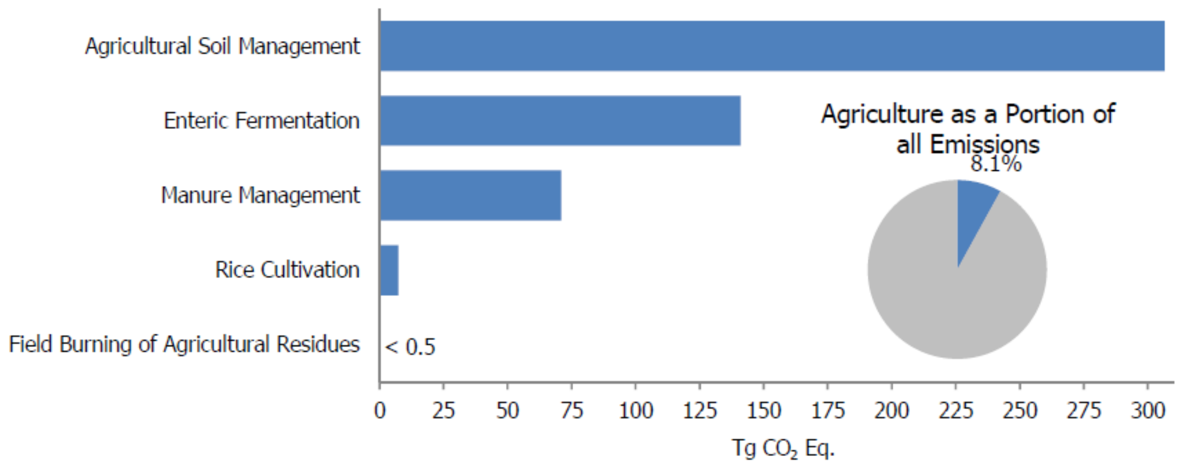
6. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon-dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 6-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as liming of agricultural soils and conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 6-1: 2012 Agriculture Chapter Greenhouse Gas Emission Sources



In 2012, the Agriculture sector was responsible for emissions of 526.3 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 8.1 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 25.0 percent and 9.4 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 74.8 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2012, CH_4 emissions from agricultural activities increased by 13.6 percent, while N_2O emissions fluctuated from year to year, but overall increased by 9.5 percent.

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990		2005		2008	2009	2010	2011	2012
CH_4	**177.3**		**197.7**		**206.5**	**204.7**	**206.2**	**202.4**	**201.5**
Enteric Fermentation	137.9		142.5		147.0	146.1	144.9	143.0	141.0
Manure Management	31.5		47.6		51.5	50.5	51.8	52.0	52.9
Rice Cultivation	7.7		7.5		7.8	7.9	9.3	7.1	7.4
Field Burning of Agricultural Residues	0.3		0.2		0.3	0.2	0.2	0.3	0.3
N_2O	**296.6**		**314.5**		**336.9**	**334.2**	**327.9**	**325.8**	**324.7**
Agricultural Soil Management	282.1		297.3		319.0	316.4	310.1	307.8	306.6
Manure Management	14.4		17.1		17.8	17.7	17.8	18.0	18.0
Field Burning of Agricultural Residues	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Total	**473.9**		**512.2**		**543.4**	**538.9**	**534.2**	**528.3**	**526.3**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990		2005		2008	2009	2010	2011	2012
CH_4	**8,445**		**9,416**		**9,835**	**9,749**	**9,820**	**9,638**	**9,597**
Enteric Fermentation	6,566		6,785		6,999	6,956	6,898	6,809	6,714
Manure Management	1,499		2,265		2,452	2,403	2,466	2,478	2,519
Rice Cultivation	366		358		370	378	444	339	351
Field Burning of Agricultural Residues	13		9		13	12	11	12	12
N_2O	**957**		**1,014**		**1,087**	**1,078**	**1,058**	**1,051**	**1,047**
Agricultural Soil Management	910		959		1,029	1,021	1,000	993	989
Manure Management	46		55		57	57	57	58	58
Field Burning of Agricultural Residues	+		+		+	+	+	+	+

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

6.1 Enteric Fermentation (IPCC Source Category 4A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4.Total livestock CH_4 emissions in 2012 were 141.0 Tg CO_2 Eq. (6,714 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2012. Emissions from dairy cattle in 2012 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

From 1990 to 2012, emissions from enteric fermentation have increased by 2.3 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with production increases. For example, beef cattle emissions increased 0.6 percent from 1990 to 2012, while beef cattle populations actually declined by 5 percent and beef production increased 14 percent (USDA 2013), and while dairy emissions increased 6 percent over the entire time series, the population has declined by 2 percent and milk production increased 36 percent (USDA 2013). This indicates that while emission factors per head are increasing, emission factors per unit of product are going down. Generally, from 1990 to 1995 emissions increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions generally increased from 2005 to 2007, as both dairy and beef populations underwent increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again from 2008 to 2012 as beef cattle populations again decreased. Regarding trends in other animals, during the timeframe of this analysis, populations of sheep have decreased 53 percent while horse populations have nearly doubled, with each annual increase ranging from about 2 to 9 percent. Goat and swine populations have increased 25 percent and 23 percent, respectively, during this timeframe, though with some slight annual decreases. The population of American bison tripled, while mules and asses have increased by a factor of five.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	2005	2008	2009	2010	2011	2012
Beef Cattle	100.0	105.8	107.5	106.3	105.4	103.1	100.6
Dairy Cattle	33.1	31.6	34.1	34.4	34.1	34.5	35.0
Swine	1.7	1.9	2.1	2.1	2.0	2.1	2.1
Horses	0.8	1.5	1.6	1.6	1.6	1.6	1.7
Sheep	1.9	1.0	1.0	1.0	0.9	0.9	0.9
Goats	0.3	0.3	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.4	0.3	0.3	0.3	0.3	0.3
Mules and Asses	+	+	0.1	0.1	0.1	0.1	0.1
Total	**137.9**	**142.5**	**147.0**	**146.1**	**144.9**	**143.0**	**141.0**

Notes: Totals may not sum due to independent rounding.

\+ Does not exceed 0.05 Tg CO_2 Eq.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	2005	2008	2009	2010	2011	2012
Beef Cattle	4,763	5,037	5,119	5,062	5,019	4,911	4,789
Dairy Cattle	1,574	1,503	1,622	1,639	1,626	1,643	1,668
Swine	81	92	101	99	97	98	100
Horses	40	70	74	75	77	78	79
Sheep	91	49	48	46	45	44	43
Goats	13	14	16	16	16	16	16
American Bison	4	17	16	15	15	14	14
Mules and Asses	1	2	3	4	4	4	5
Total	**6,566**	**6,785**	**6,999**	**6,956**	**6,898**	**6,809**	**6,714**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

National cattle population statistics were disaggregated into the following cattle sub-populations:

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

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.9. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) QuickStats database (USDA 2013).

Diet characteristics were estimated by region for dairy, foraging beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (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. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990-1993, 1994-1998, 1999-2003, 2004-2006, 2007, and 2008 onward.[178] Base year Y_m values by region were estimated using Donovan (1999). A ruminant

[178] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003, as well.

digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA:APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5 and 6 month old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.9.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2012. Also, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle. Annual livestock population data for sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA NASS (USDA 2013). Horse, goat and mule, burro, and donkey population data were available for 1987, 1992, 1997, 2002, 2007 (USDA 1992, 1997, 2013); the remaining years between 1990 and 2012 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992 and 2007 through 2012). American bison population estimates were available from USDA for 2002 and 2007 (USDA 2013) and from the National Bison Association (1999) for 1997 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and ratios extrapolation beyond 2007, as described in more detail in Annex 3.9. Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology based on a Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2012 emission estimates in this report.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 6-5. Based on this analysis, enteric fermentation CH_4 emissions in 2012 were estimated to be between 125.5 and 166.4 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2012 emission estimate of 141.0 Tg CO_2 Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the previous uncertainty analysis because the FAO population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are now from the same USDA source as the other animal types, and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emissions estimates at that time.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2012 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	141.0	125.5	166.4	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2012 estimates.
[c] The overall uncertainty calculated in 2003, and applied to the 2012 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. Recent updates to the forage portion of the diet values for cattle made this the area of emphasis for QA/QC this year, with specific attention to the data sources and comparisons of the current estimates with previous estimates.

In addition, over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current inventory submission now utilizes the transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

Calves 4-6 months were added to emission estimates for the first time in the current Inventory. The inclusion of calves has increased emissions from beef cattle by approximately 3 percent per year. In addition, for the first time calf populations for enteric fermentation were differentiated into dairy and beef calves. During this process, total calf populations were updated slightly, so that the enteric fermentation calf populations differ an average of 0.9 percent per year from manure management calf populations. This issue will be resolved in the next inventory when the manure management inventory uses updated calf population values from the CEFM. Additional recalculations include the following:

- In the previous Inventory, aggregation in the 1992 feedlot cattle was linked incorrectly. This correction resulted in a decrease in emissions for that year of 0.2 percent.
- The USDA published minor revisions in several categories that affected historical emissions estimated for cattle in 2011, including dairy cow milk production for several states and cattle populations for January 1, 2012. These changes had an insignificant impact on the overall results.
- Calves 4-6 months were added to emission estimates for the first time in the current Inventory. The inclusion of calves has increased emissions from beef cattle by approximately 3 percent per year. In addition, for the first time calf populations for enteric fermentation were differentiated into dairy and beef calves. During this process, total calf populations were updated slightly, so that the enteric fermentation calf populations differ an average of 0.9 percent per year from manure management calf populations.
- Horse population data was obtained for 1987 and 1992 from USDA census data, resulting in a change in population estimates for 1990 through 1996. This resulted in an average decrease of 6.3 percent for those years relative to the previous report.
- Populations of American bison and mules and asses were revised to extrapolate data beyond the 2007 census based on a linear trend rather than following trends in bison slaughter and holding values constant. These changes resulted in average decrease of 3.2 percent and increase of 31.4 percent, respectively, for those years. Additionally, the name of this population group was revised from mules, burros, and donkeys to mules and asses to be consistent with the CRF tables.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Future improvements for enteric fermentation could include some of the following options:

- Updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;

- Investigation of the availability of annual data for the DE and crude protein values of specific diet and feed components for foraging and feedlot animals;
- Given the many challenges in characterizing dairy diets, further investigation may be conducted on additional sources or methodologies for estimating DE for dairy;
- Assumptions about weights and weight gains for beef cows can be evaluated further such that trends beyond 2007 are updated, rather than held constant;
- Mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States. The estimated weight for dairy cows (1,500 lbs), based solely on Holstein cows, will be reduced in future inventories;
- The possible updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses); and
- The investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry.
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

6.2 Manure Management (IPCC Source Category 4B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the N cycle through the nitrification and denitrification of the organic N in livestock dung and urine.[179] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure to the groundwater below, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct

[179] Direct and indirect 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.

N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS). Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions in 2012 were 52.9 Tg CO_2 Eq. (2,519 Gg); in 1990, emissions were 31.5 Tg CO_2 Eq. (1,499 Gg). This is a 68 percent increase in emissions from 1990. Emissions increased on average by 0.9 Tg CO_2 Eq. (3.0 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 53 and 115 percent, respectively. From 2011 to 2012, there was a 1.7 percent increase in total CH_4 emissions, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

Although the majority of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. Although national dairy animal populations have generally been decreasing since 1990, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus the shift toward larger dairy and swine facilities has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, and 2007 farm-size distribution data reported in the *Census of Agriculture* (USDA 2009a).

In 2012, total N_2O emissions were estimated to be 18.0 Tg CO_2 Eq. (58 Gg); in 1990, emissions were 14.4 Tg CO_2 Eq. (46 Gg). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 25 percent increase from 1990 to 2012 and a 0.1 percent increase from 2011 through 2012. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	2005	2008	2009	2010	2011	2012
CH_4[a]	**31.5**	**47.6**	**51.5**	**50.5**	**51.8**	**52.0**	**52.9**
Dairy Cattle	12.6	22.4	26.0	25.9	26.0	26.5	27.1
Beef Cattle	2.7	2.8	2.8	2.7	2.8	2.8	2.7
Swine	13.1	19.2	19.7	18.8	19.9	19.8	20.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	2.8	2.7	2.7	2.7	2.7	2.7	2.7
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2

American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O^b	**14.4**	**17.1**	**17.8**	**17.7**	**17.8**	**18.0**	**18.0**
Dairy Cattle	5.3	5.7	5.8	5.8	5.9	5.9	6.0
Beef Cattle	6.1	7.4	7.8	7.8	7.8	8.0	7.9
Swine	1.2	1.8	2.0	2.0	1.9	2.0	2.0
Sheep	0.1	0.4	0.4	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.5	1.7	1.7	1.6	1.6	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.2	0.2
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+
Total	**45.8**	**64.7**	**69.3**	**68.2**	**69.6**	**70.0**	**70.9**

+ Less than 0.5 Gg.
[a]Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.
[b]Includes both direct and indirect N_2O emissions.
Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.
NA: Not available

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	2005	2008	2009	2010	2011	2012
CH_4^a	**1,499**	**2,265**	**2,452**	**2,403**	**2,466**	**2,478**	**2,519**
Dairy Cattle	599	1,069	1,238	1,233	1,239	1,262	1,291
Beef Cattle	128	135	132	131	134	132	128
Swine	624	914	938	896	948	941	957
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	129	128	129	127	127
Horses	9	12	10	11	11	11	12
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O^b	**46**	**55**	**57**	**57**	**57**	**58**	**58**
Dairy Cattle	17	18	19	19	19	19	19
Beef Cattle	20	24	25	25	25	26	26
Swine	4	6	6	6	6	6	6
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+

+ Less than 0.5 Gg.
[a]Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.
[b]Includes both direct and indirect N_2O emissions.
Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.
NA: Not available

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management. See Annex 3.11 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH_4 emissions:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- Volatile solids (VS) production rate (by animal type and state or United States);
- Methane producing potential (B_o) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2012 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from USDA National Agriculture Statistics Service (NASS). For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 6.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, and 2007, horse and mule and ass population data for 1987, 1992, 1997, 2002 and 2007, and American bison population for 2002 and 2007 were obtained from the *Census of Agriculture* (USDA 2009a). American bison population data for 1990-1999 were obtained from the National Bison Association (1999).

- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM used for cattle, please see section 6.1, Enteric Fermentation.

- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA; APHIS 1996; Bush 1998; Ott 2000; USDA 2009a) and EPA (ERG 2000a; EPA 2002a; 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA; APHIS 2000; UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.

- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996, 2008 and ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the 2006 IPCC Guidelines. American bison VS production was assumed to be the same as NOF bulls.

- The maximum CH_4 producing capacity of the VS (B_o) was determined for each animal type based on literature values (Morris 1976; Bryant et al, 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.
- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2012). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) were multiplied by the maximum CH_4 producing capacity of the VS (B_o) (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N_2O emissions:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volitalization ($EF_{volitalization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volitalization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

N_2O emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex rates were assumed to be the same as NOF bulls.
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.1).

To estimate N_2O emissions for cattle (except for calves) and American bison, the estimated amount of N excreted (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year).

Next, indirect N_2O emissions from volatilization (kg N_2O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{tas}$) divided by 100, and the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions.

The direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year).

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. These uncertainty estimates were directly applied to the 2012 emission estimates as there have not been significant changes in the methodology since that time.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2012 were estimated to be between 43.4 and 63.5 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2012 emission estimate of 52.9 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 15.1 and 22.4 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2012 emission estimate of 18.0 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2012 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	52.9	43.4	63.5	-18%	+20%
Manure Management	N_2O	18.0	15.1	22.4	-16%	+24%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the previous and current inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure N data were checked by comparing state-level data with bottom up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted and the sum of county estimates for the full time series.

Any updated data, including population, are validated by experts to ensure the changes are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_o, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the 2006 IPPC default values.

For additional verification, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default 2006 IPCC values. Table 6-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC default emission factors. The U.S. implied emission factors fall within the range of the 2006 IPCC default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the 2006 IPCC default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy and swine across the time series. This increase reflects the dairy and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions.

Table 6-9: 2006 IPCC Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)	Implied CH_4 Emission Factors (kg/head/year)						
		1990	2005	2008	2009	2010	2011	2012
Dairy Cattle	48-112	42.3	81.2	90.7	89.6	91.0	92.0	93.5
Beef Cattle	1-2	1.5	1.6	1.5	1.5	1.6	1.6	1.6
Swine	10-45	11.6	15.0	13.9	13.6	14.6	14.3	14.4
Sheep	0.19-0.37	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Goats	0.13-0.26	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Poultry	0.02-1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	1.56-3.13	4.3	3.1	2.5	2.5	2.6	2.6	2.6
Mules and Asses	0.76-1.14	0.9	0.9	0.9	0.9	0.9	0.9	0.9
American Bison	NA	1.8	2.0	2.1	2.1	2.1	2.1	2.1

In addition, 2006 default IPCC emission factors for N_2O were compared to the U.S. Inventory implied N_2O emission factors. Default N_2O emission factors from the 2006 IPCC Guidelines were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. Inventory values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

The CEFM produces population, VS and Nex data for cattle, excepting calves, that are used in the manure management inventory. As a result, all changes to the CEFM described in Section 6.1 Enteric Fermentation contributed to changes in the population, VS and Nex data used for calculating CH_4 and N_2O cattle emissions from manure management. State animal populations were updated to reflect updated USDA NASS datasets. Population changes occurred for poultry and swine in 2011. Changes also occurred for horses and mules and asses for 1990 through 1996 due to incorporation of older census data. VS for mules and asses was updated this year due to a calculation error when the animal group was incorporated in 2011.

Planned Improvements

The uncertainty analysis will be updated in the future to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

In the next Inventory report, the population, VS, and Nex values for calves calculated by the CEFM will be incorporated into the manure management emission estimates. Calf populations will be differentiated into dairy and beef calves so that populations between enteric fermentation and manure management will be equal. Also, the 2012 Agricultural Census data will also be incorporated into the inventory when it becomes available. These data will be used to update animal population and WMS estimates.

6.3 Rice Cultivation (IPCC Source Category 4C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields (Baicich 2013). When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen present in the soil, causing anaerobic soil conditions. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root system) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead, so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with shallower flooding depths (Sass 2001). Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. Rice in the United States is grown under continuously flooded, shallow water conditions; none is grown under deepwater conditions (USDA 2012). Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). The factors that determine the amount of organic material available to decompose under anaerobic conditions (i.e., organic fertilizer use, soil type, rice variety[180], and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation.

[180] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Rice is cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However most rice farmers recycle crop residues from the previous rice or rotational crop, which are left standing, disked, or rolled into fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of southwest Louisiana, Texas, and Florida often allow for a second, or ratoon, rice crop. Ratoon crops are much less common or non-existent in Arkansas, California, Mississippi, and Missouri. In 2012, Arkansas reported a larger-than-usual ratoon crop because an early start to the planting season allowed more farmers to attempt a ratoon crop (Hardke 2013). Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop (Wang 2013). This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow the stubble to decay aerobically), the amount of organic material that is available for anaerobic decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (Table 6-10 and Table 6-11). In 2012, CH_4 emissions from rice cultivation were 7.4 Tg CO_2 Eq. (351 Gg). Annual emissions fluctuated unevenly between the years 1990 and 2012, ranging from an annual decrease of 24 percent from 2010 and 2011 to an annual increase of 18 percent from 2009 to 2010. There was an overall decrease of 16 percent between 1990 and 2006, due to an overall decrease in primary crop area. However, emission levels increased again by 14 percent between 2006 and 2012 due to an overall increase in total rice crop area. All states except Arkansas and Missouri reported a decrease in rice crop area from 2011 to 2012. The factors that affect the rice acreage in any year vary from state to state and are typically the result of weather phenomena (Baldwin et al. 2010).

Table 6-10: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990		2005		2008	2009	2010	2011	2012
Primary	**5.6**		**6.7**		**5.9**	**6.2**	**7.2**	**5.2**	**5.3**
Arkansas	2.4		3.3		2.8	3.0	3.6	2.3	2.6
California	0.7		0.9		0.9	1.0	1.0	1.0	1.0
Florida	+		+		+	+	+	+	+
Louisiana	1.1		1.1		0.9	0.9	1.1	0.8	0.8
Mississippi	0.5		0.5		0.5	0.5	0.6	0.3	0.3
Missouri	0.2		0.4		0.4	0.4	0.5	0.3	0.4
Oklahoma	+		+		0.0	0.0	0.0	0.0	0.0
Texas	0.7		0.4		0.3	0.3	0.4	0.4	0.3
Ratoon	**2.1**		**0.8**		**1.9**	**1.8**	**2.1**	**1.9**	**2.1**
Arkansas	+		+		+	+	+	+	0.4
Florida	+		+		+	+	+	+	+
Louisiana	1.1		0.5		1.2	1.1	1.4	1.0	1.1
Texas	0.9		0.4		0.6	0.7	0.7	0.9	0.5
Total	**7.7**		**7.5**		**7.8**	**7.9**	**9.3**	**7.1**	**7.4**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-11: CH_4 Emissions from Rice Cultivation (Gg)

State	1990		2005		2008	2009	2010	2011	2012
Primary	**268**		**319**		**282**	**294**	**343**	**247**	**253**
Arkansas	115		157		134	141	171	111	123
California	34		45		44	48	48	50	48
Florida	1		1		1	1	1	2	1
Louisiana	52		50		45	45	51	40	38
Mississippi	24		25		22	23	29	15	12
Missouri	8		21		19	19	24	12	17
Oklahoma	+		+		+	+	+	+	+
Texas	34		19		17	16	18	17	13
Ratoon	**98**		**39**		**89**	**84**	**101**	**92**	**98**
Arkansas	+		1		+	+	+	+	20
Florida	2		+		1	2	2	2	2

Louisiana	52	22	59	51	68	46	50
Texas	45	17	29	31	32	44	26
Total	**366**	**358**	**370**	**378**	**444**	**339**	**351**

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

Methodology

IPCC Good Practice Guidance (GPG) (2000) recommends using harvested rice areas, and seasonally integrated emission factors (i.e., emission factors for each commonly occurring set of rice production conditions in the country developed from standardized field measurements representing the mix of different conditions that influence CH_4 emissions in the area). To that end, the recommended GPG methodology and Tier 2 U.S.-specific seasonally integrated emission factors derived from U.S. based rice field measurements were used. Following a literature review of the most recent research on CH_4 emissions from U.S. rice production, regional emission factors were derived. California-specific winter flooded and non-winter flooded emission factors were applied to California rice area harvested. Average U.S. seasonal emission factors were applied to Arkansas, Florida, Louisiana, Missouri, Mississippi, and Texas as sufficient data to develop state-specific and/or daily emission factors were not available. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season for those states where ratooning occurs. Within California, some rice crops are flooded during the winter to prepare the fields for seedbeds for the next growing season, in addition to creating waterfowl habitat (Young 2013); consequently, emissions from winter-flooded and non-winter flooded areas are also estimated using separate emission factors. Winter flooded rice crops generate CH_4 year round due to the anaerobic conditions the winter flooding creates (EDF 2011). Thus for winter flooded rice crops in California, an annual CH_4 emission factor is used. For non-winter flooded California rice crops, a seasonal emission factor is applied. It has been found that up to 50 percent of the year-round CH_4 emissions in winter flooded rice crops will occur in the winter, but almost all of the CH_4 emissions from non-winter flooded rice crops occur during the growing season (Fitzgerald 2000). This approach is consistent with IPCC (2000).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-12, and the ratooned crop area as a percent of primary crop area is shown in Table 6-13. Primary crop areas for 1990 through 2012 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2013). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 6-14. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2012 (Anderson 2008 through 2013; Beighley 2012; Buehring 2009 through 2011; Guethle 1999 through 2010; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007 through 2008).

Table 6-12: Rice Area Harvested (Hectares)

State/Crop	1990	2005	2008	2009	2010	2011	2012
Arkansas							
Primary	485,633	661,675	564,549	594,901	722,380	467,017	520,032
Ratoon[a]	-	662	6	6	7	5	26,002
California	159,854	212,869	209,227	225,010	223,796	234,723	225,010
Florida							
Primary	4,978	4,565	5,463	5,664	5,330	8,212	6,244
Ratoon	2,489	-	1,639	2,266	2,275	2,311	2,748
Louisiana							
Primary	220,558	212,465	187,778	187,778	216,512	169,162	160,664
Ratoon	66,168	27,620	75,111	65,722	86,605	59,207	64,265
Mississippi	101,174	106,435	92,675	98,341	122,622	63,942	52,206
Missouri	32,376	86,605	80,534	80,939	101,578	51,801	71,631
Oklahoma	617	271	77	-	-	-	-

Texas								
Primary	142,857	81,344	69,607	68,798	76,083	72,845	54,229
Ratoon	57,143	21,963	36,892	39,903	41,085	56,091	33,080
Total Primary	**1,148,047**	**1,366,228**	**1,209,911**	**1,261,431**	**1,468,300**	**1,067,702**	**1,090,016**
Total Ratoon	**125,799**	**50,245**	**113,648**	**107,897**	**129,971**	**117,613**	**126,094**
Total	**1,273,847**	**1,416,473**	**1,323,559**	**1,369,328**	**1,598,271**	**1,185,315**	**1,216,111**

[a] Arkansas ratooning occurred only in 1998, 1999, and 2005 through 2012, with particularly high ratoon rates in 2012.
"-" No reported value
Note: Totals may not sum due to independent rounding.

Table 6-13: Ratooned Area as Percent of Primary Growth Area

State	1990	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Arkansas	+	+	+	+	+	+	+	+	+	0.1%	+	+	+	+	+	+	5%
Florida	50%	50%	50%	65%	41%	60%	54%	100%	77%	0%	28%	30%	30%	40%	43%	28%	44%
Louisiana	30%	30%	30%	30%	40%	30%	15%	35%	30%	13%	20%	35%	40%	35%	40%	35%	40%
Texas	40%	40%	40%	40%	50%	40%	37%	38%	35%	27%	39%	36%	53%	58%	54%	77%	61%

+ Indicates ratooning less than 0.1 percent of primary growth area.

Table 6-14: Non-USDA Data Sources for Rice Harvest Information (Citation Year)

State/Crop	1990	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Arkansas - Ratoon			Wilson (2002 – 2007, 2009 – 2012)												Hardke (2013)
Florida – Primary	Scheuneman (1999 – 2001)			Deren (2002)	Kirstein (2003)			Gonzales (2006 – 2013) Kirstein (2006)							
Florida – Ratoon	Scheuneman (1999-2001)			Deren (2002)	Kirstein (2003-2004)		Cantens (2005)	Gonzales (2006 – 2013)							
Louisiana – Ratoon	Bollich (2000)		Linscombe (1999, 2001 – 2013)												
Oklahoma – Primary					Lee (2003-2007)					Anderson (2008 – 2013)					
Texas – Ratoon	Klosterboer (1999 – 2003)					Stansel (2004,2005)		Texas Ag Experiment Station (2006 – 2013)							

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments that involved atypical or nonrepresentative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results were then sorted by state, season (i.e., primary and ratoon), flooding practices, and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added).

Eleven California-specific primary crop experimental results were added for California rice emissions this year. These California-specific studies were selected because they met the criteria of experiments on primary crops with added synthetic and organic fertilizer, without residue burning, and without winter flooding (Bossio 1999; Fitzgerald et al. 2000). The seasonal emission rates estimated in these studies were averaged to derive a seasonal emission factor for California's primary, non-winter flooded rice crop. Similarly, separate California-specific studies meeting the same criteria, (i.e., primary crops with added synthetic and organic fertilizer, without residue burning) but with winter flooding (Bossio 1999; Fitzgerald et al. 2000; McMillan et al. 2007) were averaged to derive an annual emission factor for California's primary, winter-flooded rice crop. Approximately 60 percent of California's rice crop is winter-flooded (Environmental Defense Fund, Inc. 2011), therefore the California-specific winter flooded emission factor was applied to 60 percent of the California rice area harvested and the California-specific non-winter flooded emission factor was applied to the 40 percent of the California rice area harvested. The resultant seasonal emission factor for the California non-winter flooded crop is 133 kg CH_4/hectare-season, and the annual emission factor for the California winter-flooded crop is 266 kg CH_4/hectare-season.

For the remaining states, a non-California U.S. seasonal emission factor was derived by averaging seasonal emissions rates from primary crops with added synthetic and organic fertilizer (Byrd 2000; Kongchum 2005; Rogers et al. 2011; Sass et al. 1991a, 1991b, 2002a, 2002b; Yao 2000). The seasonal emissions rates from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993; Lindau et al. 1995) were averaged to derive a seasonal emission factor for the ratoon crop. The resultant seasonal emission factor for the primary crop is 237 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

Box 6-1: Comparison of the U.S. Inventory Seasonal Emission Factors and IPCC (1996) Default Emission Factor

Emissions from rice production were estimated using a Tier 2 methodology consistent with IPCC (2000) Good Practice Guidance. Default emission factors using experimentally determined seasonal CH_4 emissions from U.S. rice fields for both primary and ratoon crops were derived from a literature review. The 1996 IPCC Guidelines default seasonal emission factors are compared because a U.S.-specific seasonal emission factor is provided instead of the global daily emission factor provided in the 2006 IPCC guidelines, and the standard global seasonal emission factor provided in the *IPCC Good Practice Guidance* (2000). As explained above, four different emission factors were calculated: 1) a seasonal California-specific rate without winter flooding (133 kg CH_4/hectare-season), 2) an annual California specific-rate with winter flooding (266 kg CH_4/hectare-season), 3) a seasonal non-California primary crop rate (237 kg CH_4/hectare-season), and 4) a seasonal non-California ratoon crop rate (780 kg CH_4/hectare-season). These emission factors represent averages across rice field measurements representing typical water management practices and synthetic and organic amendment application practices in the United States according to regional experts (Anderson 2013; Beighly 2012; Fife 2011; Gonzalez 2013; Linscombe 2013; Vayssières 2013; Wilson 2012). The IPCC (1996) default factor for U.S. (i.e., Texas) rice production of both primary and ratoon crops is 250 kg CH_4/hectare-season .This default value is based on a study by Sass and Fisher (1995) which reflects a growing season in Texas of approximately 275 days. Data results in the evaluated studies were provided as seasonal emission factors; therefore, neither daily emission factors nor growing season length was estimated. Some variability within season lengths in the evaluated studies is assumed. The Tier 2 emission factors used here represent rice cultivation practices specific to the United States. For comparison, the 2012 U.S. emissions from rice production are 7.4 Tg CO_2 Eq. using the four U.S.-specific emission factors for both primary and ratoon crops and 6.4 Tg CO_2 Eq. using the IPCC (1996) emission factor.

Table 6-15: Non-California Seasonal Emission Factors (kg CH_4/ha-season)

Primary		Ratoon	
Low	61	Low	481
High	500	High	1490
Mean	237	Mean	780

Table 6-16: California Emission Factors (kg CH_4/ha)

Winter Flooded (Annual)[a]		Non-Winter Flooded (Seasonal)[b]	
Low	131	Low	62
High	369	High	221
Mean	266	Mean	133

[a] Percentage of CA rice crop winter flooded: 60 percent
[b] Percentage of CA rice crop not winter flooded: 40 percent

Uncertainty and Time-Series Consistency

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, particularly fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 61 to 500 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the California winter flooding, California non-winter flooding, non-California primary, and ratoon emission factors were derived using the distributions of the relevant emission factors available in the literature and described above. Variability around the rice emission factor means was not normally distributed for any crops, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the Tier 2 Monte Carlo analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is ratooned, the length of the growing season, and the extent to which flooding outside of the normal rice season is practiced. Expert judgment was used to estimate the uncertainty associated with primary rice-cropped area for each state at 1 to 5 percent, and a normal distribution was assumed. Uncertainties were applied to ratooned area by state, based on the level of reporting performed by the state. Within California, the uncertainty associated with the percentage of rice fields that are winter flooded was estimated at plus and minus 20 percent. No uncertainty estimates were calculated for the practice of flooding outside of the normal rice season outside of California because CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-17. Rice cultivation CH_4 emissions in 2012 were estimated to be between 3.57 and 14.47 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 52 percent below to 96 percent above the actual 2012 emission estimate of 7.38 Tg CO_2 Eq.

Table 6-17: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2012 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	CH_4	7.38	3.57	14.47	-52%	+96%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

An updated literature review of rice emission factor estimates was conducted for the current Inventory, resulting in an updated set of regional rice emission factors. In the previous Inventory, two U.S. average emission factors were applied to rice area harvested—one for the primary crop (210 kg CH_4/hectare-season) and one for the ratoon crop (780 kg CH_4/hectare-season). The updated emission factors, based on the recent literature, replace the primary crop emission factor with two California-specific emission factors based on flooding practices and an updated non-California primary crop emission factor of 237 kg CH_4/hectare-season. The new emission factors were applied across the full time series, as they represent the same assumptions about rice cultivation practices. The change in emission factors resulted, on average, in an 8.3 percent increase in emissions from 1990 to 2011.

Planned Improvements

A planned improvement for the 1990 through 2013 Inventory will be the expansion of the California specific rice emission factors to include an emission factor for the period prior to the passage of the Air Resources Board (ARB) Mandate phasing out rice residue burning. This non-flooded residue burned emission factor will take into account the phase down of rice straw burning that occurred in California from 1990 to 2002. During this time period, the percentage of acres burned annually decreased from 75 percent in 1992 to 13 percent in 2002 (California Air Resources Board 2003). California studies that include rice burning on non-flooded lands will be used to develop the pre-2002 rice burning emission factor, and further research will be conducted to determine the percentage of winter flooded acres to which the current California winter flooded emission factor will be applied. This new time series dependent emission factor will be applied to non-flooded burned acres during the 1990 through 2002 time period to capture the significant change in the percentage of rice acreage burned due to the California ARB Mandate. Following 2002, the current methodology and emission factors will be applied.

Another possible future improvement is to create additional state- or region-specific emission factors for rice cultivation. This prospective improvement would likely not take place for another 2 to 3 years, because the analyses needed for it are currently taking place.

6.4 Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[181] A number of agricultural activities increase mineral N availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add or lead to greater release of mineral N to the soil, including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils in croplands and grasslands (i.e., soils with a high organic matter content, otherwise known as Histosols).[182] Other

---

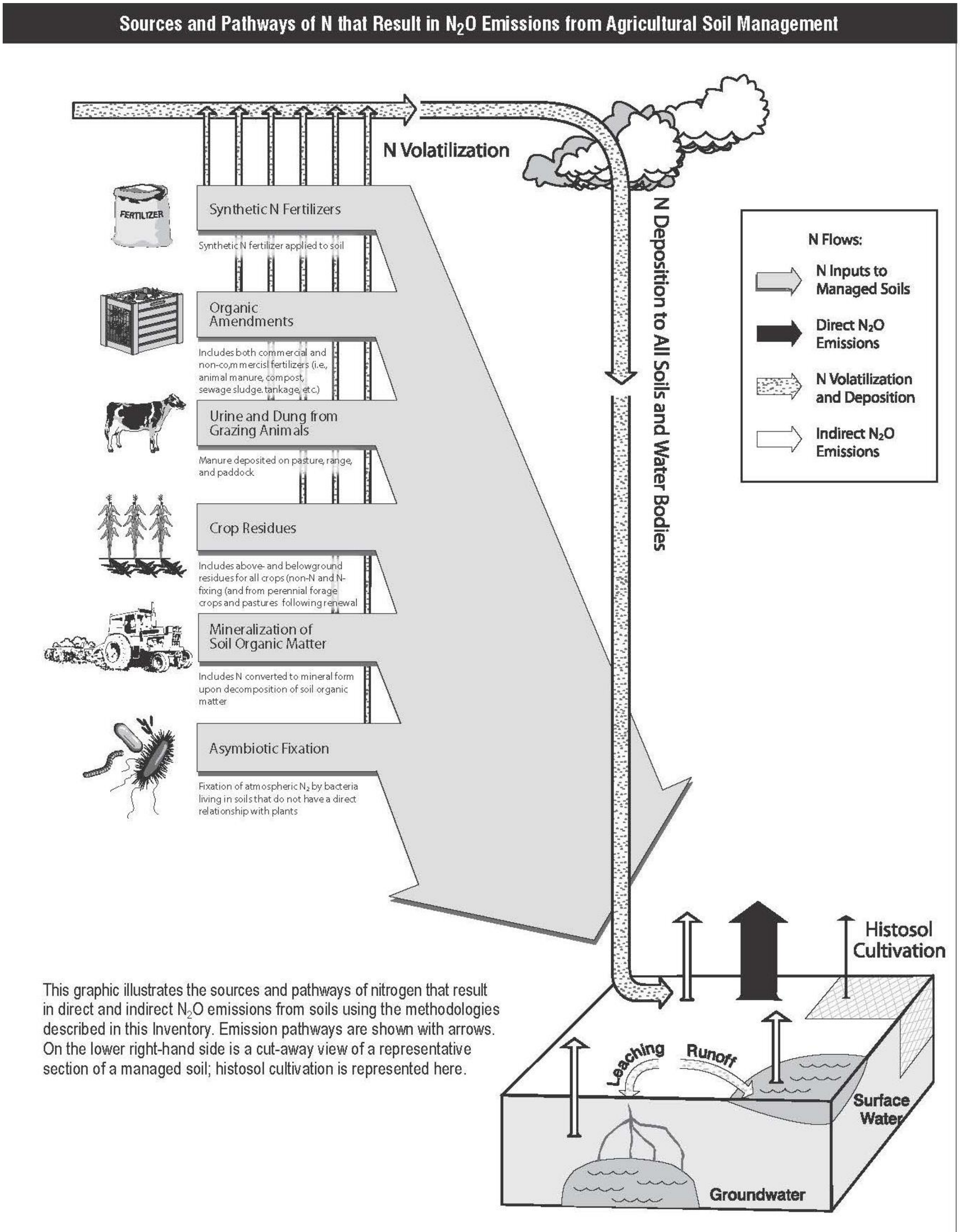
181 Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product 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).

182 Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils, and thereby affect direct emissions. Mineral N is also made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, and these processes are influenced by agricultural management through impacts on moisture and temperature regimes in soils.[183] The N mineralization from decomposition of soil organic matter and also asymbiotic N fixation are included based on the recommendation from the IPCC (2006) for complete accounting of management impacts on greenhouse gas emissions, as discussed in the Methodology section. Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[184] Direct emissions from agricultural lands (i.e., cropland and grassland as defined in Chapter 7, Land Representation Section) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. However, indirect N_2O emissions from all land-uses (cropland, grassland, forest lands, and settlements) are reported in this section.

[183] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.
[184] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x.

Figure 6-2: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2012 were 306.6 Tg CO_2 Eq. (989 Gg N_2O) (see Table 6-18 and Table 6-19). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2012, although overall emissions were 8.7 percent higher in 2012 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. On average, cropland accounted for approximately 61 percent of total direct emissions, while grassland accounted for approximately 39 percent. The percentages for indirect emissions are approximately 76 percent for croplands, 22 percent for grasslands, and the remaining 2 percent is from forest lands and settlements. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 6-20 and Table 6-21.

Table 6-18: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990		2005		2008	2009	2010	2011	2012
Direct	**240.7**		**253.3**		**269.5**	**267.6**	**264.0**	**261.9**	**260.9**
Cropland	155.1		162.8		166.5	165.2	162.1	161.0	159.8
Grassland	85.6		90.5		103.0	102.5	101.9	100.9	101.1
Indirect (All Land-Use Types)	**41.4**		**44.0**		**49.5**	**48.8**	**46.1**	**45.8**	**45.7**
Cropland	31.6		32.7		38.2	37.6	35.1	35.2	34.9
Grassland	9.5		10.6		10.6	10.4	10.2	9.9	10.2
Forest Land	+		0.1		0.1	0.1	0.1	0.1	0.1
Settlements	0.4		0.6		0.6	0.6	0.6	0.6	0.6
Total	**282.1**		**297.3**		**319.0**	**316.4**	**310.1**	**307.8**	**306.6**

+ Less than 0.05 Tg CO_2 Eq.

Table 6-19: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990		2005		2008	2009	2010	2011	2012
Direct	**776**		**817**		**869**	**863**	**852**	**845**	**842**
Cropland	500		525		537	533	523	519	515
Grassland	276		292		332	331	329	325	326
Indirect (All Land-Use Types)	**134**		**142**		**160**	**157**	**149**	**148**	**147**
Cropland	102		105		123	121	113	114	112
Grassland	31		34		34	34	33	32	33
Forest Land	0		+		+	+	+	+	+
Settlements	1		2		2	2	2	2	2
Total	**910**		**959**		**1,029**	**1,021**	**1,000**	**993**	**989**

+ Less than 0.5 Gg N_2O

Table 6-20: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type ($Tg\ CO_2$ Eq.)

Activity	1990		2005		2008	2009	2010	2011	2012
Cropland	**155.1**		**162.8**		**166.5**	**165.2**	**162.1**	**161.0**	**159.8**
Mineral Soils	**150.4**		**158.7**		**162.5**	**161.1**	**158.1**	**157.0**	**155.7**
Synthetic Fertilizer	65.5		65.8		69.5	69.0	68.6	67.4	67.3
Organic Amendment[b]	14.0		15.3		15.8	15.7	15.4	15.5	15.5
Residue N[a]	3.9		4.8		4.6	4.6	4.5	4.5	4.4
Mineralization and Asymbiotic Fixation	67.0		72.9		72.5	71.8	69.5	69.6	68.5
Organic Soils[e]	**4.7**		**4.1**		**4.0**	**4.0**	**4.0**	**4.0**	**4.0**
Grassland	**85.6**		**90.5**		**103.0**	**102.5**	**101.9**	**100.9**	**101.1**
Mineral Soils	**85.6**		**90.5**		**103.0**	**102.5**	**101.9**	**100.9**	**101.1**
Synthetic Fertilizer	0.5		1.0		1.0	1.0	1.0	1.0	0.9
PRP Manure	24.5		25.5		26.6	26.3	25.8	25.0	25.4
Managed Manure	0.3		0.3		0.3	0.3	0.3	0.3	0.3
Sewage Sludge	0.3		0.5		0.5	0.5	0.5	0.6	0.6
Residue N[c]	2.0		2.4		2.6	2.6	2.6	2.5	2.5
Mineralization and Asymbiotic Fixation	58.2		60.8		72.0	71.9	71.7	71.5	71.3
Total	**240.7**		**253.3**		**269.5**	**267.6**	**264.0**	**261.9**	**260.9**

[a] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.
[b] Organic amendment inputs include managed manure amendments, daily spread manure amendments, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).
[c] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N
[d] Accounts for managed manure and daily spread manure amendments that are applied to grassland soils.
[e] Includes drainage of organic soils for both cropland and grasslands.

Table 6-21: Indirect N_2O Emissions from all Land-Use Types ($Tg\ CO_2$ Eq.)

Activity	1990		2005		2008	2009	2010	2011	2012
Cropland	**31.6**		**32.7**		**38.2**	**37.6**	**35.1**	**35.2**	**34.9**
Volatilization & Atm. Deposition	15.1		15.9		15.5	15.3	15.3	15.5	15.4
Surface Leaching & Run-Off	16.4		16.8		22.7	22.3	19.8	19.8	19.5
Grassland	**9.5**		**10.6**		**10.6**	**10.4**	**10.2**	**9.9**	**10.2**
Volatilization & Atm. Deposition	4.9		5.5		5.5	5.5	5.4	5.3	5.4
Surface Leaching & Run-Off	4.5		5.1		5.1	5.0	4.8	4.5	4.8
Forest Land	**+**		**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization & Atm. Deposition	+		+		+	+	+	+	+
Surface Leaching & Run-Off	+		0.1		0.1	0.1	0.1	0.1	0.1
Settlements	**0.4**		**0.6**		**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Volatilization & Atm. Deposition	0.1		0.2		0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2		0.4		0.4	0.4	0.4	0.4	0.4
Total	**41.4**		**44.0**		**49.5**	**48.8**	**46.1**	**45.8**	**45.7**

+ Less than 0.05 $Tg\ CO_2$ Eq.

Figure 6-3 and Figure 6-6 show regional patterns in direct N_2O emissions, and also show N losses from volatilization, leaching, and runoff that lead to indirect N_2O emissions. Annual emissions and N losses in 2012 are shown for the Tier 3 Approach only.

Direct N_2O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern and western Minnesota, eastern and southern Nebraska, in addition to eastern South Dakota and North Dakota), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (Figure 6-3). New York, Pennsylvania, Michigan and Wisconsin also have relatively high production of corn and soybeans. Direct emissions are high in Kansas, Missouri and Texas, primarily from irrigated cropping in western Texas, dryland wheat in Kansas, and hay cropping in eastern Texas and Missouri. Direct emissions are low in many parts of the eastern United States because a small portion of land is cultivated, and also low in many western states where rainfall and access to irrigation water are limited.

Direct emissions (Tg CO_2 Eq./state/year) from grasslands are highest in the central and western United States (Figure 6-4) where a high proportion of the land is used for cattle grazing. Most areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions because the total amount of grassland is much lower than in the central and western United States, however, emissions from these areas tend to be higher on a per unit area basis compared to other areas of the country.

Indirect emissions from croplands and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO_3^- leaching, N volatilization) do not respond in exactly the same manner as the processes that control direct emissions (nitrification and denitrification). For example, coarser-textured soils facilitate relatively high indirect emissions in Florida grasslands due to high rates of N volatilization and NO_3^- leaching, even though they have only moderate rates of direct N_2O emissions.

Figure 6-3: Crops, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2012 (Tg CO_2 Eq./year)

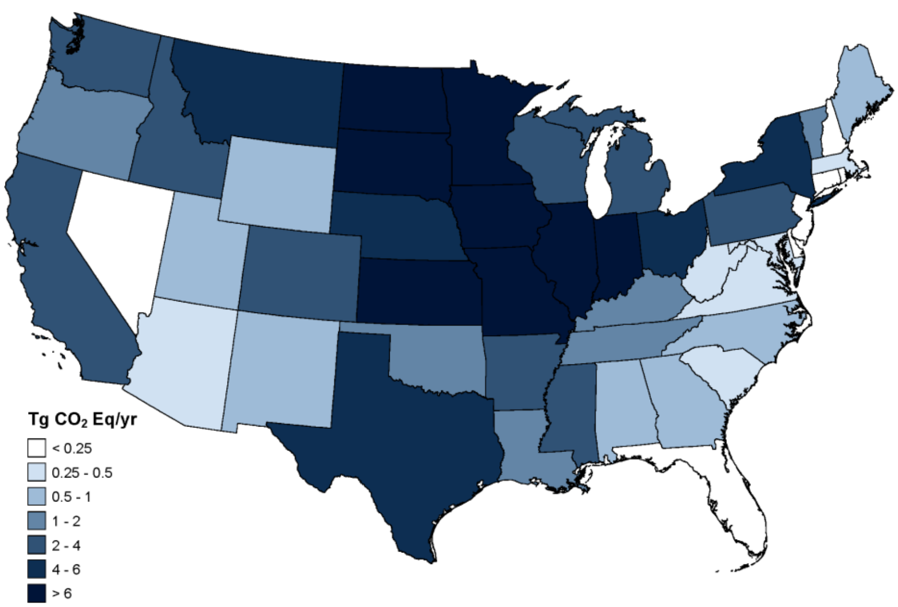


Figure 6-4: Grasslands, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2012 (Tg CO_2 Eq./year)

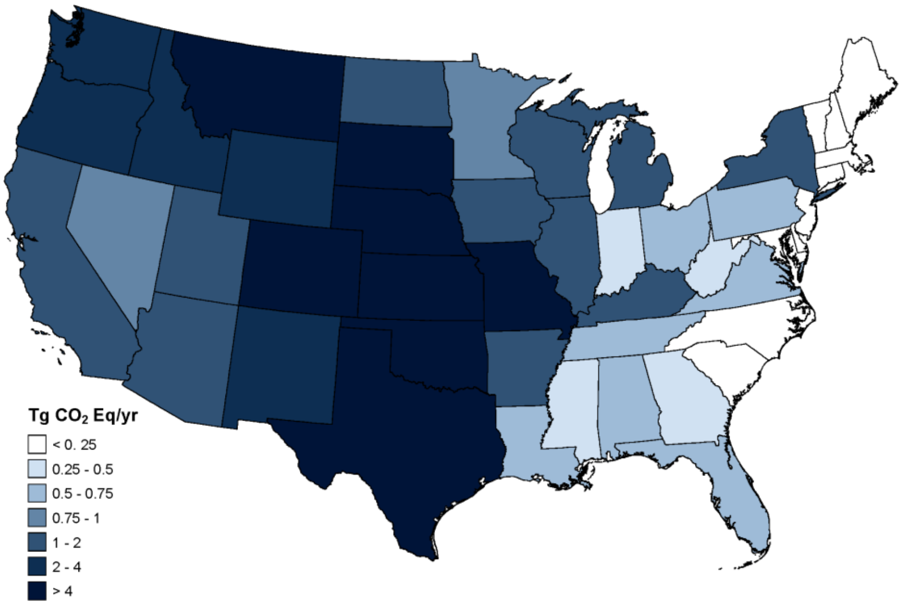


Figure 6-5: Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2012 (Gg N/year)

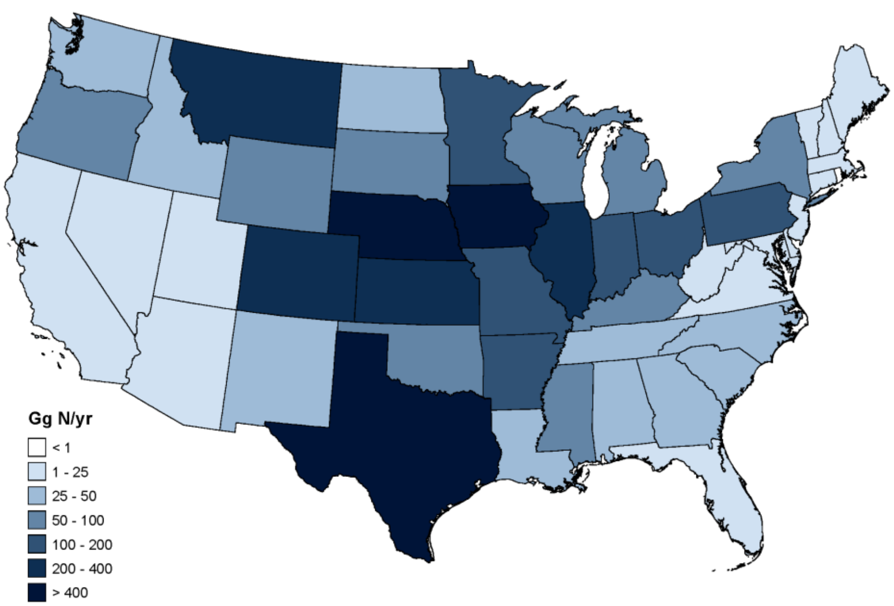
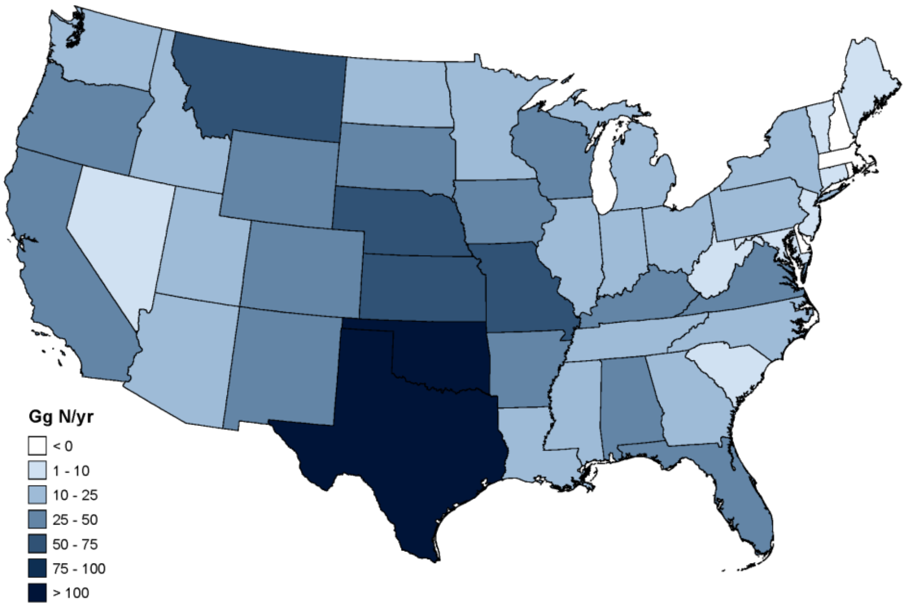


Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2012 (Gg N/year)



Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide the Agricultural Soil Management source category into five components: (1) direct emissions due to N additions to cropland and grassland mineral soils, including synthetic fertilizers, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from soil organic matter mineralization due to land use and management change, (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (5) indirect emissions from soils and water due to N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

The United States has adopted recommendations from IPCC (2006) on methods for agricultural soil management. These recommendations include (1) estimating the contribution of N from crop residues to indirect soil N_2O emissions; (2) adopting a revised emission factor for direct N_2O emissions to the extent that Tier 1 methods are used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils based on harvest yield data to the extent that Tier 1 methods are used in the Inventory; (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation (i.e., computing total emissions from managed land); (6) reporting all emissions from managed lands because management affects all processes leading to soil N_2O emissions; and (7) estimating emissions associated with land use and management change which can significantly change the N mineralization rates from soil organic matter.[185] One recommendation from IPCC (2006) that has not been

[185] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

completely adopted is the accounting of emissions from pasture renewal, which involves occasional plowing to improve forage production. Pastures are replanted occasionally in rotation with annual crops, and this practice is represented in the Inventory. However, renewal of pasture that is not occasionally rotated with annual crops is uncommon in the United States, and is not estimated.

Direct N_2O Emissions

The methodology used to estimate direct emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3 process-based model (DAYCENT) was used to estimate direct emissions from a variety of crops that are grown on mineral soils on mineral (i.e., non-organic) soils, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat; as well as the direct emissions from non-federal grasslands with the exception of sewage sludge amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 6-2 for further elaboration). Moreover, the Tier 3 approach allows for the inventory to address direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2009). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 points in agricultural land for the conterminous United States that are included in the Tier 3 methods.[186] Each point is associated with an “expansion factor” that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected for 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992, and 1994-1997). In 1998, the NRI program began collecting annual data, and data are currently available through 2007.

Box 6-2: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs and the environmental conditions at specific locations. Consequently, the Tier 3 approach produces more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (e.g., daily weather, soil types, etc.), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In

[186] NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2007. There are another 148,731 NRI survey points that are cropland) and are not included in the Tier 3 analysis. The soil N_2O emissions associated with these points are estimated with the IPCC Tier 1 method.

contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

The Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DayCent (e.g., tobacco, sugarcane, orchards, vineyards, and other crops); (2) direct emissions from Pasture/Range/Paddock on federal grasslands, which were not estimated with the Tier 3 DAYCENT model; and (3) direct emissions from drainage of organic soils in croplands and grasslands.

Tier 3 Approach for Mineral Cropland Soils

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops based on the cropping histories in the National Resources Inventory (USDA-NRCS 2009). The crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Crops simulated by DAYCENT are grown on approximately 93 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton and wheat) is simulated with NASA-CASA production algorithm (Potter et al.1993; Potter et al. 2007) using the MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m. A prediction algorithm was developed to estimate EVI (Gurung et al. 2009) for gap-filling during years over the inventory time series when EVI data were not available (e.g., data from the MODIS sensor were only available after 2000 following the launch of the Aqua and Terra Satellites; see Annex 3.11 for more information). DAYCENT also simulated soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions.

DAYCENT was used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter, in addition to asymbiotic fixation. Note that commercial organic fertilizers are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

Synthetic fertilizer data were based on fertilizer use and rates by crop type for different regions of the United States that were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of livestock manure application to cropland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. The adjustments were based on county-scale ratios of manure available for application to soils in other years relative to 1997 (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 was assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management Section 6.2 and Annex 3.11.

The IPCC approach considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DAYCENT simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of symbiotic N fixation, mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs. The DAYCENT simulations also accounted for the approximately 3 percent of all crop residues that were assumed to be burned based on state inventory data (ILENR 1993; Oregon

Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996), and therefore N_2O emissions were reduced by 3 percent from crop residues to account for the burning.

Additional sources of data were used to supplement the mineral N (USDA ERS 1997, 2011), livestock manure (Edmonds et al. 2003), and land-use information (USDA-NRCS 2009). The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage data has an influence on soil organic matter decomposition and subsequent soil N_2O emissions. The time series of tillage data began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the inventory. Daily weather data were used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes were obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011).

Each NRI point was run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N_2O emission estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2012 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to key practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al., 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of crop types not simulated by DAYCENT, such as tobacco, sugarcane, and millet. For the Tier 1 Approach, estimates of direct N_2O emissions from N applications were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments were not included in the DAYCENT simulations because county-level data were not available.[187] Consequently, commercial organic fertilizer, as well as additional manure that was not added to crops in the DAYCENT simulations, were included in the Tier 1 analysis. The influence of land-use change on soil N_2O emissions in the Tier 1 approach has not been addressed in this analysis, but is a planned improvement. The following sources were used to derive activity data:

[187] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and sewage sludge is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and sewage sludge.

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for crops not simulated by DAYCENT, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated at the count- level by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. For 2002 through 2012, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2012).[188] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to crops that were not simulated by DAYCENT.
- Similarly, a process-of-elimination approach was used to estimate manure N additions for crops that were not simulated by DAYCENT because little information exists on application rates for these crops. The amount of manure N applied in the Tier 3 approach to crops and grasslands was subtracted from total manure N available for land application (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), and this difference was assumed to be applied to crops that are not simulated by DAYCENT.
- Commercial organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991 through 1994; AAPFCO 1995 through 2011). Commercial fertilizers do include some manure and sewage sludge, but the amounts are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the sewage sludge amendment data discussed later in this section.
- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994, 1998, 2003, 2005, 2006, 2008, 2009, 2010a), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 Approach.

Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 methods were used to estimate direct N_2O emissions due to drainage of organic soils in croplands or grasslands at a state scale. State-scale estimates of the total area of drained organic soils were obtained from the National Resources Inventory (NRI) (USDA-NRCS 2009) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994, 1998) were used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006). Annual data were available between 1990 and 2007. Emissions are assumed to be similar to 2007 from 2008 to 2012 because no additional activity data are currently available from the NRI for the latter years. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total tropical area was multiplied by the IPCC default emission factor for tropical regions (IPCC 2006).

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) were combined to estimate emissions from non-federal grasslands and Pasture/Range/Paddock manure N additions for federal grasslands, respectively. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native

[188] Values were not available for 2012 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value.

grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, which may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2009) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread), and synthetic fertilizer application. Other N inputs were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach for Mineral Cropland Soils section. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (Section 6.2) and Annex 3.11. Biological N fixation is simulated within DAYCENT, and therefore was not an input to the model.

Manure N deposition from grazing animals in Pasture/Range/Paddock systems (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI point were based on amount of N excreted by livestock in PRP systems. The total amount of N excreted in each county was divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting input rates were used in the DAYCENT simulations. DAYCENT simulations of non-federal grasslands accounted for approximately 68 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state was assumed to be excreted on federal grasslands, and the N_2O emissions were estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands were only available at the national scale, and it was not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N_2O emissions from grassland soils, and consequently, emissions from sewage sludge were estimated using the IPCC (2006) Tier 1 method.

Grassland area data were consistent with the Land Representation reported in Section 7.1 for the conterminous United States. Data were obtained from the U.S. Department of Agriculture National Resources Inventory (NRI)[189] and the U.S. Geological Survey (USGS) National Land Cover Dataset, which were reconciled with the Forest Inventory and Analysis Data.[190] The area data for pastures and rangeland were aggregated to the county level to estimate non-federal and federal grassland areas.[191]

N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N were estimated using the Tier 1 method by multiplying the N input by the appropriate emission factor. Emissions from manure N were estimated at the state level and aggregated to the entire country, but emissions from sewage sludge N were calculated exclusively at the national scale.

As previously mentioned, each NRI point was simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Soil N_2O emission estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2012 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

[189] USDA-NRCS 2009, Nusser and Goebel 1997, <http://www.ncgc.nrcs.usda.gov/products/nri/index.htm>.

[190] Forest Inventory and Analysis Data, <http://fia.fs.us/tools-data/data>.

[191] NLCD, Vogelman et al. 2001, <http://www.mrlc.gov>.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for cropland mineral soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 6-18 and Table 6-19).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). Indirect N_2O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, sewage sludge), and deposition of PRP manure. N made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3^-) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands, grasslands, forest lands, and settlements.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N from Managed Soils

As in the direct emissions calculation, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods were combined to estimate the amount of N that was volatilized and eventually emitted as N_2O. DAYCENT was used to estimate N volatilization for land areas whose direct emissions were simulated with DAYCENT (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section. Nitrogen volatilization for all other areas was estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DAYCENT, PRP manure N excreted on federal grasslands, sewage sludge application on grasslands). The Tier 1 method and default fractions were also used to estimate N subject to volatilization from N inputs on settlements and forest lands (see the Land Use, Land-Use Change, and Forestry chapter). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (Table 6-21).

Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method were combined to estimate the amount of N that was subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT was used to simulate the amount of N transported from lands in the Tier 3 Approach. N transport from all other areas was estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff. This N transport estimate includes N applications on croplands that were not simulated by DAYCENT, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, and N inputs on settlements and forest lands. For both the DAYCENT Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching was assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation plus irrigation does not exceed 80 percent of PET. For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions that occur in groundwater and waterways (Table 6-21).

Uncertainty and Time-Series Consistency

Uncertainty was estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions approximated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT were estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions were estimated with a simple error propagation approach (IPCC 2006). Uncertainties from the Tier 1 and Tier 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.11. The combined uncertainty for direct soil N_2O emissions ranged from 17 percent below to 28 percent above the 2012 emissions estimate of 260.9 Tg CO_2 Eq., and the combined uncertainty for indirect soil N_2O emissions ranged from 45 percent below to 151 percent above the 2012 estimate of 45.7 Tg CO_2 Eq.

Table 6-22: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2012 (Tg CO_2 Eq. and Percent)

Source	Gas	2012 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	260.9	215.4	334.4	-17%	28%
Indirect Soil N_2O Emissions	N_2O	45.7	25.3	114.5	-45%	151%

Note: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

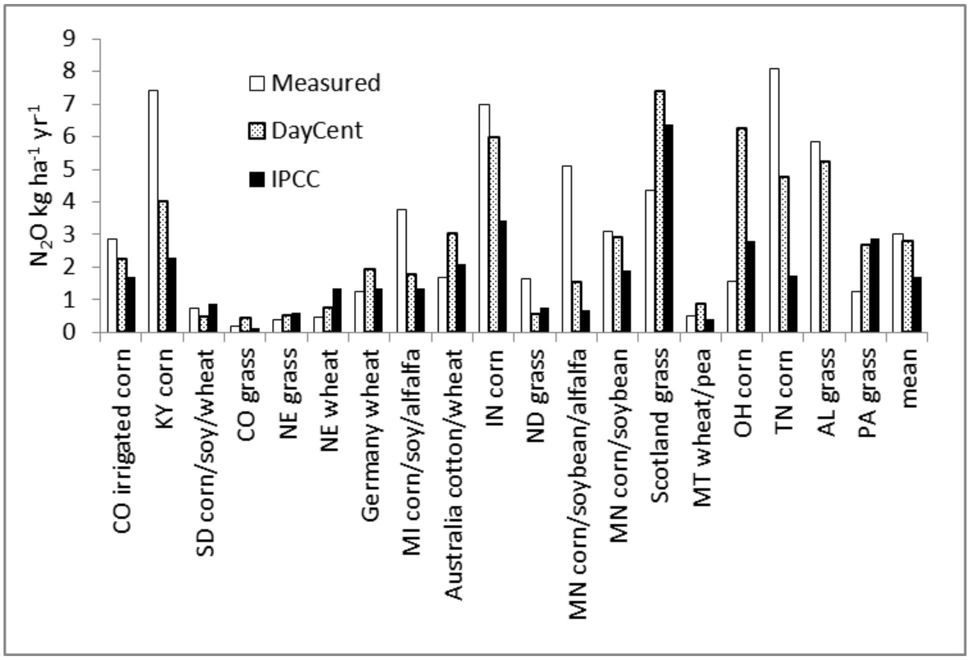
Additional uncertainty is associated with no estimation of N_2O emissions for croplands and grasslands in Hawaii and Alaska, with the exception of drainage for organic soils in Hawaii. Agriculture is not extensive in either state so the emissions are likely to be small compared to the conterminous United States.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section above.

QA/QC and Verification

DAYCENT results for N_2O emissions and NO_3^- leaching were compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005, Del Grosso et al. 2008), and further evaluated by comparing to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data were available for 24 sites in the United States, 5 in Europe, and one in Australia, representing over 60 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at most sites compared to the IPCC Tier 1 estimate (Figure 6-7). In general, IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates are less biased. DAYCENT accounts for key site-level factors (weather, soil characteristics, and management) that are not addressed in the IPCC Tier 1 Method, and thus the model is better able to represent the variability in N_2O emissions. Nitrate leaching data were available for four sites in the United States, representing 12 different combinations of fertilizer amendments/tillage practices. DAYCENT does have a tendency to under-estimate very high N_2O emission rates; estimates are increased to correct for this bias based on a statistical model derived from the comparison of model estimates to measurements (See Annex 3.11 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3^- leaching, and is an improvement over the IPCC Tier 1 method.

Figure 6-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach.



Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of croplands and grasslands and unit conversion factors were checked, as were the program scripts that were used to run the Monte Carlo uncertainty analysis. Links between spreadsheets were checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and an error was found relating to residue N inputs. Some crops that were simulated by DAYCENT were also included in the Tier 1 method. To correct this double-counting of N inputs, residue inputs from crops simulated by DAYCENT were removed from the Tier 1 calculations.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) Driving the DAYCENT simulations with input data for the excretion of C and N onto Pasture/Range/Paddock based on national livestock population data instead being internally generated by the DAYCENT model (note that revised total PRP N additions increased from 6.9 to 7.2 Tg N on average); 2) expanding the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions and bias correction; 3) refining the temperature algorithm that is used for simulating crop production and carbon inputs to the soil in the DAYCENT biogeochemical model; and (4) recalculation of Tier 2 organic soil N_2O emissions using annual data from the NRI rather than estimating emissions for every 5 years and holding emissions constant between the years. These changes resulted in an increase in emissions of approximately 23 per cent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N_2O emissions from 40 to 29 percent. The differences are mainly due to the refinement of temperature algorithm in the model and expansion of the number of field studies used to develop the statistical function for estimating uncertainty in the model structure and parameters. In particular, additional studies showed very high N_2O emissions during some years that were not captured by DAYCENT. This resulted in a relatively large adjustment in a portion of the DAYCENT simulated N_2O emissions to capture the high N_2O emission rates.

Planned Improvements

Several planned improvements are underway. The first is to update the time series of land use and management data from the USDA National Resources Inventory so that it is extended from 2008 through 2010. Fertilization and tillage activity data will also be updated as part of this improvement. The remote-sensing based data on the Enhanced Vegetation Index will be extended through 2010 in order to use the EVI data to drive crop production in DAYCENT. The update will extend the time series of activity data for the Tier 2 and 3 analyses through 2010, and incorporate latest changes in agricultural production for the United States.

Second, improvements are planned for the DAYCENT biogeochemical model. Model structure will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops, such as wheat. In addition, crop parameters associated with temperature effects on plant production will be further improved in DAYCENT with additional model calibration.

Experimental study sites will continue to be added for quantifying model structural uncertainty. Studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority because they provide more robust estimates of annual emissions compared to studies that sample trace gas emissions weekly or less frequently.

Another planned improvement is to account for the use of fertilizers formulated with nitrification inhibitors in addition to slow-release fertilizers (e.g., polymer-coated fertilizers). Field data suggests that nitrification inhibitors and slow-release fertilizers reduce N_2O emissions significantly. The DAYCENT model can represent nitrification inhibitors and slow-release fertilizers, but accounting for these in national simulations is contingent on testing the model with a sufficient number of field studies and collection of activity data about the use of these fertilizers.

An improvement is also underway to simulate crop residue burning in the DAYCENT based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (Section 6.5). The methodology for Field Burning of Agricultural Residues was significantly updated recently, but the new estimates of crop residues burned have not been incorporated into the Agricultural Soil Management source. Moreover, the data have only been used to reduce the N_2O after DAYCENT simulations in the current Inventory, but the planned improvement is to drive the simulations with burning events based on the new spatial data that is used in Section 6.5.

Also, the treatment of N excretion from Pasture, Range and Paddock manure in both the Manure Management and Agricultural Soil Management sections will be reconciled to ensure consistency in the next version of the Inventory. Currently some managed manure, in addition to daily spread as noted in the methodology section, is included in the Pasture, Range and Paddock manure for Agricultural Soil Management resulting in minor differences.

All of these improvements are expected to be completed for the 1990 through 2013 Inventory report. However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

Alaska and Hawaii are not included in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii. Some minor crops that should be in the Tier 1 analysis are also missing from the analysis, which will be added as a planned improvement. A planned improvement over the next two years is to add these states into the Inventory analysis.

6.5 Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and then applied to soils; landfilled; or, as discussed in the chapter, burned in the field. Field burning of crop residues is not considered a net source of CO_2, because the C released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning of agricultural residues is not a common method of disposal in the United States. In the United States, the primary crop types whose residues may be burned are corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). In 2012, CH_4 and N_2O emissions from field burning of agricultural residues were 0.3 Tg CO_2 Eq. (12 Gg) and 0.1 Tg. CO_2 Eq. (0.3 Gg), respectively. Annual emissions from this source over the period 1990 to 2012 have remained relatively constant, averaging approximately 0.2 Tg CO_2 Eq. (12 Gg) of CH_4 and 0.1 Tg CO_2 Eq. (0.3 Gg) of N_2O (see Table 6-23 and Table 6-24).

Table 6-23: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990		2005		2008	2009	2010	2011	2012
CH_4	**0.3**		**0.2**		**0.3**	**0.2**	**0.2**	**0.3**	**0.3**
Corn	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Rice	+		+		+	+	0.1	+	+
Soybeans	+		+		+	+	+	+	+
Sugarcane	0.1		+		+	+	+	+	+
Wheat	0.1		0.1		0.1	0.1	0.1	0.1	0.1
N_2O	**0.1**		**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Corn	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Rice	+		+		+	+	+	+	+
Soybeans	+		+		+	+	+	+	+
Sugarcane	+		+		+	+	+	+	+
Wheat	+		+		+	+	+	+	+
Total	**0.4**		**0.3**		**0.4**	**0.4**	**0.3**	**0.4**	**0.4**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-24: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990		2005		2008	2009	2010	2011	2012
CH_4	**13**		**9**		**13**	**12**	**11**	**12**	**12**
Corn	1		1		1	2	2	2	2
Cotton	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Rice	2		2		2	2	2	2	2
Soybeans	1		1		1	1	1	1	1
Sugarcane	3		1		2	2	2	2	2
Wheat	6		4		6	5	5	5	5
N_2O	**+**		**+**		**+**	**+**	**+**	**+**	**+**
Corn	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Rice	+		+		+	+	+	+	+

Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
CO	**268**	**184**	**270**	**247**	**241**	**255**	**253**
NO_x	**8**	**6**	**8**	**8**	**8**	**8**	**8**

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

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with IPCC (2006) (for more details, see Box 6-3). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$\text{C or N released} = \Sigma \text{ for all crop types and states } \left[\frac{\text{AB}}{\text{CAH} \times \text{CP} \times \text{RCR} \times \text{DMF} \times \text{BE} \times \text{CE} \times (\text{FC or FN})} \right]$$

where,

Area Burned (AB)	=	Total area of crop burned, by state
Crop Area Harvested (CAH)	=	Total area of crop harvested, by state
Crop Production (CP)	=	Annual production of crop in Gg, by state
Residue/Crop Ratio (RCR)	=	Amount of residue produced per unit of crop production, by state
Dry Matter Fraction (DMF)	=	Amount of dry matter per unit of biomass for a crop
Fraction of C or N (FC or FN)	=	Amount of C or N per unit of dry matter for a crop
Burning Efficiency (BE)	=	The proportion of prefire fuel biomass consumed[192]
Combustion Efficiency (CE)	=	The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

Crop production and area harvested were available by state and year from USDA (2012) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH_4, CO, N_2O and NO_x emissions from the field burning of agricultural residues:

$$CH_4 \text{ and CO, or } N_2O \text{ and } NO_x \text{ Emissions from Field Burning of Agricultural Residues} =$$

$$\text{C or N Released} \times \text{ER for C or N} \times \text{CF}$$

where,

Emissions Ratio (ER) = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released
Conversion Factor (CF) = conversion, by molecular weight ratio, of CH_4-C to C (16/12), or CO-C to C (28/12), or N_2O-N to N (44/28), or NO_x-N to N (30/14)

Emissions from Burning of Agricultural Residues were calculated using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The equation varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A comparison of the methods and factors used in (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990 through 2009 Inventory report to determine the magnitude of the difference in overall estimates resulting from the two approaches. The IPCC (2006) approach was not used because crop-specific

[192] In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable 'fraction oxidized in burning.' This variable is equivalent to (burning efficiency × combustion efficiency).

emission factors for N_2O were not available for all crops, therefore the crop specific methodology provided in the IPCC/UNEP/OECD/IEA (1997) approach was used.

The IPCC (2006) default approach resulted in 12 percent higher emissions of CH_4 and 25 percent higher emissions of N_2O than the estimates in the 1990 through 2009 Inventory. It is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current estimates are based on U.S.-specific, crop-specific, published data.

Crop production data for all crops except rice in Florida and Oklahoma were taken from USDA's QuickStats service (USDA 2013). Rice production and area data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon rice crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2013), and rice crop yields for Arkansas (USDA 2013) were applied to Oklahoma acreages[193] (Lee 2003 through 2006; Anderson 2008 through 2013). The production data for the crop types whose residues are burned are presented in Table 6-25. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state[194] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[195] McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. State-level area burned data were divided by state-level crop area harvested data to estimate the percent of crop area burned by crop for each state. The average fraction of area burned by crop across all states is shown in Table 6-26. All crop area harvested data were from USDA (2013), except for rice acreage in Florida and Oklahoma, which is not measured by USDA (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2013; Lee 2003 through 2006; Anderson 2008 through 2013). Data on crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average 5 year percent area burned, based on data availability and inter-annual variability. This average was taken at the crop and state level. Table 6-26 shows these percent area estimates aggregated for the United States as a whole, at the crop level. State-level estimates based on state-level crop area harvested and burned data were also prepared, but are not presented here.

All residue/crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The datum for sugarcane is from Kinoshita (1988) and that of cotton from Huang et al. (2007). The residue/crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). These data are listed in Table 6-27. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). Emission ratios and conversion factors for all gases (see Table 6-28) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-25: Agricultural Crop Production (Gg of Product)

Crop	1990		2005		2008	2009	2010	2011	2012

[193] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

[194] Alaska and Hawaii were excluded.

[195] McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general "other crops/fallow" category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and "other" categories.

Corn[a]	201,534		282,263		307,142	332,549	316,165	313,949	273,832
Cotton	3,376		5,201		2,790	2,654	3,942	3,391	3,770
Lentils	40		238		109	265	393	215	240
Rice	7,114		10,132		9,272	9,972	11,027	8,389	9,048
Soybeans	52,416		83,507		80,749	91,417	90,605	84,192	82,055
Sugarcane	25,525		24,137		25,041	27,608	24,821	26,512	29,193
Wheat	74,292		57,243		68,016	60,366	60,062	54,413	61,755

[a] Corn for grain (i.e., excludes corn for silage).

Table 6-26: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990		2005		2008	2009	2010	2011	2012
Corn	+		+		+	+	+	+	+
Cotton	1 %		1 %		1 %	1 %	1 %	1 %	1 %
Lentils	3 %		+		1 %	1 %	+	1 %	1 %
Rice	10 %		6 %		9 %	9 %	8 %	10 %	9 %
Soybeans	+		+		+	+	+	+	+
Sugarcane	59 %		26 %		39 %	37 %	38 %	40 %	37 %
Wheat	3 %		2 %		3 %	3 %	3 %	3 %	3 %

+ Less than 0.5 percent

Table 6-27: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 6-28: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

Uncertainty and Time-Series Consistency

Due to data and time limitations, uncertainty resulting from the fact that emissions from burning of Kentucky bluegrass and "other" residues are not included in the emissions estimates was not incorporated into the uncertainty analysis. The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-29. Methane emissions from field burning of agricultural residues in 2012 were estimated to be between 0.15 and 0.36 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 41percent below and 42 percent above the 2012 emission estimate of 0.25 Tg CO_2 Eq.[196] Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.07 and 0.14 Tg CO_2 Eq., or approximately 30 percent below and 32 percent above the 2012 emission estimate of 0.10 Tg CO_2 Eq.

Table 6-29: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2012 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.25	0.15	0.36	-41%	42%
Field Burning of Agricultural Residues	N_2O	0.10	0.07	0.14	-30%	32%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. For some crops and years in Florida and Oklahoma, the total area burned as measured by McCarty (2010) was greater than the area estimated for that crop, year, and state by Gonzalez (2004-2008) and Anderson (2007) for Florida and Oklahoma, respectively, leading to a percent area burned estimate of greater than 100 percent. In such cases, it was assumed that the percent crop area burned for that state was 100 percent.

Recalculations Discussion

The current Inventory was updated to incorporate state-level estimates of percentage of crop area burned. This represents an improvement on the previous methodology, which used state-level percentage burned data to generate a national average due to uncertainty analysis constraints. In addition, the crop production data for 2011 and 2012 were updated relative to the previous report using data from USDA (2013). Rice cultivation data for Florida and Oklahoma, which are not reported by USDA, were updated for 2012 through communications with state experts. Overall, these improvements resulted in an average increase in emissions of 14.4 percent from 1990 through 2011. Emissions increased the most for 1996 (31.3 percent), and decreased in 2003 (-2.8 percent), the only year in which emissions decreased. These changes are due almost entirely to the methodology updates and applying percentage of crop area burned at the state level. The changes in crop production values had a negligible impact on emissions.

Planned Improvements

Further investigation will be conducted into inconsistent area burned data from Florida and Oklahoma as mentioned in the QA/QC and verification section, and attempts will be made to revise or further justify the assumption of 100 percent of area burned for those crops and years where the estimated percent area burned exceeded 100 percent. The availability of useable area harvested and other data for bluegrass and the "other crops" category in McCarty (2010) will also be investigated in order to try to incorporate these emissions into the estimate. More crop area burned data are becoming available and will be analyzed for incorporation into the next Inventory report.

---

[196] This value of 0.25 Tg CO_2 is rounded and reported as 0.3 Tg CO_2 in Table 6-21 and the text discussing Table 6-21. For the uncertainty calculations, the value of 0.25 Tg CO_2 was used to allow for more precise uncertainty ranges.