14.7	134.6	99.7	101.6	(120.7)
1993	18.3	17.2	15.9	17.5	15.7	15.6	134.8	99.3	101.3	(122.5)
1994	17.3	17.1	15.1	17.2	16.7	17.3	137.0	102.1	104.7	(118.4)
1995	17.0	16.3	14.1	16.5	16.7	16.7	134.5	101.1	103.9	(112.2)
1996	18.7	17.1	14.7	17.3	18.0	16.9	135.4	100.7	103.4	(117.3)
1997	19.7	17.8	13.4	17.7	19.0	15.1	134.2	100.7	103.1	(114.2)
1998	21.4	18.7	14.1	18.4	20.7	15.2	134.2	99.5	101.7	(119.0)
1999	20.0	18.5	12.8	18.0	21.9	16.2	133.7	100.9	102.9	(112.9)
2000	16.5	17.6	8.7	16.8	22.1	15.3	127.9	100.5	102.4	(93.4)

2001	17.4	18.2	9.6	17.2	23.2	15.7	126.9	98.7	100.1	(98.2)
2002	17.0	17.3	9.4	16.2	23.8	16.3	126.5	99.6	100.9	(93.7)
2003	21.4	17.6	12.1	16.3	26.6	17.0	121.8	92.4	93.5	(104.1)
2004	21.0	17.8	12.4	16.4	26.9	18.1	123.5	93.6	94.8	(105.4)
2005	18.7	18.6	11.6	17.3	25.5	18.8	120.1	89.6	91.2	(106.0)
2006	12.7	18.3	10.0	17.4	21.7	20.6	117.6	87.6	90.2	(100.3)
2007	2.3	17.5	3.7	17.1	17.0	21.2	104.4	80.4	83.7	(76.1)
2008	(5.2)	16.6	(1.8)	16.7	13.0	20.7	94.5	75.4	79.6	(54.5)
2009	(3.1)	16.3	0.0	16.6	14.1	22.7	97.6	75.9	81.0	(60.8)
2010	(2.1)	16.1	2.0	16.8	13.9	25.0	102.7	77.5	83.9	(69.1)
2011	(0.0)	16.1	2.4	17.0	14.0	23.8	106.7	80.8	87.4	(71.0)
2012	3.5	16.3	3.7	17.1	15.3	23.6	111.2	83.2	90.4	(76.5)
2013	6.9	16.5	5.3	17.3	17.1	23.5	115.0	85.2	92.5	(82.6)
2014	8.7	16.7	6.1	17.4	17.7	23.3	117.0	86.1	93.6	(86.0)
2015	10.2	16.9	6.7	17.5	18.5	23.1	119.1	87.4	94.9	(88.7)
2016	11.1	17.0	7.6	17.6	18.5	23.1	122.1	89.3	96.9	(92.4)
2017	18.1	17.9	8.3	17.9	22.6	19.3	108.1	75.4	82.0	(95.7)
2018	17.9	18.9	8.6	18.3	21.6	19.0	110.1	75.9	83.2	(98.8)

Note: 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, 2007, Howard and Jones 2016, Howard and Liang 2019).

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-226. 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-227. 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-223 and Table A-224. 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.

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 *Land Converted to Forest Land* – Soil C Methods.

Table A-226: 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-life 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 U.S." *Forest Products Journal* 58:56–72.

Table A-227: 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 U.S." *Forest Products Journal* 58:56–72.

Table A-228: Net CO_2 Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	1995	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Forest	**(610.1)**	**(598.7)**	**(543.3)**	**(560.0)**	**(464.0)**	**(513.6)**	**(572.6)**	**(570.2)**	**(576.3)**	**(548.2)**	**(577.4)**	**(556.2)**	**(583.2)**	**(568.5)**	**(573.8)**	**(532.8)**	**(587.4)**	**(565.5)**	**(552.0)**	**(564.5)**
Aboveground Biomass	(425.1)	(416.1)	(383.4)	(387.2)	(369.4)	(378.3)	(391.3)	(392.0)	(394.0)	(391.4)	(398.1)	(391.3)	(405.3)	(394.3)	(403.1)	(390.8)	(404.6)	(397.0)	(381.2)	(385.2)
Belowground Biomass	(98.6)	(96.6)	(89.7)	(90.2)	(86.5)	(88.4)	(90.8)	(90.9)	(91.3)	(90.0)	(91.8)	(90.3)	(92.1)	(92.8)	(92.5)	(88.9)	(92.9)	(91.1)	(87.6)	(88.6)
Dead Wood	(81.9)	(82.8)	(80.3)	(82.2)	(73.2)	(78.2)	(84.1)	(83.9)	(84.7)	(81.5)	(84.8)	(83.4)	(87.1)	(83.7)	(84.5)	(80.3)	(88.4)	(87.6)	(83.1)	(86.4)
Litter	(5.0)	(3.5)	10.7	0.4	66.0	32.4	(5.2)	(3.0)	(5.1)	16.4	0.3	(1.4)	(3.8)	5.2	(0.5)	30.2	(3.1)	(0.9)	(3.5)	(3.1)
Soil (Mineral)	0.3	(0.1)	(1.1)	(1.3)	(1.4)	(1.6)	(1.8)	(1.1)	(2.0)	(2.4)	(2.9)	4.6	3.7	(4.4)	5.7	(2.7)	(0.6)	8.2	1.4	(3.3)
Soil (Organic)	(0.6)	(0.5)	(0.3)	(0.3)	(0.2)	(0.2)	(0.1)	(0.1)	+	+	(0.8)	4.9	0.6	0.6	0.3	(1.0)	1.4	2.3	1.4	1.4
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(112.2)**	**(98.2)**	**(93.7)**	**(104.1)**	**(105.4)**	**(106.0)**	**(100.3)**	**(76.1)**	**(54.5)**	**(60.8)**	**(69.1)**	**(71.0)**	**(76.5)**	**(82.6)**	**(86.0)**	**(88.7)**	**(92.4)**	**(95.7)**	**(98.8)**
Products in Use	(54.8)	(51.7)	(35.1)	(34.5)	(44.4)	(45.4)	(42.6)	(36.6)	(13.5)	6.6	(0.0)	(7.4)	(8.7)	(13.6)	(19.3)	(22.3)	(24.6)	(27.8)	(30.3)	(31.5)
SWDS	(69.0)	(60.5)	(63.1)	(59.3)	(59.6)	(60.0)	(63.4)	(63.7)	(62.6)	(61.1)	(60.8)	(61.7)	(62.3)	(62.8)	(63.3)	(63.7)	(64.1)	(64.6)	(65.5)	(67.2)
Total Net Flux	**(733.9)**	**(710.9)**	**(641.5)**	**(653.7)**	**(568.1)**	**(619.0)**	**(678.6)**	**(670.5)**	**(652.4)**	**(602.7)**	**(638.2)**	**(625.3)**	**(654.2)**	**(645.0)**	**(656.4)**	**(618.8)**	**(676.1)**	**(657.9)**	**(647.7)**	**(663.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Parentheses indicate negative values.

Table A-229: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	1995	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Forest	**(166.4)**	**(163.3)**	**(148.2)**	**(152.7)**	**(126.5)**	**(140.1)**	**(156.2)**	**(155.5)**	**(157.2)**	**(149.5)**	**(157.5)**	**(151.7)**	**(159.1)**	**(155.0)**	**(156.5)**	**(145.3)**	**(160.2)**	**(154.2)**	**(150.5)**	**(153.9)**
Aboveground Biomass	(115.9)	(113.5)	(104.6)	(105.6)	(100.7)	(103.2)	(106.7)	(106.9)	(107.4)	(106.8)	(108.6)	(106.7)	(110.5)	(107.5)	(109.9)	(106.6)	(110.4)	(108.3)	(104.0)	(105.1)
Belowground Biomass	(26.9)	(26.3)	(24.5)	(24.6)	(23.6)	(24.1)	(24.8)	(24.8)	(24.9)	(24.6)	(25.0)	(24.6)	(25.1)	(25.3)	(25.2)	(24.2)	(25.3)	(24.9)	(23.9)	(24.2)
Dead Wood	(22.3)	(22.6)	(21.9)	(22.4)	(20.0)	(21.3)	(22.9)	(22.9)	(23.1)	(22.2)	(23.1)	(22.7)	(23.8)	(22.8)	(23.1)	(21.9)	(24.1)	(23.9)	(22.7)	(23.6)
Litter	(1.4)	(1.0)	2.9	0.1	18.0	8.8	(1.4)	(0.8)	(1.4)	4.5	0.1	(0.4)	(1.0)	1.4	(0.1)	8.2	(0.8)	(0.3)	(1.0)	(0.8)
Soil (Mineral)	0.1	(0.0)	(0.3)	(0.3)	(0.4)	(0.4)	(0.5)	(0.3)	(0.5)	(0.7)	(0.8)	1.3	1.0	(1.2)	1.6	(0.7)	(0.2)	2.2	0.4	(0.9)
Soil (Organic)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	0.0	(0.2)	1.3	0.2	0.2	0.1	(0.3)	0.4	0.6	0.4	0.4
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(30.6)**	**(26.8)**	**(25.6)**	**(28.4)**	**(28.7)**	**(28.9)**	**(27.3)**	**(20.8)**	**(14.9)**	**(16.6)**	**(18.8)**	**(19.4)**	**(20.9)**	**(22.5)**	**(23.4)**	**(24.2)**	**(25.2)**	**(26.1)**	**(26.9)**
Products in Use	(14.9)	(14.1)	(9.6)	(9.4)	(12.1)	(12.4)	(11.6)	(10.0)	(3.7)	1.8	(0.0)	(2.0)	(2.4)	(3.7)	(5.3)	(6.1)	(6.7)	(7.6)	(8.3)	(8.6)
SWDS	(18.8)	(16.5)	(17.2)	(16.2)	(16.3)	(16.4)	(17.3)	(17.4)	(17.1)	(16.7)	(16.6)	(16.8)	(17.0)	(17.1)	(17.3)	(17.4)	(17.5)	(17.6)	(17.9)	(18.3)
Total Net Flux	**(200.2)**	**(193.9)**	**(174.9)**	**(178.3)**	**(154.9)**	**(168.8)**	**(185.1)**	**(182.9)**	**(177.9)**	**(164.4)**	**(174.1)**	**(170.5)**	**(178.4)**	**(175.9)**	**(179.0)**	**(168.8)**	**(184.4)**	**(179.4)**	**(176.7)**	**(180.9)**

+ Absolute value does not exceed 0.05 MMT C.

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Parentheses indicate negative values.

Table A-230: Forest area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	1995	2000	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Forest Area (1000 ha)	***279,748***	***279,840***	***280,025***	***279,762***	***279,783***	***279,814***	***279,861***	***279,918***	***279,931***	***279,957***	***279,960***	***279,977***	***280,041***	***280,041***	***279,893***	***279,787***	***279,682***
Carbon Pools																	
Forest	**51,527**	**52,358**	**53,161**	**54,042**	**54,198**	**54,355**	**54,505**	**54,663**	**54,815**	**54,974**	**55,129**	**55,286**	**55,431**	**55,592**	**55,746**	**55,897**	56,051
Aboveground Biomass	11,833	12,408	12,962	13,590	13,697	13,805	13,911	14,020	14,127	14,237	14,345	14,455	14,561	14,672	14,780	14,884	14,989
Belowground Biomass	2,350	2,483	2,612	2,759	2,783	2,808	2,833	2,858	2,883	2,908	2,933	2,958	2,982	3,008	3,033	3,056	3,081
Dead Wood	2,120	2,233	2,346	2,477	2,500	2,523	2,545	2,568	2,591	2,615	2,638	2,661	2,683	2,707	2,731	2,753	2,777
Litter	3,662	3,670	3,676	3,649	3,649	3,651	3,646	3,646	3,647	3,648	3,646	3,646	3,638	3,639	3,639	3,640	3,641
Soil (Mineral)	25,636	25,636	25,637	25,639	25,639	25,640	25,641	25,641	25,640	25,639	25,640	25,639	25,640	25,640	25,637	25,637	25,638
Soil (Organic)	5,927	5,928	5,928	5,929	5,929	5,929	5,929	5,929	5,927	5,927	5,927	5,927	5,927	5,927	5,926	5,926	5,926
Harvested Wood	**1,895**	**2,061**	**2,218**	**2,382**	**2,410**	**2,430**	**2,445**	**2,462**	**2,481**	**2,500**	**2,521**	**2,543**	**2,567**	**2,591**	**2,616**	**2,642**	**2,669**
Products in Use	1,249	1,326	1,395	1,459	1,469	1,473	1,471	1,471	1,473	1,475	1,479	1,484	1,490	1,497	1,505	1,513	1,521
SWDS	646	735	823	923	941	958	974	991	1,008	1,025	1,042	1,059	1,076	1,094	1,112	1,129	1,148
Total Stock	**53,423**	**54,419**	**55,380**	**56,424**	**56,607**	**56,786**	**56,950**	**57,124**	**57,295**	**57,474**	**57,650**	**57,829**	**57,998**	**58,183**	**58,362**	**58,539**	**58,720**

Table A-231: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (CRF Category 4.1) and 6.2 *Forest Land Remaining Forest Land* (CRF Category 4A1) (kha)

Year	Forest Land (managed) - 6.1 Representation of the U.S. Land Base	Forest Land (managed) - 6.2 Forest Land Remaining Forest Land	Difference between Forest Land Areas (managed) – 6.1 and Forest Land Remaining Forest Land – 6.2 area estimates
1990	280,393	279,748	645
1991	280,412	279,768	644
1992	280,407	279,764	642
1993	280,449	279,818	631
1994	280,421	279,814	606
1995	280,414	279,840	574
1996	280,437	279,870	566
1997	280,442	279,894	548
1998	280,436	279,919	518
1999	280,501	279,992	509
2000	280,518	280,025	493
2001	280,113	279,631	481
2002	280,157	279,675	482
2003	280,180	279,720	460
2004	280,224	279,767	457
2005	280,207	279,749	458
2006	280,216	279,762	454
2007	280,236	279,783	453
2008	280,266	279,814	452
2009	280,313	279,861	452
2010	280,369	279,918	452
2011	280,384	279,931	453
2012	280,386	279,957	429
2013	280,394	279,960	435
2014	280,438	279,977	461
2015	280,528	280,041	487
2016	280,529	280,041	487
2017	280,380	279,893	487
2018	280,274	279,787	487

Land Converted to Forest Land

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. Forest Inventory and Analysis data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools within an age class transition matrix for the 20-year conversion period (where possible). The 2015 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently, the classifications from 1990 to 2001 were based on less than 20 years. Furthermore, the FIA data used to compile estimates of carbon sequestration in the age class transition matrix are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series. Estimates for aboveground and belowground biomass, dead wood and litter were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2018b, 2018c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and 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 (USDA Forest Service 2018d). Further discussion and example calculations are provided in Woodall et al. 2011 and Domke et al. 2012.

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. See model (1) in the *Forest Land Remaining Forest Land* section of the Annex.

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-220. Regions and forest types are the same classifications described in Smith et al. (2003). An example calculation for understory C in aspen-birch forests in the Northeast is provided in the *Forest Land Remaining Forest Land* section of the Annex.

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-220) are set to coefficient A, which is a C density (T C/ha) for these types only.

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 (USDA Forest Service 2018d).

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-221. 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-222. 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).

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. 2016).

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 through 2014 (Domke et al. 2016).

Random forest, a machine learning tool (Domke et al. 2016), 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 model (3) and parameters are described in the *Forest Land Remaining Forest Land* section of the Annex.

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•ha−1.

Mineral Soil

A Tier 2 method is applied to estimate soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land-use, and land management activity, and then assigned reference C levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003; Ogle et al. 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2010 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). See Annex 3.12 for more information about this method (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management).

Table A-231 summarizes the annual change in mineral soil C stocks from U.S. soils that were estimated using a Tier 2 method (MMT C/year). The range is a 95 percent confidence interval estimated from the standard deviation of the NRI sampling error and uncertainty associated with the 1000 Monte Carlo simulations (See Annex 3.12). Table A-232 summarizes the total land areas by land use/land use change subcategory that were used to estimate soil C stock changes for mineral soils between 1990 and 2015.

Land Converted to Forest land area estimates

Forest land area estimates in section 6.3 *Land Converted to Forest Land* (CRF Category 4A2) of this Inventory are compiled using NFI data. Forest Land area estimates obtained from these data are also used as part of section 6.1 Representation of the U.S. Land Base (CRF Category 4.1). The Forest Land area estimates in section 6.3 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. The National

Land Cover Dataset is used in addition to NFI estimates in section 6.1 Representation of the U.S. Land Base and Forest Land in Hawaii is included in that section. This results in small differences in the managed Forest Land area in sections 6.1 and 6.3 of this Inventory (Table A-233). There are also other factors contributing to the small differences in area such as harmonization of aspatial and spatial data across all land use categories in section 6.1 over the entire Inventory time series.

Table A-231: Annual change in Mineral Soil C stocks from U.S. agricultural soils that were estimated using a Tier 2 method (MMT C/year)

Category	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018
Cropland Converted to Forest Land	0.08 (0.03 to 0.13)	0.07 (0.03 to 0.12)	0.07 (0.02 to 0.12)	0.07 (0.02 to 0.13)	0.06 (0.01 to 0.11)	0.06 (0.01 to 0.11)	0.06 (0.01 to 0.11)	0.06 (0.01 to 0.1)	0.05 (0.01 to 0.1)	0.05 (0.01 to 0.1)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)
Grassland Converted to Forest Land	-0.05 (-0.08 to -0.01)	-0.05 (-0.1 to -0.01)	-0.07 (-0.12 to -0.01)	-0.08 (-0.14 to -0.02)	-0.08 (-0.15 to -0.02)	-0.07 (-0.13 to -0.02)	-0.08 (-0.14 to -0.02)	-0.08 (-0.15 to -0.02)	-0.09 (-0.16 to -0.02)	-0.08 (-0.15 to -0.02)	-0.08 (-0.18 to 0.02)	-0.08 (-0.17 to 0.02)	-0.07 (-0.17 to 0.02)
Other Lands Converted to Forest Land	0.17 (0.13 to 0.21)	0.22 (0.14 to 0.25)	0.24 (0.17 to 0.29)	0.30 (0.22 to 0.36)	0.32 (0.22 to 0.38)	0.31 (0.21 to 0.38)	0.31 (0.21 to 0.38)	0.32 (0.19 to 0.39)	0.31 (0.19 to 0.41)	0.31 (0.17 to 0.43)	0.31 (0.13 to 0.5)	0.31 (0.12 to 0.5)	0.31 (0.12 to 0.51)
Settlements Converted to Forest Land	0.01 (0 to 0.02)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.02)	0.01 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.02 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)
Wetlands Converted to Forest Land	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)
Total Lands Converted to Forest Lands	**0.22**	**0.25**	**0.26**	**0.30**	**0.31**	**0.31**	**0.30**	**0.30**	**0.29**	**0.30**	**0.31**	**0.31**	**0.31**

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A-232: Total land areas (hectares) by land use/land use change subcategory for mineral soils between 1990 to 2015

Conversion Land Areas (Hectares x10^6)	1990	1995	2000	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Converted to Forest Land	0.17	0.16	0.17	0.16	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
Grassland Converted to Forest Land	0.75	0.81	0.80	0.81	0.82	0.84	0.84	0.84	0.83	0.84	0.84	0.83	0.80
Other Lands Converted to Forest Land	0.05	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Settlements Converted to Forest Land	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Wetlands Converted to Forest Land	0.01	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 Lands Converted to Forest Lands[a]	**0.99**	**1.06**	**1.05**	**1.08**	**1.09**	**1.11**	**1.11**	**1.10**	**1.10**	**1.10**	**1.10**	**1.09**	**1.06**

Note: Estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2018).

Table A-233: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base and 6.3 *Land Converted to Forest Land* (kha)

	Area (Thousand Hectares)		
Year	Forest Land (managed) - 6.1 Representation of the U.S. Land Base	Forest Land (managed) - 6.3 Land Converted to Forest Land	Difference between Forest Land (managed) – 6.1 Areas and Land Converted to Forest Land – 6.3 Areas
1990	1,228	1,120	108
1991	1,230	1,119	110
1992	1,272	1,154	118
1993	1,268	1,139	129
1994	1,328	1,172	156
1995	1,362	1,175	187
1996	1,367	1,171	197
1997	1,388	1,178	210
1998	1,428	1,187	241
1999	1,399	1,151	248
2000	1,428	1,163	265
2001	1,442	1,162	280
2002	1,440	1,162	278
2003	1,443	1,161	282
2004	1,435	1,153	282
2005	1,474	1,191	283
2006	1,485	1,200	285
2007	1,487	1,202	285
2008	1,512	1,221	291
2009	1,512	1,222	291
2010	1,498	1,207	291
2011	1,494	1,207	287
2012	1,517	1,207	310
2013	1,513	1,207	306
2014	1,465	1,189	276
2015	1,416	1,168	249
2016	1,267	1,102	165
2017	1,272	1,107	164
2018	1,272	1,107	164

Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see Table 6-11 in the FLRFL section) are consistent with the IPCC-recommended Tier 1 methodology (IPCC 2006). Specifically, they are considered approach 1 (propagation of error [Section 3.2.3.1]) (IPCC 2006). To better understand the effects of covariance, the contributions of sampling error and modeling error were parsed out. In addition, separate analyses were produced for forest ecosystem and HWP flux.

Estimates of forest C stocks in the United States are based on C estimates assigned to each of several thousand inventory plots from a regular grid. Uncertainty in these estimates and uncertainty associated with change estimates arise from many sources including sampling error and modeling error. Here we focus on these two types of error but acknowledge several other sources of error are present in the overall stock and stock change estimates. In terms of sampling based uncertainty, design based estimators described by Bechtold and Patterson (2005) were used to quantify the variance of C stock estimates. In this section we denote the estimate of C stock at time *t* as Ct and the variances of the estimate of C stock for time *t* as Var(Ct). These calculations follow Bechtold and Patterson (2005). The variance of stock change is then:

$$Var(Ct2-Ct1)=Var(Ct2)+Var(Ct1)-2\cdot Cov(Ct2,Ct1) \quad (15)$$

The uncertainty of a stock estimate associated with sampling error is U(Ct)s= Var(Ct)0.5. The uncertainty of a stock changes estimate associated with sampling error is U(ΔC)s=Var(Ct2-Ct1)0.5.

Model-based uncertainty is important because the pool-level C models have error. The total modeling mean-squared error (MSEm) is approximately 1,622 $(Mg/ha)^2$. The percent modeling error at time *t* is

$$\%U(Ct)m =100\cdot MSEm/dt \quad (16)$$

Where dt is the total C stock density at time t calculated as Ct/At where At is the forest area at time *t*.

The uncertainty of Ct from modeling error is

$$U(Ct)m=Ct\cdot\%U(Ct)m/100 \quad (17)$$

The model-based uncertainty with respect to stock change is then

$$U(\Delta C)m=(U(Ct1)m + U(Ct2)m - 2\cdot Cov(U(Ct1m,Ct2m)))0.5 \quad (18)$$

The sampling and model based uncertainty are combined for an estimate of total uncertainty. We considered these sources of uncertainty independent and combined as follow for stock change for stock change (ΔC):

$$U(\Delta C)=(U(\Delta C)m2+ U(\Delta C)s2)0.5 \text{ and the 95 percent confidence bounds was +- } 2\cdot U(\Delta C) \quad (19)$$

The mean square error (MSE) of pool models was (MSE, $[Mg\ C/ha]^2$): soil C (1143.0), litter (78.0), live tree (259.6), dead trees (101.5), understory (0.9), down dead wood (38.9), total MSE (1,621.9).

Numerous assumptions were adopted for creation of the forest ecosystem uncertainty estimates. Potential pool error correlations were ignored. Given the magnitude of the MSE for soil, including correlation among pool error would not appreciably change the modeling error contribution. Modeling error correlation between time 1 and time 2 was assumed to be 1. Because the MSE was fixed over time we assumed a linear relationship dependent on either the measurements at two points in time or an interpolation of measurements to arrive at annual flux estimates. Error associated with interpolation to arrive at annual flux is not included.

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.

The uncertainty about HWP and forest ecosystem net C flux were combined and assumed to be additive. Typically when propagating error from two estimates the variances of the estimates are additive. However, the uncertainty around the HWP flux was approximated using a Monte Carlo approach which resulted in the lack of a variance estimate for HWP C flux. Therefore, we considered the uncertainty additive between the HWP sequestration and the *Forest Land Remaining Forest Land* sequestration. Further, we assumed there was no covariance between the two estimates which is plausible as the observations used to construct each estimate are independent.

Emissions from Forest Fires

CO_2 Emissions from Forest Fires

As stated in other sections, the forest inventory approach implicitly accounts for CO_2 emissions due to disturbances. Net C stock change is estimated from successive 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, CH_4, and N_2O emissions from disturbances such as fire. These estimated emissions from forest fires are based on IPCC (2006) methodology, which includes a combination of U.S.-specific data on forest area burned, potential fuel available, and individual fire severity along with IPCC default emission factors and some combustion factors.

Emissions were calculated following IPCC (2006) methodology, according to equation 2.27 of IPCC (2006, Volume 4, Chapter 2), which in general terms is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission Factor} \times 10^{-3}$$

Where the estimate for emissions is in units of metric tons (MT), which is generally summarized as million metric tons (MMT) per year. Area burned is the annual total area of forest fire in hectares. Fuel available is the mass of fuel available for combustion in metric tons dry weight per hectare. Combustion factor is the proportion of fuel consumed by fire and is unitless. The emission factor is gram of emission (in this case CO_2) per kilogram dry matter burnt, and the '10-3' balances units. The first three factors are based on datasets specific to U.S. forests, whereas the emissions factor and in some cases an emission factor employ IPCC (2006) default values. Area burned is based on annual area of forest coincident with fires according to Monitoring Trends in Burn Severity (MTBS) (MTBS Data Summaries 2018; Eidenshink et al. 2007) dataset summaries, which include fire data for all 49 states that are a part of these estimates. That is, the MTBS data used here include the 48 conterminous states as well as Alaska, including interior Alaska; but note that the fire data used are also reduced to only include managed land (Ogle et al. 2018). Summary information includes fire identity, origin, dates, location, spatial perimeter of the area burned, and a spatial raster mosaic reflecting variability of the estimated fire severity within the perimeter. In addition to forest fires, the MTBS data include all wildland and prescribed fires on other ecosystems such as grasslands and rangelands; the 'forest fire' distinction is not explicitly included as a part of identifying information for each fire.

Area of forest within the MTBS fire perimeters was determined according to one of the National Land Cover (NLCD) 2016 datasets (Homer et al. 2015, Yang et al. 2018), which include land cover maps for seven of the years over the 2001-2016 interval. Alternate estimates of forest land would provide different estimates; for example, Ruefenacht et al. (2008) and the FIADB (USDA Forest Service 2017) provide slightly different estimates and differences vary with location. Some of these differences can be incorporated into the estimates of uncertainty. The choice of NLCD cover for these estimates is because it readily facilitates incorporating the MTBS per-fire severity estimates. The Alaska forest area was allocated to managed and unmanaged areas according to Ogle et al. (2018). The use of the NLCD land cover images to identify forest land within each MTBS-delineated fire identified forest on 15,837 of the 19,558 fires on the 48 conterminous states for 1990-2017 (data for 2018 were unavailable when these estimates were summarized; therefore 2017, the most recent available estimate, is applied to 2018). Similarly, there were 828 of the 1,044 fires in Alaska for 1990-2017 (data for 2018 were unavailable when these estimates were summarized; therefore 2017, the most recent available estimate, is applied to 2018) that included some forest land and are considered managed lands.

The area of forest burned as calculated on some of the individual MTBS-delineated fires are different than the forest areas calculated for the previous inventory; these corrections potentially apply to fires between 1990 and 2016. A minor source of change in calculated forest area is the addition of NLCD land cover images. The NLCD 2016 data (Yang et al. 2018) includes years 2001, 2003, 2006, 2008, 2011, 2013, and 2016, which provide greater temporal resolution relative to the 2001, 2006, and 2011 years used in the previous inventory. This is likely to only have a minor effect on estimated forest area burned. Most of the differences in annual forest area burned (and thus associated emissions) as seen in Table A-235 relative to the same table in the previous inventory are due to improperly adjusting the proportion of forest land within a fire to account for no-data values in an MTBS raster image rather than a similar modified NLCD raster image that conformed to the spatial extent of the fire. This calculation error only affected some fires; specifically those where the Landsat images included masked areas (such as for cloud cover). The greater the masked area, the greater the error in estimated forest land within the fire bounds.

Estimates of fuel availability are based on plot level forest inventory data, which are summarized by ecological province (see description of the data field 'ecosubcd' in the FIADB, USDA Forest Service 2015). These data are applied to estimates for fires located within the respective regions. Plot level C stocks (Smith et al. 2013, USDA Forest Service 2019) are grouped according to live aboveground biomass (live trees and understory), large dead wood (standing dead and down dead wood), and litter. We assume that while changes in forests have occurred over the years since the 1990 start of the reporting interval, the current general range of plot level C densities as determined by forest types and stand structures can be used as a representation of the potential fuel availability over forest lands. The current forest inventory data and the distribution of metric tons dry matter per hectare are used as the inputs for fuel availability.

Each MTBS defined fire perimeter has an associated burn severity mosaic that includes spatial information on burn severity, which generally varies across the burned area. Combustion is set to similarly vary. Probabilistic definitions are assigned for combustion factors as uniform sampling distributions for each the live, dead wood, and litter fuels. Currently, the uniform distributions for live biomass combustion are defined as 0-0.3, 0.2-0.8, and 0.7-1.0, for burn severity classes 2, 3, and 4 respectively. Similarly, for dead wood combustion, distributions are defined as 0-0.05, 0.05-0.5, 0.3-0.9 and 0.8-1.0, for burn severity classes 1, 2, 3, and 4 respectively. Finally, litter combustion distributions are defined as 0-0.05, 0.-0.1, 0.1-0.7, 0.7-1.0, and 1.0, for burn severity classes 'increased greenness', 1, 2, 3, and 4 respectively (see MTBS documentation for additional information on classifications). Specific classifications not noted above as well as unburned forest within the perimeter are assumed to have zero fire-based emissions. The combustion factors used here for temperate forests are interim probabilistic ranges generally based on MTBS related publications and are subject to change with ongoing improvements (see Planned Improvements in the LULUCF chapter).

The burned area perimeter dataset also was used to identify Alaska fires that were co-located with the area of permanent inventory plots of the USDA Forest Service's (2017) forest inventory along the southern coastal portion of the state. The majority of the MTBS-identified burned forest areas in Alaska that coincide with the Forest Service's permanent plot inventoried area were on the northern (or Cook Inlet) side of the Kenai Peninsula, which is generally identified as boreal forest. The few fires that were located in the coastal maritime ecoregion (about 1% of Alaska fires) were assigned fuel and combustion factors as described above. Fuel estimates were not available for the balance of the Alaska fires (on boreal forest) so they were calculated according to default values for boreal forests (see Table 2.4 Volume 4, Chapter 2 of IPCC 2006). Note that the values used for Alaska (Table 2.4 of IPCC 2006) represent the product of fuel available and the combustion factor.

The emission factor is an IPCC (2006) default, which for CO_2 is 1,569 g CO_2 per kg dry matter of fuel (see Table 2.5 Volume 4, Chapter 2 of IPCC 2006). Table A-235 provides summary values of annual area of forest burned and emissions calculated as described above following equation 2.27 of IPCC (2006, in Volume 4, Chapter 2). The emission factor for CO_2 from Table 2.5 Volume 4, Chapter 2 of IPCC (2006) is provided in Table A-234. Separate calculations were made for each wild and prescribed fire in each state for each year. The results as MT CO_2 were summed to the MMT CO_2 per year values represented in Table A-235, and C emitted per year was based on multiplying by the conversion factor 12/44 (IPCC 2006).

Table A-234: Areas (Hectares) from Wildfire Statistics and Corresponding Estimates of C and CO_2 (MMT/year) Emissions for Wildfires and Prescribed Fires[a]

		1990	1995	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018[b]
Conterminous 48 States - Wildfires	Forest area burned (1000 ha)	83.4	103.0	508.1	402.1	115.9	716.1	1,244.3	279.9	521.1	954.4	507.4	1,156.4	1,156.4
	C emitted (MMT/yr)	1.7	1.1	5.0	5.6	2.1	6.6	30.0	3.5	16.5	31.6	9.3	38.5	38.5
	CO_2 emitted (MMT/yr)	6.2	4.1	18.5	20.5	7.8	24.1	109.9	12.9	60.3	115.8	34.0	141.1	141.1
Alaska - Wildfires	Forest area burned (1000 ha)	82.5	1.4	59.6	686.7	103.9	28.0	14.9	185.3	53.7	638.4	26.8	23.8	23.8
	C emitted (MMT/yr)	1.4	0.0	1.0	12.0	1.8	0.5	0.3	3.3	0.9	11.2	0.5	0.4	0.4
	CO_2 emitted (MMT/yr)	5.3	0.1	3.8	44.1	6.7	1.8	1.0	11.9	3.5	41.2	1.7	1.5	1.5
Prescribed Fires (all 49 states)	Forest area burned (1000 ha)	5.0	10.6	15.4	43.5	496.3	166.7	71.1	232.2	237.0	150.8	250.4	227.2	227.2
	C emitted (MMT/yr)	0.1	0.1	0.2	0.4	6.2	1.7	0.8	2.6	2.8	1.7	2.6	2.3	2.3
	CO_2 emitted (MMT/yr)	0.2	0.3	0.8	1.5	22.9	6.3	2.9	9.6	10.4	6.1	9.7	8.6	8.6
Wildfires (all 49 states)	CH_4 emitted (kt/yr)	34.4	12.6	66.8	193.7	43.4	77.5	332.0	74.3	191.1	470.2	106.8	426.8	426.8
	N_2O emitted (kt/yr)	1.9	0.7	3.7	10.7	2.4	4.3	18.4	4.1	10.6	26.0	5.9	23.6	23.6
	CO emitted (kt/yr)	783.8	286.2	1,520.5	4,401.9	988.2	1,764.4	7,559.8	1,694.1	4,345.2	10,707.6	2,432.1	9,729.9	9,729.9
	NO_x emitted (kt/yr)	21.9	8.0	42.6	123.6	27.7	49.5	212.0	47.4	122.1	300.2	68.3	272.5	272.5

Prescribed Fires (all 49 states)	CH_4 emitted (kt/yr)	0.7	0.8	2.6	4.6	68.6	18.7	8.6	28.9	31.2	18.3	29.0	25.6	25.6
	N_2O emitted (kt/yr)	0.0	0.0	0.1	0.3	3.8	1.0	0.5	1.6	1.7	1.0	1.6	1.4	1.4
	CO emitted (kt/yr)	16.9	18.0	58.1	105.1	1,561.2	426.4	197.2	657.1	709.8	417.5	659.7	583.7	583.7
	NO_x emitted (kt/yr)	0.5	0.5	1.6	2.9	43.8	12.0	5.5	18.4	19.9	11.7	18.5	16.4	16.4

[a] 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.
[b] The data for 2018 were unavailable when these estimates were summarized; therefore 2017, the most recent available estimate, is applied to 2018.

Table A-235: Emission Fators for Extra Tropical Forest Burning and 100-year GWP (AR4), or Equivalence Ratios, of CH_4 and N_2O to CO_2

Emission Factor (g per kg dry matter burned)[a]		Equivalence Ratios[b]	
CH_4	4.70	CH_4 to CO_2	25
N_2O	0.26	N_2O to CO_2	298
CO_2	1,569	CO_2 to CO_2	1

[a] Source: IPCC (2006).
[b] Source: IPCC (2007).

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO2 gases–specifically, methane (CH_4) and nitrous oxide (N_2O)–from forest fires are estimated using the same methodology described above (i.e., equation 2.27 of IPCC 2006, Volume 4, Chapter 2). The only difference in calculations is the gas-specific emission factors, which are listed in Table A-235. The summed annual estimates are provided in Table A-234. Conversion of the CH_4 and N_2O estimates to CO_2 equivalents (as provided in Chapter 6-2) is based on global warming potentials (GWPs) provided in the IPCC Fourth Assessment Report (AR4) (IPCC 2007), which are the equivalence ratios listed in Table A-235.

Uncertainty about the non-CO_2 estimates is based on assigning a probability distribution to represent the estimated precision of each factor in equation 2.27 of the 2006 IPCC Guidelines (IPCC 2006). These probability distributions are randomly sampled with each calculation, and this is repeated a large number of times to produce a histogram, or frequency distribution of values for the calculated emissions. That is, a simple Monte Carlo ("Approach 2") method was employed to propagate uncertainty in the equation (IPCC 2006). The probabilities used for the factors in equation 2.27 are considered marginal distributions. The distribution for forest area burned is a uniform distribution based on the difference in local estimates of forest area – NLCD versus FIA inventory estimates. Fuel availability is the standard error for the inventory plots within each eco-province. Combustion factor uncertainty is defined above, and emission factors are normal distributions with mean and standard deviations as defined in the tables IPCC (2006) Tables 2.4, 2.5, and 2.6. These were sampled independently by year, and truncated to positive values where necessary. The equivalence ratios (Table A-235) to represent estimates as CO_2 equivalent were not considered uncertain values for these results.

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3.14. Methodology for Estimating CH_4 Emissions from Landfills

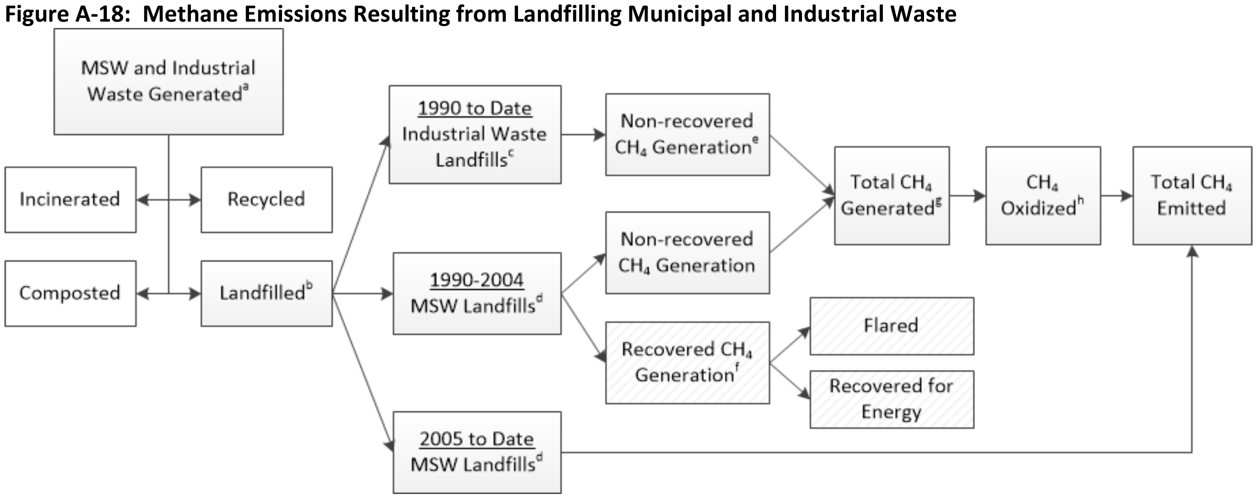
Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in solid waste. By volume, landfill gas is about half CH_4 and half CO_2.[121] The amount and rate of CH_4 generation depends upon the quantity and composition of the landfilled material, as well 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.

Methane emissions from landfills are estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based off directly measured amounts of recovered CH_4 from the landfill gas and is expressed by Equation HH-8 in CFR Part 98.343 of the EPA's Greenhouse Gas Reporting Program (GHGRP).

The current Inventory methodology uses both methods to estimate CH_4 emissions across the time series. The 1990-2015 Inventory was the first Inventory to incorporate directly reported GHGRP net CH_4 emissions data for landfills. In previous Inventories, only the first order decay method was used. EPA's GHGRP requires landfills meeting or exceeding a threshold of 25,000 metric tons of CH_4 generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH_4 generation, gas collection system details, CH_4 recovery, and CH_4 emissions. EPA's GHGRP provides a consistent methodology, a broader range of values for the oxidation factor, and allows for facility-specific annual waste disposal data to be used, thus these data are considered Tier 3 (highest quality data) under the *2006 IPCC Guidelines*. Using EPA's GHGRP data was a significant methodological change and required a merging of the GHGRP methodology with the Inventory methodology used in previous years to ensure time-series consistency.

Figure A-18 presents the CH_4 emissions process—from waste generation to emissions—in graphical format. A detailed discussion of the steps taken to compile the 1990 to 2018 Inventory are presented in the remainder of this Annex.

Figure A-18: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



[a] MSW waste generation is not calculated because annual quantities of waste disposal are available through EPA 2018; annual production data used for industrial waste (Lockwood Post's Directory and the USDA).

[121] 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.

[b] Quantities of MSW landfilled for 1940 through 1988 are based on EPA 1988 and EPA 1993; 1989 through 2004 are based on *BioCycle* 2010; 2005 through 2018 are incorporated through the directly reported emissions from MSW landfills to the Greenhouse Gas Reporting Program (EPA 2018). Quantities of industrial waste landfilled are estimated using a disposal factor and industrial production data sourced from Lockwood Post's Directory and the USDA.

[c] The *2006 IPCC Guidelines* – First Order Decay (FOD) Model is used for industrial waste landfills. Two different methodologies are used in the time series for MSW landfills.

[d] For 1990 to 2004, the *2006 IPCC Guidelines* – FOD Model is used. For 2005 to 2018, directly reported net CH_4 emissions from the GHGRP for 2010 to the current Inventory year are used with the addition of a scale-up factor equal to 9 percent of each year's emissions. The scale-up factor accounts for emissions from landfills that do not report to the GHGRP. The GHGRP emissions from 2010 to the current Inventory year are also used to back-cast emissions for 2005 to 2009 to merge the FOD methodology with the GHGRP methodology. Additional details on how the scale-up factor was developed and the back-casting approach are included in Step 4 of this Annex chapter.

[e] Methane recovery from industrial waste landfills is not incorporated into the Inventory because it does not appear to be a common practice according to the GHGRP dataset.

[f] Data are pulled from three recovery databases: EIA 2007, flare vendor database, and EPA (GHGRP) 2015(a). These databases have not been updated past 2015 because the Inventory strictly uses net emissions from the GHGRP data which already accounts for CH_4 recovery.

[g] For years 1990 to 2004, the total CH_4 generated from MSW landfills and industrial waste landfills are summed. For years 2005 to 2018, only the industrial waste landfills are considered because the directly reported GHGRP emissions are used for MSW landfills.

[h] An oxidation factor of 10 percent is applied to all CH_4 generated in years 1990 to 2004 for MSW landfills and in all years of the time series for industrial waste landfills (*2006 IPCC Guidelines*; Mancinelli and McKay 1985; Czepiel et al 1996). For years 2005 to 2018, directly reported CH_4 emissions from the GHGRP are used for MSW landfills. Various oxidation factor percentages are included in the GHGRP dataset (0, 10, 25, and 35) with an average across the dataset of approximately 20 percent.

Step 1: Estimate Annual Quantities of Solid Waste Placed in MSW Landfills for 1940 to 2004

To estimate the amount of CH_4 generated in a landfill in a given year, information is needed on the quantity and composition of the waste in the landfill for multiple decades, as well as the landfill characteristics (e.g., size, aridity, waste density). Estimates and/or directly measured amounts of waste placed in municipal solid waste (MSW) and industrial waste landfills are available through various studies, surveys, and regulatory reporting programs (i.e., EPA's GHGRP). The composition of the amount of waste placed in these landfills is not readily available for most years the landfills were in operation. Consequently, and for the purposes of estimating CH_4 generation, the Inventory methodology assumes that all waste placed in MSW landfills is bulk MSW (waste that is composed of both organic and inorganic materials), and that all waste placed in industrial waste landfills is from either pulp and paper manufacturing facilities or food and beverage facilities.

States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor do they report end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data, specifically the SOG surveys, published approximately every two years, with the most recent publication date of 2014. The SOG survey was the only continually updated nationwide survey of waste disposed in landfills in the United States and was the primary data source with which to estimate nationwide CH_4 generation from MSW landfills. Currently, EPA's GHGRP waste disposal data, EPA's Advancing Sustainable Materials Management: Facts and Figures report waste disposal data, and MSW management data published by the Environmental Research and Education Foundation (EREF) are available.

The SOG surveys collected data from the state agencies and then applied the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (BioCycle 2006; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents were asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. While these wastes may have been disposed of in MSW landfills, they were not the primary type of waste material disposed and were typically inert. In the most recent survey, state agencies were asked to provide already filtered, MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. All state disposal data were adjusted for imports and exports across state lines where imported waste was included in a state's total while exported waste was not. Methodological changes occurred over the time frame the SOG survey has been published, and this affected the fluctuating trends observed in the data (RTI 2013).

State-specific landfill MSW generation data and a national average disposal factor for 1989 through 2004 were obtained from the SOG survey every two years (i.e., 2002, 2004 as published in BioCycle 2006). The landfill inventory calculations start with hard numbers (where available) as presented in the SOG documentation for the report years 2002 and 2004. In-between year waste generation is interpolated using the prior and next SOG report data. For example, waste generated in 2003 = (waste generation in 2002 + waste generation in 2004)/2. In 2006, BioCycle published their 15th Nationwide Survey which also contained estimations of landfilled quantities generated for the years 1990 through 2000. In-between year waste generation is again interpolated using the prior and next SOG report data in order to determine an approximate quantity for waste generation in the year 2001. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in each year of the time series. The SOG survey is voluntary and not all states provide data in each survey year. To estimate waste generation for states that did not provide data in any given reporting year, one of the following methods was used (RTI 2013):

- For years when a state-specific waste generation rate was available from the previous SOG reporting year submission, the state-specific waste generation rate for that particular state was used.

  – or –

- For years where a state-specific waste generation rate was not available from the previous SOG reporting year submission, the waste amount is generated using the national average waste generation rate. In other words, Waste Generated = Reporting Year U.S. Population × the National Average Waste Generation Rate
    - The National Average Waste Generation Rate is determined by dividing the total reported waste generated across the reporting states by the total population for reporting states.
    - This waste generation rate may be above or below the waste generation rate for the non-reporting states and contributes to the overall uncertainty of the annual total waste generation amounts used in the model.

Use of these methods to estimate solid waste generated by states is a key aspect of how the SOG data was manipulated and why the results differ for total solid waste generated as estimated by SOG and in the Inventory. In the early years (2002 data in particular), SOG made no attempt to fill gaps for non-survey responses. For the 2004 data, the SOG team used proxy data (mainly from the WBJ) to fill gaps for non-reporting states and survey responses.

Another key aspect of the SOG survey is that it focuses on MSW-only data. The data states collect for solid waste typically are representative of total solid waste and not the MSW-only fraction. In the early years of the SOG survey, most states reported total solid waste rather than MSW-only waste. The SOG team, in response, "filtered" the state-reported data to reflect the MSW-only portion.

This data source also contains the waste generation data reported by states to the SOG survey, which fluctuates from year to year. Although some fluctuation is expected, for some states, the year-to-year fluctuations are quite significant (>20 percent increase or decrease in some case) (RTI 2013). The SOG survey reports for these years do not provide additional explanation for these fluctuations and the source data are not available for further assessment. Although exact reasons for the large fluctuations are difficult to obtain without direct communication with states, staff from the SOG team that were contacted speculate that significant fluctuations are present because the particular state could not gather complete information for waste generation (i.e., they are missing part of recycled and composted waste data) during a given reporting year. In addition, SOG team staff speculated that some states may have included C&D and industrial wastes in their previous MSW generation submissions, but made efforts to exclude that (and other non-MSW categories) in more recent reports (RTI 2013).

Recently, the EREF published a report, *MSW Management in the United States*, which includes state-specific landfill MSW generation and disposal data for 2010 and 2013 using a similar methodology as the SOG surveys (EREF 2016). Because of this similar methodology, EREF data were used to populate data for years where BioCycle data was not available when possible. State-specific landfill waste generation data for the years in between the SOG surveys and EREF report (e.g., 2001, 2003, etc.) were either interpolated or extrapolated based on the SOG or EREF data and the U.S. Census population data (U.S. Census Bureau 2019).

Historical waste data, preferably since 1940, are required for the FOD model to estimate CH_4 generation for the Inventory time series, as the *2006 IPCC Guidelines* recommend at least 50 years of waste disposal data to estimate CH_4 emissions. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (MCF of 1) and those disposed in uncategorized site as (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills.

For 1989 to 2004, 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 (BioCycle 2001, 2004, 2006, 2010) and recent data from the Environmental Research & Education Foundation (EREF 2016), adjusted to include U.S. Territories.[122] The SOG surveys and EREF (2016) provide state-specific landfill waste generation data, collectively back to 1989. The SOG survey is no longer updated, but is available every two years for the years 2002 and 2004 (as published in BioCycle 2006). A linear interpolation was used to estimate the amount of waste generated in 2001, 2003.

Estimates of the quantity of waste landfilled are determined by applying a waste disposal factor to the total amount of waste generated. A national average waste disposal factor is determined for each year a SOG survey and EREF report 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 and EREF data, and extrapolated for years after the last year of data. Methodological changes have occurred over the time that the SOG survey has been published, and this has resulted in fluctuating trends in the data.

Table A-236 shows estimates of waste quantities contributing to CH_4 emissions. The table shows SOG (Biocycle 2010) and EREF (EREF 2016) estimates of total waste generated and total waste landfilled (adjusted for U.S. Territories) for various years over the 1990 to 2017 timeframe even though the Inventory methodology does not use the data for 2005 onward.

Table A-236: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

	1990		2005		2012	2013	2014	2015	2016	2017	2018
Total MSW Generated[a]	270		368		319	319	320	322	324	326	328
Percent of MSW Landfilled	77%		64%		63%	64%	64%	65%	65%	65%	65%
Total MSW Landfilled	**205**		**234**		**200**	**201**	**202**	**208**	**209**	**211**	**212**
MSW last 30 years	4,876		5,992		6,388	6,411	6,432	6,455	6,476	6,497	6,515
MSW since 1940[b]	6,808		9,925		11,474	11,675	11,878	12,085	12,294	12,505	12,716
Total Industrial Waste Landfilled	**9.7**		**10.9**		**10.5**	**10.3**	**10.4**	**10.3**	**10.3**	**10.3**	**10.1**
Food and Beverage Sector[c]	6.4		6.9		6.2	6.0	6.2	6.1	6.1	6.0	5.8
Pulp and Paper Sector[d]	3.3		4.0		4.2	4.2	4.2	4.2	4.2	4.2	4.3

[a] 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* 2001, 2004, 2006, and 2010 for years 1989 to 2014 (1981 to 2004, and 2006 to 2011 are not presented in table). Values for years 2010 to 2018 are based on EREF (2016) and annual population data from the U.S. Census Bureau (2019).

[b] This estimate represents the cumulative amount of waste that has been placed in landfills since 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; *BioCycle* 2001, 2004, 2006, and 2010; and EREF 2016.

[c] Food production values for 1990 to 2018 are from ERG. 2019 USDA-NASS Ag QuickStats available at http://quickstats.nass.usda.gov (FAO 2019).

[d] Production data from 1990 and 2001 are from Lockwood-Post's Directory, 2002. Production data from 2002 to 2018 are from the FAOStat database available at: http://faostat3.fao.org/home/index.html#DOWNLOAD. Accessed on May 20, 2019.

[122] 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 2019) and the per capita rate for waste landfilled from BioCycle (2010).

EPA compared the SOG and EREF estimates of total waste generated and landfilled presented in Table A-235 to the recently published *Advancing Sustainable Materials Management: Facts and Figures* report (EPA 2019b, Table 2, latest year of data is 2017) and found inconsistencies between the estimates of MSW landfilled between the two data sources. These inconsistencies are expected, as the data sources use two different methodologies to estimate MSW landfilled. Both the SOG and EREF estimates of total MSW landfilled are derived via a bottom-up approach using information at the facility-level to estimate MSW for the sector as a whole, while the *Advancing Sustainable Materials Management: Facts and Figures* report uses a top-down (materials flow mass balance) approach to estimate the same quantity. The materials flow methodology is generally based on production data for each material at the state-(recycling, composting) or national-(waste generation) level. Discarded or landfilled material is Subtitle D waste only and assumed to be the calculated difference between generation and recovery through recycling and composting (EPA 2019a). Subtitle D wastes do not include construction and demolition waste, for example, which many GHGRP-reporting facilities accept and include in their GHG reports.

As a quality check, EPA compared the MSW landfilled estimates from the SOG, EREF, and *Advancing Sustainable Materials Management: Facts and Figures* reports with MSW landfilled amounts for the 2017 year as reported to the EPA's GHGRP under subpart HH (MSW Landfills). On average, the SOG and EREF estimations were 36 percent less than GHGRP reported waste quantities (including a scale-up factor of 9 percent to account for operational facilities that do not report to the GHGRP) for the year 2017. Estimates of MSW landfilled from the *Advancing Sustainable Materials Management: Facts and Figures* report for the year 2017 were, on average, 60 percent less than the GHGRP waste quantities used in the Inventory. While this percent difference is large, it is not unexpected. The GHGRP uses a facility-specific, bottom-up approach to estimating emissions while the *Advancing Sustainable Materials Management: Facts and Figures* report uses a top-down approach which incorporates many assumptions about disposal and recycling at a national level. The *Advancing Sustainable Materials Management: Facts and Figures* report also specifically omits certain types of waste that are explicitly included in the GHGRP reports, such as construction and demolition waste, biosolids (sludges), and other inert wastes (EPA 2019a). The exclusion of these waste categories likely accounts for much of the discrepancies between these two data sets.

EPA is now using facility-reported data from subpart HH of the GHGRP to calculate emissions from the Landfills sector for the Inventory years 2005-present, replacing the need for now discontinued SOG surveys and intermittent EREF estimates of MSW landfilled for this timeframe. To maintain a more consistent methodology across the entire Landfill sector time series, EPA has kept the SOG and EREF estimates of MSW landfilled as a basis for emissions calculations for Inventory years 1990-2004 since these methodologies use a bottom-up approach like the GHGRP methodology used in the latter portion of the time series. While there remain some differences in the methods used between these data sources, the uncertainty factors (Table 7-5) for MSW Landfills are intended to account for these variabilities in the waste disposal estimates.

Step 2: Estimate CH_4 Generation at MSW Landfills for 1990 to 2004

The FOD method is exclusively used for 1990 to 2004. For the FOD method, methane generation is based on nationwide MSW generation data, to which a national average disposal factor is applied; it is not landfill-specific.

The FOD method is presented below and is similar to Equation HH-5 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$CH_{4,\text{Solid Waste}} = [CH_{4,\text{MSW}} + CH_{4,\text{Ind}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$	=	Net CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$	=	CH_4 generation from MSW landfills
$CH_{4,\text{Ind}}$	=	CH_4 generation from industrial landfills
R	=	CH_4 recovered and combusted (only for MSW landfills)
Ox	=	CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere

The input parameters needed for the FOD model equations are the mass of waste disposed each year (discussed under Step 1), degradable organic carbon (DOC) as a function of methane generation potential (Lo), and the decay rate constant (k). The equation below provides additional detail on the activity data and emission factors used in the $CH_{4,MSW}$ equation presented above.

$$CH_{4,MSW} = \left[\sum_{x=S}^{T-1}\left\{W_x \times Lo \times \frac{16}{12} \times \left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\}\right]$$

where,

$CH_{4,MSW}$	=	Total CH_4 generated from MSW landfills
T	=	Reporting year for which emissions are calculated
x	=	Year in which waste was disposed
S	=	Start year of calculation
W_x	=	Quantity of waste disposed of in the landfill in a given year
L_o	=	Methane generation potential (100 m^3 CH_4/Mg waste; EPA 1998, 2008)
16/12	=	conversion factor from CH_4 to C
k	=	Decay rate constant (yr^{-1}, see Table A-237)

The DOC is determined from the CH_4 generation potential (L_0 in m^3 CH_4/Mg waste) as shown in 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 (100 m^3 CH_4/Mg waste; EPA 1998, 2008),
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).

DOC values can be derived for individual landfills if a good understanding of the waste composition over time is known. A default DOC value is used in the Inventory because waste composition data are not regularly collected for all landfills nationwide. When estimating CH_4 generation for the years 1990 to 2004, a default DOC value is used. This DOC value is calculated from a national CH_4 generation potential[123] of 100 m^3 CH_4/Mg waste (EPA 2008) as described below.

The DOC value used in the CH_4 generation estimates from MSW landfills for 1990-2004 is 0.2028, and is based on the CH_4 generation potential of 100 m^3 CH_4/Mg waste (EPA 1998; EPA 2008). After EPA developed the L_o value, RTI analyzed data from a set of 52 representative landfills across the United States in different precipitation ranges to evaluate L_o, and ultimately the national 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 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

[123] Methane generation potential (L_o) varies with the amount of organic content of the waste material. A higher L_o occurs with a higher content of organic waste.

estimate to use in the FOD model for the national inventory for years 1990 through 2004, and is the value used to derive the DOC value of 0.2028.

In 2004, the FOD model was also applied to the gas recovery data for the 52 landfills to calculate a decay rate constant (k) directly for L_0 = 100 m^3/Mg. The decay rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three precipitation ranges, shown in Table A-237 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A-237: 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 25 inches/year of precipitation) and 0.04 yr^{-1} for non-arid areas. The SWANA (1998) 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 versus 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 2010. 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-238.

Table A-238: 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.

The *2006 IPCC Guidelines* also require annual proportions of waste disposed of in managed landfills versus unmanaged and uncategorized sites prior to 1980. Based on the historical data presented by Mintz et al. (2003), a timeline was developed for the transition from the use of unmanaged and uncategorized sites 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 uncategorized sites. The uncategorized sites represent those sites where not enough information was available to assign a percentage to unmanaged shallow versus unmanaged deep solid waste disposal sites. Between 1940 and 1980, the fraction of waste that was 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 the uncategorized sites, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006). The recommended IPCC default value for the MCF for managed landfills of 1 (IPCC 2006) has been used for the managed landfills for the years where the first order decay methodology was used (i.e., 1990 to 2004).

Step 3: Estimate CH_4 Emissions Avoided from MSW Landfills for 1990 to 2004

The estimated landfill gas recovered per year (R) at MSW landfills is based on a combination of four databases that include recovery from flares and/or landfill gas-to-energy projects:

- a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007),
- a database of LFGE projects that is primarily based on information compiled by EPA LMOP (EPA 2016)[124],
- the flare vendor database (contains updated sales data collected from vendors of flaring equipment), and the
- EPA's GHGRP MSW landfills database (EPA 2015a).

The EPA's GHGRP MSW landfills database was first introduced as a source for recovery data for the 1990 to 2013 Inventory (2 years before the full GHGRP data set started being used for net CH_4 emissions for the Inventory). 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 only contains a portion of the landfills in the United States (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. For landfills in this database, methane recovery data reported data for 2010 and later were linearly back-casted to 1990, or the date the landfill gas collection system at a facility began operation, whichever is earliest.

A destruction efficiency of 99 percent was applied to amounts of CH_4 recovered to estimate CH_4 emissions avoided for all recovery 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 EPA's LMOP.

Step 3a: Estimate CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGE) and Flaring Projects for 1990 to 2004

The quantity of CH_4 avoided due to LFGE systems was estimated based on information from three sources: (1) a database developed by the EIA for the voluntary reporting of greenhouse gases (EIA 2007); (2) a database compiled by LMOP and referred to as the LFGE database for the purposes of this inventory (EPA 2016); and (3) the GHGRP MSW landfills dataset (EPA 2015a). The EIA database included location information for landfills with LFGE projects, estimates of CH_4 reductions, descriptions of the projects, and information on the methodology used to determine the CH_4 reductions. In general, 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 LFGE 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 LFGE project. The GHGRP MSW landfills database contains the most detailed data on landfills that reported under EPA's GHGRP for years 2010 through 2015, however the amount of CH_4 recovered is not specifically allocated to a flare versus a LFGE project. The allocation into flares or LFGE was performed by matching landfills to the EIA and LMOP databases for LFGE 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 LFGE databases; consequently, it was straightforward to identify landfills that were in both databases against those in EPA's GHGRP MSW landfills database.

The same landfill may be included one or more times across these four databases. To avoid double- or triple-counting CH_4 recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database. In summary, the GHGRP > EIA > LFGE > flare vendor database.

If a landfill in the GHGRP MSW landfills database was also in the EIA, LFGE, and/or flare vendor database, the avoided emissions were only based on EPA's GHGRP MSW landfills database to avoid counting the recovery amounts multiple times across the different databases. In other words, the CH_4 recovery from the same landfill was not included in the total recovery from the EIA, LFGE, or flare vendor databases. While the GHGRP contains facility-reported

[124] The LFGE database was not updated for the 1990 to 2018 Inventory because the methodology does not use this database for years 2005 and later, thus the LMOP 2016 database is the most recent year reflected in the LFGE database for the Inventory.

information on MSW Landfills starting in the year 2010, EPA has back-casted GHGRP emissions to the year 2005 in order to merge the two methodologies (more information provided in Steps 4a and 4b). Prior to 2005, if a landfill in EPA's GHGRP was also in the LFGE or EIA databases, the landfill gas project information, specifically the project start year, from either the LFGE or EIA databases was used as the cutoff year for the estimated CH_4 recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGE database under a project that started in 2002 that is still operational, the CH_4 recovery data in the GHGRP database for that facility was back-casted to the year 2002 only.

If a landfill in the EIA database was also in the LFGE and/or the flare vendor database, the CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. The EIA database only includes facility-reported data through 2006; the amount of CH_4 recovered in this database for years 2007 and later were assumed to be the same as in 2006. Nearly all (93 percent) of landfills in the EIA database also report to EPA's GHGRP.

If both the flare data and LFGE recovery data were available for any of the remaining landfills (i.e., not in the EIA or EPA's GHGRP databases), then the CH_4 recovered were based on the LFGE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGE database is based on the most recent EPA LMOP database (published annually). The remaining portion of avoided emissions is calculated by the flare vendor database, which estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity. New flare vendor sales data have not been collected since 2015 because these data are not used for estimates beyond 2005 in the time series. Given that each LFGE project is likely to also have a flare, double counting reductions from flares and LFGE projects in the LFGE database was avoided by subtracting emission reductions associated with LFGE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor).

Step 3b: Estimate CH_4 Emissions Avoided Through Flaring for the Flare Database for 1990 to 2004

To avoid double counting, flares associated with landfills in EPA's GHGRP, EIA and LFGE databases were not included in the total quantity of CH_4 recovery from the flare vendor database. As with the LFGE 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, EPA's GHGRP, or LFGE databases). Several vendors have provided information on the size of the flare rather than the flare design gas flow rate for most years of the Inventory. Flares sales data has not been obtained since the 1990-2015 Inventory year, when the net CH_4 emission directly reported to EPA's GHGRP began to be used to estimate emission from MSW landfills.

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 3c: Reduce CH_4 Emissions Avoided Through Flaring for 1990 to 2004

If comprehensive data on flares were available, each LFGE project in EPA's GHGRP, EIA, and LFGE databases would have an identified flare because it is assumed that most LFGE projects have flares. However, given that the flare vendor database only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGE projects. These LFGE 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 LFGE project would be counted. To avoid overestimating emissions avoided from flaring, the CH_4 avoided from LFGE 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 to 2009 and 1990 to 2014 inventory years to reduce the total number of flares in the flare vendor database that were not matched to landfills and/or LFGE projects in the EIA and LFGE databases. Each flare in the flare vendor database not associated with a LFGE project in the EIA, LFGE, or EPA's GHGRP databases was investigated to determine if it could be matched. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database and was corrected during the review. 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, LFGE and EPA's GHGRP databases. The remaining flares did not have adequate information through the name, location, or owner to identify it to a landfill in any of the recovery databases or through an Internet search; it is these flares that are included in the flare correction factor for the current inventory year.

A large majority of the unmatched flares are associated with landfills in the LFGE database that are currently flaring but are also considering LFGE. These landfills projects considering a LFGE project are labeled as candidate, potential, or construction in the LFGE database. The flare vendor database was improved in the 1990 to 2009 inventory year to match flares with operational, shutdown as well as candidate, potential, and construction LFGE 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 through 2009 Inventory. The revised state-by-state flare correction factors were applied to the entire Inventory time series (RTI 2010).

Step 4: Estimate CH_4 Emissions from MSW Landfills for 2005 to 2009

During preparation of the 1990-2015 Inventory, EPA engaged with stakeholders both within and outside of the landfill industry on the methodology used in the Inventory, the data submitted by facilities under EPA's GHGRP Subpart HH for MSW Landfills, and the application of this information as direct inputs to the MSW landfill methane emissions estimates in the 1990–2015 Inventory. Based on discussions with stakeholders, EPA developed several options for improving the Inventory through methodological changes and moved forward with using the directly reported net GHGRP methane emissions from 2010 to 2015 for MSW landfills in the 1990-2015 Inventory.

The Inventory methodology now uses directly reported net CH_4 emissions for the 2010 to 2018 reporting years from EPA's GHGRP to back-cast emissions for 2005 to 2009. The emissions for 2005 to 2009 are recalculated each year the Inventory is published to account for the additional year of reported data and any revisions that facilities make to past GHGRP reports. When EPA verifies the greenhouse gas reports, comparisons are made with data submitted in earlier reporting years and errors may be identified in these earlier year reports. Facility representatives may submit revised reports for any reporting year in order to correct these errors. Facilities reporting to EPA's GHGRP that do not have landfill gas collection and control systems use the FOD method. Facilities with landfill gas collection and control must use both the FOD method and a back-calculation approach. The back-calculation approach starts with the amount of CH_4 recovered and works back through the system to account for gas not collected by the landfill gas collection and control system (i.e., the collection efficiency).

Including the GHGRP net emissions data was a significant methodological change from the FOD method previously described in Steps 1 to 3 and only covered a portion of the Inventory time series. Therefore, EPA needed to merge the previous method with the new (GHGRP) dataset to create a continuous time series and avoid any gaps or jumps in. estimated emissions in the year the GHGRP net emissions are first included (i.e., 2010).

To accomplish this, EPA back-casted GHGRP net emissions to 2005 to 2009 and added a scale-up factor to account for emissions from landfills that do not report to the GHGRP. A description of how the scale-up factor was determined and why the GHGRP emissions were back-casted are included below as Step 4a and Step 4b, respectively. The methodology described in this section was determined based on the good practice guidance in Volume 1: Chapter 5 Time Series Consistency of the *2006 IPCC Guidelines*. Additional details including other options considered are included in RTI 2017a and RTI 2018.

Step 4a: Developing and Applying the Scale-up Factor for MSW Landfills for 2005 to 2009

Landfills that do not meet the reporting threshold are not required to report to the GHGRP. As a result, the GHGRP dataset is only partially complete when considering the universe of MSW landfills. In theory, national emissions from MSW landfills equals the emissions from landfills that report to the GHGRP plus emissions from landfills that do not report to the GHGRP. Therefore, for completeness, a scale-up factor had to be developed to estimate the amount of emissions from the landfills that do not report to the GHGRP.

To develop the scale-up factor, EPA completed four main steps:

1. We determined the number of landfills that do not report to the GHGRP (hereafter referred to as the non-reporting landfills). Source databases included the LMOP database 2017 (EPA, 2017) and the Waste Business Journal (WBJ) Directory 2016 (WBJ, 2016). This step identified 1,544 landfills that accepted MSW between 1940 and 2016 and had never reported to the GHGRP.
2. We estimated annual waste disposed and the total waste-in-place (WIP) at each non-reporting landfill as of 2016. Both databases include critical details about individual landfills to estimate annual methane emissions, including the year waste was first accepted, the year the landfill closed (as applicable), and the estimated amount of waste disposed. But not all details are included for all landfills. A total of 969 of the 1,544 landfills (63 percent) contained the critical information necessary to estimate WIP.
    a. For 234 non-reporting landfills, there was not enough information in the source databases to estimate WIP.
    b. For 341 of the non-reporting landfills, WIP could be estimated with assumptions that either (i) "forced" the year that waste was first accepted as 30 years prior to the landfill closure year (if a closure date was included); or (ii) forced a closure year of 2016 waste used if the landfill was known to be closed and a closure year was not included in the source database.
3. We summed the total WIP for the non-reporting landfills. Using the assumptions mentioned above, the total WIP in 2016 across the non-reporting landfills was approximately 0.922 million metric tons.
4. We calculated the scale-up factor (9%) by dividing the non-reporting landfills WIP (0.92 million metric tons) by the sum of the GHGRP WIP and the non-reporting landfills WIP (10.0 million metric tons).

Table A- 239. Revised Waste-in-Place (WIP) for GHGRP Reporting and Non-reporting Landfills in 2016

Category	Estimated WIP (million metric tons)	Percentage
Non-reporting facilities	0.92	9 percent (the applied scale-up factor)
GHGRP facilities	9.08	91 percent
Total	10.0	100 percent

The same 9% scale-up factor is applied in each year the GHGRP reported emissions are used in the Inventory.

Step 4b: Back-casting GHGRP Emissions for MSW Landfills for 2005 to 2009 to Ensure Time Series Consistency

Regarding the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). Chapter 5 however, does not recommend back-casting emissions to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data becomes available for multiple years, which was the case with the GHGRP data, where directly reported net CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using (1) the FOD method from 1990 to 2009, or (2) using the FOD method for a portion of that time series and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. Therefore, EPA decided to back-cast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC good practice guidance.

EPA used the Excel Forecast function to back-cast net methane emissions using the GHGRP data. The forecast function is used to predict a future value by using existing values, but we have applied it to predict previous values. Although it is not ideal, it allowed for expeditious implementation. In the forecast function, the known values are existing x-values and y-values (i.e., the years and data for the GHGRP, 2010 to 2015). The unknown y-values are the years to be estimated (i.e., all years prior to 2009). The following Excel formula was used: =FORECAST(year to back-cast, GHGRP data for 2010 to 2015, years 2010 to 2015). The forecast function is a linear regression; thus, it will not account for annual fluctuations in CH_4 emissions when used for multiple years.

The years to back-cast the GHGRP data were first determined for the 1990-2015 Inventory when a 12.5% scale-up factor was used. EPA plotted the net CH_4 emissions from the adjusted 1990-2014 methodology against the back-casted GHGRP emissions for 1990 to 2009 and directly reported CH_4 emissions for 2010 to 2015 with a scale-up factor of 12.5% applied to all years the GHGRP data are used, 2005 to 2014) as presented in Figure A-19. Only data up until 2014 are presented in Figure A-19 and Figure A-20 below, as they directly compare to the 1990-2014 revised Inventory. The results for the two methods are nearly identical for the years 2005 to 2010, which provides a basis for back-casting the GHGRP emissions data to 2005 only. However, after applying the 12.5% scale-up factor across the time series, the GHGRP emissions data were now larger than the revised Inventory estimates for the years 2010 to 2015. This difference was addressed through revisions to the scale-up factor after a more detailed review of the non-reporting landfills, resulting in a revised scale-up factor of 9% (described above in Step 4a), which more closely aligns emissions estimates between the two methodologies as presented in Figure A-20. EPA therefore decided to maintain back-casting of the GHGRP emissions from 2005 to 2009 only.

Figure A-19: Comparison of the revised 1990-2014 Inventory methodology against the GHGRP emissions (back-casted from 2009 to 1990) and directly reported emissions for 2010 to 2014with a 12.5% scale-up factor

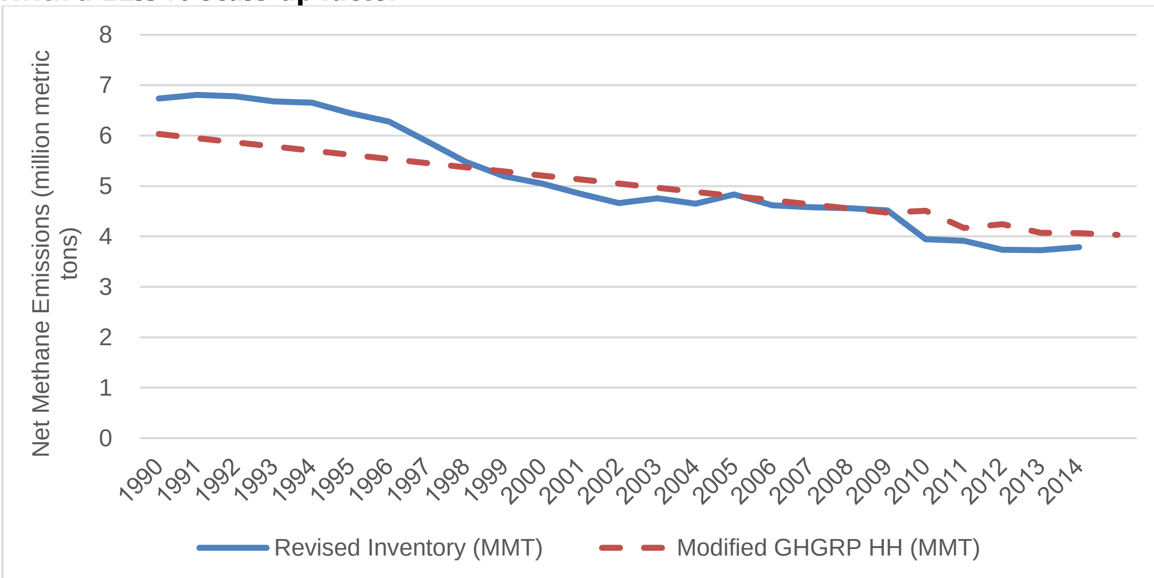
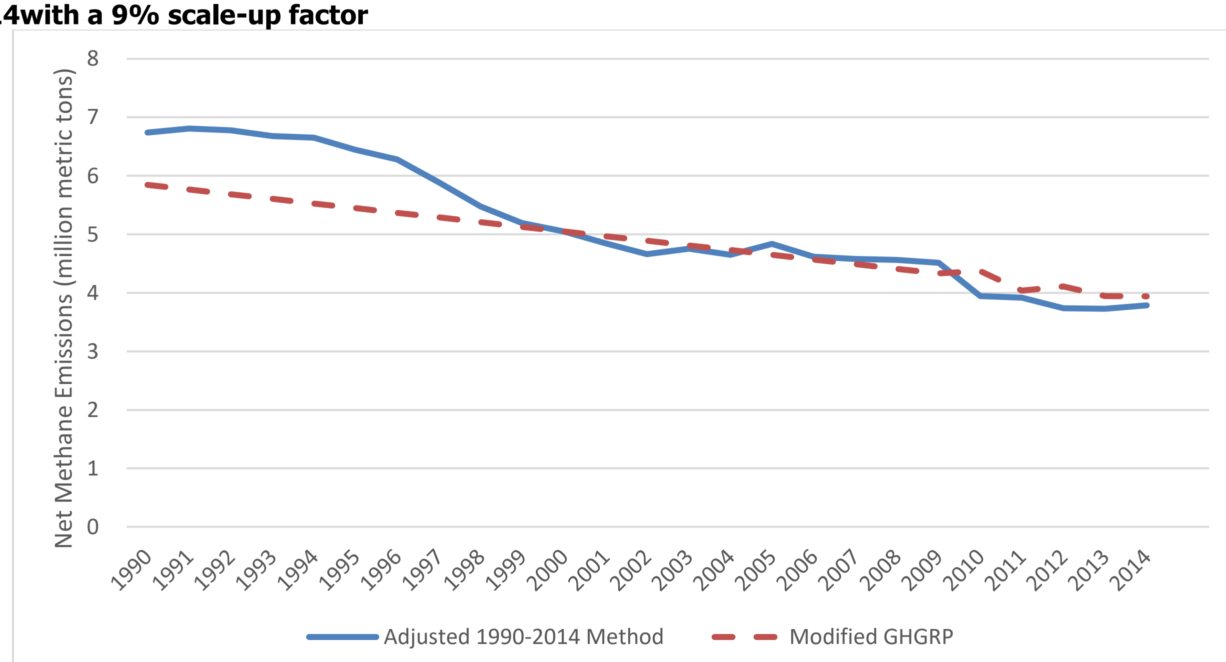


Figure A-20: Comparison of the revised 1990-2014 Inventory methodology against the GHGRP emissions (back-casted from 2009 to 1990) and directly reported emissions for 2010 to 2014with a 9% scale-up factor



An important factor in this approach is that the back-casted emissions for 2005 to 2009 are subject to change with each Inventory because the GHGRP dataset may change as facilities revise their annual reports. The revisions are generally minor considering the entire GHGRP dataset and EPA has not determined any revisions to the back-casting approach or scale-up factor are necessary to date. EPA will continue to evaluate the data submitted to the GHGRP each year to determine if any changes are needed to the back-casting approach or the scale-up factor.

Step 5: Estimate CH_4 Emissions from MSW Landfills for 2010 to the Current Inventory Year

CH_4 emissions directly reported to EPA's GHGRP are used for 2010 to 2018. Inherent in these direct emissions are the use of various GHGRP default emission factors such as the gas collection and control system collection efficiencies (where applicable), decay rate (k), and degradable organic carbon (DOC).

Facilities reporting to subpart HH of the GHGRP can report their k and DOC values under one of three waste type options: (1) Bulk waste option, where all waste is accounted for within one bulk k and DOC value; (2) Modified bulk waste option, where waste disposed of at the landfill can be binned into bulk MSW excluding inerts and construction and demolition waste, construction and demolition waste, and inerts; and (3) Waste Composition option, where waste disposed of can be delineated into specific waste streams (i.e., food waste, garden waste, textiles, etc.) OR where facilities report a known quantity of inert waste and consider the remaining waste as bulk MSW (using the same k and DOC value for MSW as the bulk waste option).

The GHGRP requires facilities with a gas collection and control system to report their emissions using both a forward-estimating (i.e., using a first order decay approach, accounting for soil oxidation) and a back-calculating (i.e., using methane recovery and collection efficiency data, accounting for soil oxidation) method as described in Chapter 7 of this Inventory. To determine collection efficiency, facilities are required to report the amount of waste-in-place (surface area and soil depth) at their landfill as categorized by one of five area types (see Table A-240).

Table A-240: Table HH-3 to Subpart HH of the EPA's Greenhouse Gas Reporting Program, Area Types Applicable to the Calculation of Gas Collection Efficiency

Description	Landfill Gas Collection Efficiency
A1: Area with no waste in-place	Not applicable; do not use this area in the calculation.
A2: Area without active gas collection, regardless of cover type	CE2: 0%.
A3: Area with daily soil cover and active gas collection	CE3: 60%.
A4: Area with an intermediate soil cover, or a final soil cover not meeting the criteria for A5 below, and active gas collection	CE4: 75%.
A5: Area with a final soil cover of 3 feet or thicker of clay or final cover (as approved by the relevant agency) and/or geomembrane cover system and active gas collection	CE5: 95%.
Weighted average collection efficiency for landfills:	
Area weighted average collection efficiency for landfills	CEave1 = (A2*CE2 + A3*CE3 + A4*CE4 + A5*CE5) / (A2 + A3 + A4 + A5).

If facilities are unable to bin their waste into these area types, they are instructed to use 0.75, or 75 percent as a default value. In the EPA's original rulemaking for the GHGRP, the EPA proposed this default collection efficiency of 75 percent because it was determined to be a reasonable central-tendency default considering the availability of data such as surface monitoring under the EPA's New Source Performance Standards for MSW Landfills (40 CFR Part 60 Subpart WWW), which suggested that gas collection efficiencies generally range from 60 to 95 percent. This 75 percent default gas collection efficiency value only applies to areas at the landfill that are under gas collection and control; for areas of the landfill that are not under gas collection and control, a gas collection efficiency of 0 percent is applied.

The 9 percent scale-up factor is applied to the net annual emissions reported to the GHGRP for 2010 to 2018 as is done for 2005 to 2009 because the GHGRP does not capture emissions from all landfills in the United States.

Step 6: Estimate CH_4 Generation at Industrial Waste Landfills for 1990 to the Current Inventory Year

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). In 2005, 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 most of the organic waste placed in industrial landfills originated from two sectors: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food processing and pulp and paper sectors 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 sector, production data published by the Lockwood-Post's Directory were used for years 1990 to 2001 and production data published by the Food and Agriculture Organization were used for years 2002 through 2017. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964. For the food processing sector, production levels were obtained or developed from the U.S. Department of Agriculture for the years 1990 through 2017 (ERG 2019). 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 sectors, the following inputs are needed to use the FOD model for estimating CH_4 generation from industrial waste landfills: 1) quantity of waste that is disposed in industrial waste landfills (as a function of production), 2) CH_4 generation potential (L_0) from which a DOC value can be calculated, and 3) the decay rate constant (k).

Research into waste generation and disposal in landfills for the pulp and paper sector indicated that the quantity of waste landfilled was about 0.050 MT/MT of product compared to 0.046 MT/MT product for the food processing sector (RTI 2006). These factors were applied to estimates of annual production to estimate annual waste disposal in industrial waste landfills. Estimates for DOC were derived from available data (EPA, 2015b; Heath et al., 2010; NCASI, 2005; Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999 as documented in RTI 2015a). The DOC value for industrial pulp and paper waste is estimated at 0.15 (L_o of 49 m^3/MT); the DOC value for industrial food waste is estimated as 0.26 (L_o of 128 m^3/MT) (RTI 2015a; 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 and 1990 to 2014 inventory years with the intent of updating values for L_o (specifically DOC) and k in the pulp and paper sector (RTI 2014). Where pulp and paper mill wastewater treatment residuals or sludge are the primary constituents of pulp and paper waste landfilled, values for k available in the literature range from 0.01/yr to 0.1/yr, while values for L_o range from 50 m^3/Mt to 200 m^3/Mt.[125] 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 available through EPA's GHGRP to warrant a change to the L_o (DOC) from 99 to 49 m^3/MT, but sufficient data were not obtained to warrant a change to k. EPA will consider an update to the k values for the pulp and paper sector as new data arises 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 unmanaged landfills, or open dumps to managed landfills was expected for industrial waste landfills; therefore, the same timeline 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 unmanaged sites, 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 7: Estimate CH_4 Oxidation from MSW and Industrial Waste Landfills

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

[125] Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; Barlaz 1998; and Skog and Nicholson 2000.

the CH_4 generated, minus the amount of gas recovered for flaring or LFGE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The literature was reviewed in 2011 (RTI 2011) and 2017 (RTI 2017b) 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 for the years 1990 to 2004 and for industrial waste landfills for the full time series.

For years 2005 to 2018, net CH_4 emissions from MSW landfills as directly reported to EPA's GHGRP, which include the adjustment for oxidation, are used. Subpart HH of the GHGRP includes default values for oxidation which are dependent on the mass flow rate of CH_4 per unit at the bottom of the surface soil prior to any oxidation, also known as methane flux rate. The oxidation factors included in the GHGRP (0, 0.10, 0.25, 0.35) are based on published, peer-reviewed literature and facility data provided through external stakeholder engagement. The EPA concluded, during review of both the literature and facility-reported emissions data, that simply revising the IPCC's Tier 1 oxidation default of 10 percent to a new singular default oxidation value would not take into account the key variable - methane flux rate - entering the surface soil layer. More information regarding analysis of methane oxidation fractions can be found in the memorandums titled "Review of Methane Flux and Soil Oxidation Data", December 7, 2012 (RTI 2012), and "Review of Oxidation Studies and Associated Cover Depth in the Peer Reviewed Literature", June 17, 2015 (RTI 2015b). More information about the landfill specific conditions required to use higher oxidation factors can be found in Table HH-4 of 40 CFR Part 98, Subpart HH, as shown below.

Table A- 241: Table HH-4 to Subpart HH of Part 98—Landfill Methane Oxidation Fractions

Under these conditions:	Use this landfill methane oxidation fraction:
I. For all reporting years prior to the 2013 reporting year	
C1: For all landfills regardless of cover type or methane flux	0.10
II. For the 2013 reporting year and all subsequent years	
C2: For landfills that have a geomembrane (synthetic) cover or other non-soil barrier meeting the definition of final cover with less than 12 inches of cover soil for greater than 50% of the landfill area containing waste	0.0
C3: For landfills that do not meet the conditions in C2 above and for which you elect not to determine methane flux	0.10
C4: For landfills that do not meet the conditions in C2 or C3 above and that do not have final cover, or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste	0.10
C5: For landfills that do not meet the conditions in C2 or C3 above and that have final cover, or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is less than 10 grams per square meter per day (g/m2/d)	0.35
C6: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is 10 to 70 g/m2/d	0.25
C7: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is greater than 70 g/m2/d	0.10

[a] Where a landfill is located in a state that does not have an intermediate or interim cover requirement, the landfill must have soil cover of 12 inches or greater in order to use an oxidation fraction of 0.25 or 0.35.
[b] Methane flux rate (in grams per square meter per day; g/m2/d) is the mass flow rate of methane per unit area at the bottom of the surface soil prior to any oxidation and is calculated as follows:

For Equation HH-5 of this subpart, or for Equation TT-6 of subpart TT of this part,

$$MF = K \times G_{CH4} \ /SArea$$

For Equation HH-6 of this subpart,

$$MF = K \times \left(G_{CH4} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

For Equations HH-7 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right) \Big/ SArea$$

For Equation HH-8 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \left\{ \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right\} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

The EPA's GHGRP also requires landfills to report the type of cover material used at their landfill as: organic cover, clay cover, sand cover, and/or other soil mixtures.

Step 8: Estimate Total CH_4 Emissions for the Inventory

For 1990 to 2004, 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-242. A different methodology is applied for 2005 to 2018 where directly reported net CH_4 emissions to EPA's GHGRP plus the 9 percent scale-up factor were applied. For 2005 to 2009, the directly reported GHGRP net emissions from 2010 to 2018 were used to back-cast emissions for 2005 to 2009. Note that the emissions values for 2005 to 2009 are re-calculated for each Inventory and are subject to change if facilities reporting to the GHGRP revise their annual greenhouse gas reports for any year. The 9 percent scale-up factor was also applied annually for 2005 to 2009.

Table A-242: CH_4 Emissions from Landfills (kt)

	1990	1995	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
MSW CH_4 Generation	8,214	9,140	10,270	10,477	10,669	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial CH_4 Generation	484	537	618	625	629	636	639	643	648	653	656	657	659	661	662	663	664	665	666
MSW CH_4 Recovered	**(718)**	**(1,935)**	**(4,894)**	**(4,995)**	**(5,304)**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
MSW CH_4 Oxidized	(750)	(720)	(538)	(548)	(537)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial CH_4 Oxidized	(48)	(54)	(62)	(63)	(63)	(64)	(64)	(64)	(65)	(65)	(66)	(66)	(66)	(66)	(66)	(66)	(66)	(67)	(67)
MSW Net CH_4 Emissions	**6,746**	**6,484**	**5,394**	**5,496**	**5,395**	**4,681**	**4,593**	**4,506**	**4,419**	**4,331**	**4,372**	**4,023**	**4,070**	**3,924**	**3,907**	**3,855**	**3,724**	**3,709**	**3,823**
Industrial Net CH4 Emissions	**436**	**483**	**556**	**563**	**566**	**572**	**575**	**578**	**583**	**588**	**590**	**591**	**593**	**595**	**596**	**597**	**598**	**599**	**599**
Net Emissions[a]	**7,182**	**6,967**	**5,394**	**5,496**	**5,395**	**5,253**	**5,168**	**5,084**	**5,002**	**4,919**	**4,963**	**4,614**	**4,662**	**4,519**	**4,503**	**4,452**	**4,322**	**4,308**	**4,422**

Notes: MSW and Industrial CH_4 generation in Table A-242 represents emissions before oxidation. Totals may not sum exactly to the last significant figure due to rounding. Parentheses denote negative values.

"-" Not applicable due to methodology change.

[a] MSW Net CH_4 emissions for years 2010 to 2018 are directly reported CH_4 emissions to the EPA's GHGRP for MSW landfills and are back-casted to estimate emissions for 2005 to 2009. A scale-up factor of 9 percent of each year's emissions from 2005 to 2018 is applied to account for landfills that do not report annual methane emissions to the GHGRP. Emissions for years 1990 to 2004 are calculated by the FOD methodology.

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