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: 2010 Agriculture Chapter Greenhouse Gas Emission Sources

In 2010, the Agriculture sector was responsible for emissions of 428.4 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 6.3 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 about 21 percent and 8 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 68 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 2010, CH_4 emissions from agricultural activities increased by 14.5 percent, while N_2O emissions fluctuated from year to year, but overall increased by 5.0 percent.

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

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**172.9**	**193.9**	**195.9**	**202.9**	**202.6**	**200.8**	**202.2**
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3
Manure Management	31.7	47.9	48.4	52.7	51.8	50.7	52.0
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**214.9**	**230.7**	**229.6**	**229.7**	**231.3**	**225.6**	**226.2**
Agricultural Soil Management	200.0	213.1	211.1	211.1	212.9	207.3	207.8
Manure Management	14.8	17.6	18.4	18.5	18.3	18.2	18.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**387.8**	**424.6**	**425.4**	**432.6**	**433.8**	**426.4**	**428.4**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**8,234**	**9,232**	**9,327**	**9,663**	**9,647**	**9,564**	**9,627**
Enteric Fermentation	6,373	6,618	6,731	6,850	6,829	6,788	6,728
Manure Management	1,511	2,280	2,303	2,508	2,465	2,416	2,478
Rice Cultivation	339	326	282	295	343	349	410
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
N_2O	**693**	**744**	**741**	**741**	**746**	**728**	**730**
Agricultural Soil Management	645	687	681	681	687	669	670
Manure Management	48	57	59	60	59	59	59

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 among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules) 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 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, 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 2010 were 141.3 Tg CO_2 Eq. (6,728 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2010. Emissions from dairy cattle in 2010 accounted for 23 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules, burros, and donkeys.

From 1990 to 2010, emissions from enteric fermentation have increased by 5.6 percent. Generally, emissions decreased from 1996 to 2003, though with a slight increase in 2002. This trend was mainly due to decreasing populations of both beef and dairy cattle and increased digestibility of feed for feedlot cattle. Emissions increased from 2004 through 2007, as both dairy and beef populations have undergone increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again in 2008 to 2010 as beef cattle populations again decreased. During the timeframe of this analysis, populations of sheep have decreased 51 percent while horse populations have increased over 87 percent, mostly between 2001 and 2006. Goat and swine populations have increased 25 percent and 20 percent, respectively, during this timeframe, though with slight decreases from 2009 to 2010, while the populations of American bison and mules, burros, and donkeys have more than quadrupled.

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

Livestock Type	1990	2005	2006	2007	2008	2009	2010
Beef Cattle	96.2	101.4	103.0	104.0	103.1	102.0	101.1
Dairy Cattle	31.8	30.4	31.1	32.4	32.9	33.2	33.0
Horses	1.9	3.5	3.6	3.6	3.6	3.6	3.6
Swine	1.7	1.9	1.0	2.1	2.1	2.1	2.0
Sheep	1.9	1.0	1.9	1.0	1.0	1.0	0.9
Goats	0.3	0.3	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.4	0.4	0.3	0.4	0.3	0.3
Mules, Burros, and Donkeys	+	+	0.1	0.1	0.1	0.1	0.1
Total	**133.8**	**139.0**	**141.4**	**143.8**	**143.4**	**142.6**	**141.3**

Notes: + Does not exceed 0.05 Tg CO2 Eq. Totals may not sum due to independent rounding.

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

Livestock Type	1990		2005	2006	2007	2008	2009	2010
Beef Cattle	4,581		4,829	4,904	4,953	4,909	4,857	4,812
Dairy Cattle	1,513		1,449	1,479	1,544	1,564	1,581	1,569
Horses	91		166	171	171	171	171	171
Swine	81		92	93	98	101	99	97
Sheep	91		49	50	49	48	46	45
Goats	13		14	15	16	16	16	16
American Bison	4		17	17	16	17	17	16
Mules, Burros, and Donkeys	1		2	2	3	3	3	3
Total	**6,373**		**6,618**	**6,731**	**6,850**	**6,829**	**6,788**	**6,728**

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, burrow, and donkeys) 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 Steers)
    - 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 2011).

Diet characteristics were estimated by region for U.S. dairy, foraging beef, and feedlot beef cattle. These estimates 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 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, 1999-2002, 2003, 2004-2006, 2007, and 2008 onwards. Base year Y_m values by region were estimated using Donovan (1999). A ruminant 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 USDA (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 3.9 for more details on the method used to characterize cattle diets and weights in the United States.

To estimate CH_4 emissions from all cattle types except calves younger than 7 months,[169] 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, and bulls), 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, 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, and bulls. To estimate emissions from cattle, 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 2010. 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 and swine were obtained for all years from USDA NASS (USDA 2011). Horse population data were obtained from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT database (FAO 2011), because USDA does not estimate U.S. horse populations annually. Goat and mule, burro, and donkey population data were available for 1987, 1992, 1997, 2002, and 2007 (USDA 1992, 1997, 2011); the remaining years between 1990 and 2010 were interpolated and extrapolated from the available estimates. American bison population estimates were available from USDA for 2002 and 2007 (USDA 2011) 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

---

[169] Because calves younger than 7 months consume mainly milk and the IPCC recommends the use of a methane conversion factor of zero for all juveniles consuming only milk, this results in no methane emissions from this subcategory of cattle.

points, and ratios of population to slaughter statistics (USDA 2011), as described in more detail in Annex 3.9. Methane emissions from sheep, goats, swine, horses, American bison, and mules, burros, and donkeys 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, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory report. There have been no significant changes to the methodology, although the source of some input variables have been updated, at this time there are not better estimates available for the uncertainty ranges around the 2010 activity data and emission factor input variables used in the current submission. Consequently, these uncertainty estimates were directly applied to the 2010 emission estimates.

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 2010 were estimated to be between 125.8 and 166.7 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2010 emission estimate of 141.3 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. Among non-cattle, horses account for the largest degree of uncertainty in the emission estimates because there is a higher degree of uncertainty among the FAO population estimates used for horses than for the USDA population estimates used for swine, goats, and sheep. American bison, mules, burros, and donkeys were excluded from the initial uncertainty estimate because they were not included in the estimate of emissions at that time, although because of their small populations they would not significantly increase the uncertainty estimate ranges of the overall emissions from enteric fermentation.

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

Source	Gas	2010 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	141.3	125.8	166.7	-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 submitted in 2003 and applied to the 2010 estimates.

c The overall uncertainty calculated in 2003, and applied to the 2010 emission estimate, did not include uncertainty estimates for American bison, mules, burros, and donkeys, and was based on the Tier 1 methodology for bulls. Consequently, there was more uncertainty with bull emissions than with other cattle types.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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 foraging 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 (N) 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

There were several modifications to the methodology that had an effect on emission estimates, including the following:

- Emissions from bulls were estimated using Tier 2 methodology. This resulted in an increase of emissions from bulls by an average of approximately 79 percent per year compared to the previous Inventory estimates which used a Tier 1 methodology, such that bulls represent 3.4 percent of total enteric fermentation emissions from cattle.
- Revisions to the DE values for foraging cattle diets were applied to 1990-2010, resulting in an average change of less than 0.1 percent for foraging beef cattle emissions estimates for 1990 through 2006 and an average increase of 0.4 percent for 2007 through 2009. Details on the current dietary assumptions are discussed in Annex 3.9.
- During the QA/QC process, it was realized that the one data point from 1988 (total births) had been revised by USDA since its original download. Therefore, the data point was corrected from 39,318.0 to 39,317.9 thousand births. This is a very minor change, but it is noted in detail specifically because it affects 1990 base year emissions by trickling through the transition matrix in the growing populations for 1989 and 1990.
- The equations used to distribute end-of-year remaining populations for feedlot cattle to the individual state populations were updated so that the population proportions reflect the current year rather than the following year populations. This did not affect total populations, but there were minor changes to the populations by state for feedlot cattle for all years.
- Previously, American bison and mules, burros, and donkeys were excluded from this source category. Emission estimates are now included for these animal types for all years, and contribute an average of 0.2 percent of total emissions from enteric fermentation across the time series.
- The USDA published revised estimates in several categories that affected historical emissions estimated for cattle, including slight revisions in 2009 cattle on feed population estimates for “other states” (aggregated data for states with small populations of cattle on feed), dairy cow milk production for several states, and steer and heifer placement and slaughter statistics. Additionally, calf births were revised for both the 2008 and 2009 estimates. These changes had an insignificant impact on the overall results.
- There were additional population changes for goats from 2003 through 2006, sheep for 2004, 2006, and 2009, and swine in 2009, as discussed in the recalculations discussion for manure management. Historical emission estimates for goats increased an average of 12.1 percent per year compared to the previous emission estimates for the years mentioned above. All other population changes resulted in a decrease in emissions of less than 1 percent for the animal type and year noted.

As a result of these changes, overall methane emissions from enteric fermentation increased an average of 111 Gg (1.7 percent) per year for 1990 through 2009.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Ongoing revisions 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 will be conducted on additional sources or methodologies for estimating DE for dairy. For example, the current method causes some significant shifts in data between years that may not mimic actual feeding conditions. Regional trend lines may be used to smooth the transition.
- The possible breakout of other animal types (i.e., sheep, swine, goats, horses) from national estimates to state-level estimates or updating to Tier 2 methodology; and
- The investigation of methodologies for including enteric fermentation emission estimates from poultry.

In addition, 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 management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. 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.[170] Indirect N_2O emissions are produced as result of the volatilization of N as NH_3 and NO_x and runoff and leaching of N during treatment, storage and transportation.

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 materials 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 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

---

[170] 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 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 does not include any leaching losses.

Estimates of CH_4 emissions in 2010 were 52.0 Tg CO_2 Eq. (2,478 Gg), 64 percent higher than in 1990. Emissions increased on average by 1.0 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 20 and 107 percent, respectively. Although the majority of 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 limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. 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 facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift 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). Methane emissions from sheep have decreased significantly since 1990 (a 56 percent decrease from 1990 to 2010); however, this is mainly due to population changes. Overall, sheep contribute less than one percent of CH_4 emissions from animal manure management. From 2009 to 2010, there was a 2.6 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.

In 2010, total N_2O emissions were estimated to be 18.3 Tg CO_2 Eq. (59 Gg); in 1990, emissions were 14.8 Tg CO_2 Eq. (48 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 24 percent increase from 1990 to 2010 and a less than 1 percent increase from 2009 through 2010.

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	2006	2007	2008	2009	2010
CH_4[a]	**31.7**	**47.9**	**48.4**	**52.7**	**51.8**	**50.7**	**52.0**
Dairy Cattle	12.6	22.4	23.1	25.7	26.0	25.9	26.0
Beef Cattle	2.7	2.8	2.9	2.9	2.8	2.7	2.8
Swine	13.1	19.2	18.9	20.6	19.7	18.8	19.9
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	2.8	2.7	2.7	2.8	2.7	2.7	2.7
Horses	0.5	0.6	0.6	0.6	0.5	0.5	0.5
N_2O[b]	**14.8**	**17.6**	**18.4**	**18.5**	**18.3**	**18.2**	**18.3**
Dairy Cattle	5.3	5.7	5.8	5.9	5.8	5.8	5.9
Beef Cattle	6.5	7.8	8.3	8.2	8.1	8.1	8.2
Swine	1.2	1.8	1.8	2.0	2.0	2.0	1.9
Sheep	0.1	0.4	0.4	0.4	0.4	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.5	1.7	1.7	1.7	1.7	1.6	1.6
Horses	0.2	0.3	0.3	0.3	0.3	0.3	0.3

Total	**46.5**	**65.5**	**66.7**	**71.1**	**70.0**	**68.9**	**70.4**

+ Less than 0.05 Tg CO_2 Eq.

[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.

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

Gas/Animal Type	1990	2005	2006	2007	2008	2009	2010
CH_4[a]	**1,511**	**2,280**	**2,303**	**2,508**	**2,465**	**2,416**	**2,478**
Dairy Cattle	599	1069	1101	1224	1238	1233	1239
Beef Cattle	128	135	138	136	132	131	134
Swine	624	914	901	982	938	896	948
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	131	134	129	128	129
Horses	22	28	27	27	24	24	24
N_2O[b]	**48**	**57**	**59**	**60**	**59**	**59**	**59**
Dairy Cattle	17	18	19	19	19	19	19
Beef Cattle	21	25	27	27	26	26	27
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	1	1	1	1	1	1	1

+ 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.

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 3.10 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 waste management system (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 2010 for all livestock types, except horses and goats were obtained from USDA 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

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 3.9. Horse population data were obtained from the FAOSTAT database (FAO 2010). Goat population data for 1992, 1997, 2002, and 2007 were obtained from the *Census of Agriculture* (USDA 2009a).

- The TAM is an annual average weight which was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996a), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) and others (EPA 1992, Safley 2000, 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 1996b, 1998b, 2000a, 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 2000b, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).
- VS production rates for all cattle except for bulls and 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 1996a, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998).
- 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, and 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.
- Anaerobic digestion system data were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2011). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).

To estimate CH_4 emissions for cattle, 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. 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 bulls and 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 1996a, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998).
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- 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, 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 animals other than cattle, 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 1000 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 2003) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report 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 2010 emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2010 were estimated to be between 42.7 and 62.5 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2010 emission estimate of 52.0 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 15.4 and 22.7 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2010 emission estimate of 18.3 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**	**2010 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	52.0	42.7	62.5	-18%	+20%
Manure Management	N_2O	18.3	15.4	22.7	-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.

The U.S. specific values for TAM, Nex, VS, B_o, MCF, and the resulting implied emission factors were also compared to the IPCC default values. 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 IPPC default values. For example, the U.S. implied CH_4 emission factor for dairy cattle is significantly higher than the IPCC default implied CH_4 emission factor. This is because U.S. dairy manure is most commonly managed in liquid systems, which produce more CH_4.

Recalculations Discussion

The CEFM produces population, VS and Nex data for cattle 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.

Data from the 2007 *Census of Agriculture* were incorporated into the inventory. Census farm size distribution data were used to update the WMS distributions for dairy and swine in 2007. The dairy and swine WMS distributions between 2002 and 2007 were extrapolated based on the 2002 and 2007 data; WMS distributions after 2007 were assumed to be equal to 2007 values. The dairy and swine WMS update caused changes in dairy and swine emission estimates from 2003 on.

In addition, census county-level population data were used to update the county-level population estimates. These estimates are used as input to the Agricultural Soil Management calculations, and to determine population-weighted state temperatures which are used to calculate MCFs for liquid systems. The county-level population update caused minor changes in methane emissions for all animals throughout the timeseries.

State animal populations were updated to reflect updated USDA NASS datasets. Population changes occurred for all animals in 2009. Sheep populations experienced changes in 2004 to 2006 and 2008 estimates due to a change in the "other states" reported by USDA NASS.

Temperature data were updated to incorporate the most recent available data. The temperature data are used to estimate MCFs for liquid systems; this update caused minor changes in CH_4 emission estimates from dairy, swine, beef, and poultry from 2007 to 2009.

Planned Improvements

Tier 1 emission estimates for mules, donkeys, burros, and American bison will be incorporated into future inventories. Although these animal groups are considered very minor sources of emissions and will not contribute significantly to the overall U.S. emissions from manure management, they will be included for completeness and consistency across source categories.

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.

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. 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. 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. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. 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 (i.e., organic fertilizer use, soil type, rice variety,[171] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season; the total amount of CH_4 released depends primarily on the amount of organic substrate available. 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.

Rice is cultivated in eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas.[172] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers apply organic fertilizers in the form of residue from the previous rice crop, which is left standing, disked, or rolled into the 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, Missouri, Oklahoma, and northern areas of Louisiana. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been

---

[171] 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.

[172] A very small amount of rice is grown on about 20 acres in South Carolina; however, this amount was determined to be too insignificant to warrant inclusion in national emission estimates.

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 6-9 and Table 6-10). In 2010, CH_4 emissions from rice cultivation were 8.6 Tg CO_2 Eq. (410 Gg). Annual emissions fluctuated unevenly between the years 1990 and 2010, ranging from an annual decrease of 14 percent to an annual increase of 17 percent. There was an overall decrease of 17 percent between 1990 and 2006, due to an overall decrease in primary crop area.[173] However, emission levels increased again by 45 percent between 2006 and 2010 due to an increase in rice crop area in all states except Oklahoma, which reported no rice production in 2009 and 2010. The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	2005	2006	2007	2008	2009	2010
Primary	**5.1**	**6.0**	**5.1**	**4.9**	**5.3**	**5.6**	**6.5**
Arkansas	2.1	2.9	2.5	2.4	2.5	2.6	3.2
California	0.7	0.9	0.9	1.0	0.9	1.0	1.0
Florida	+	+	+	+	+	+	+
Louisiana	1.0	0.9	0.6	0.7	0.8	0.8	1.0
Mississippi	0.4	0.5	0.3	0.3	0.4	0.4	0.5
Missouri	0.1	0.4	0.4	0.3	0.4	0.4	0.4
Oklahoma	+	+	+	+	+	+	+
Texas	0.6	0.4	0.3	0.3	0.3	0.3	0.3
Ratoon	**2.1**	**0.8**	**0.9**	**1.3**	**1.9**	**1.8**	**2.1**
Arkansas	+	+	+	+	+	+	+
Florida	+	+	+	+	+	+	+
Louisiana	1.1	0.5	0.5	0.9	1.2	1.1	1.4
Texas	0.9	0.4	0.4	0.3	0.6	0.7	0.7
Total	**7.1**	**6.8**	**5.9**	**6.2**	**7.2**	**7.3**	**8.6**

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

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	2005	2006	2007	2008	2009	2010
Primary	**241**	**287**	**241**	**235**	**254**	**265**	**308**
Arkansas	102	139	119	113	119	125	152
California	34	45	44	45	44	47	47
Florida	1	1	1	1	1	1	1
Louisiana	46	45	29	32	39	39	45
Mississippi	21	22	16	16	19	21	26
Missouri	7	18	18	15	17	17	21
Oklahoma	+	+	+	+	+	+	+
Texas	30	17	13	12	15	14	16
Ratoon	**98**	**39**	**41**	**60**	**89**	**84**	**101**
Arkansas	+	1	+	+	+	+	+
Florida	2	+	1	1	1	2	2
Louisiana	52	22	22	42	59	51	68

---

[173] The 14 percent decrease occurred between 2005 and 2006; the 17 percent increase happened between 1993 and 1994.

Texas	45	17	18	16	29	31	32
Total	**339**	**326**	**282**	**295**	**343**	**349**	**410**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, area-based daily emission factors (i.e., amount of CH_4 emitted per day per unit harvested area), and length of growing season to estimate annual CH_4 emissions from rice cultivation. To that end, the recommended methodology and Tier 2 U.S.-specific emission factors derived from rice field measurements were used. Average U.S. seasonal emission factors were applied since state-specific and 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. This approach is consistent with IPCC (2006).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11, and the area of ratoon crop area as a percent of primary crop area is shown in Table 6-12. Primary crop areas for 1990 through 2010 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 2011). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 6-13. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2010 (Guethle 1999 through 2010; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007 through 2008; Buehring 2009 through 2011).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	2005	2006	2007	2008	2009	2010
Arkansas							
Primary	485,633	661,675	566,572	536,220	564,549	594,901	722,380
Ratoon[a]	-	662	6	5	6	6	7
California	159,854	212,869	211,655	215,702	209,227	225,010	223,796
Florida							
Primary	4,978	4,565	4,575	6,242	5,463	5,664	5,330
Ratoon	2,489	+	1,295	1,873	1,639	2,266	2,275
Louisiana							
Primary	220,558	212,465	139,620	152,975	187,778	187,778	216,512
Ratoon	66,168	27,620	27,924	53,541	75,111	65,722	86,605
Mississippi	101,174	106,435	76,487	76,487	92,675	98,341	122,622
Missouri	32,376	86,605	86,605	72,036	80,534	80,939	101,578
Oklahoma	617	271	17	+	77	+	+
Texas							
Primary	142,857	81,344	60,704	58,681	69,607	68,798	76,083
Ratoon	57,143	21,963	23,675	21,125	36,892	39,903	41,085
Total Primary	**1,148,047**	**1,366,228**	**1,146,235**	**1,118,343**	**1,209,911**	**1,261,431**	**1,468,300**
Total Ratoon	**125,799**	**50,245**	**52,899**	**76,544**	**113,648**	**107,897**	**129,971**
Total	**1,273,847**	**1,416,473**	**1,199,135**	**1,194,887**	**1,323,559**	**1,369,328**	**1,598,271**

[a] Arkansas ratooning occurred only in 1998, 1999, and 2005 through 2010.

+ Emissions are less than 0.1 Tg CO_2 Eq.

- No reported value

Note: Totals may not sum due to independent rounding.

Table 6-12: Ratooned Area as Percent of Primary Growth Area

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

+ Indicates ratooning rate less than 0.1 percent.

Table 6-13: Non-USDA Data Sources for Rice Harvest Information

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

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[174] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

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

---

[174] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the aforementioned reasons. In addition, one measurement from the ratooned fields (i.e., the flux of 1,490 kg CH_4/hectare-season in Lindau and Bollich 1993) was excluded, because this emission rate is unusually high compared to other flux measurements in the United States, as well as IPCC (2006) default emission factors.

used to derive the emission factors applied here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the primary and ratoon emission factors were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means was not normally distributed for either primary or ratooned 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, 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. No uncertainty estimates were calculated for the practice of flooding outside of the normal rice season 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 6-14. Rice cultivation CH_4 emissions in 2010 were estimated to be between 3.0 and 21.8 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 65 percent below to 153 percent above the actual 2010 emission estimate of 8.6 Tg CO_2 Eq.

Table 6-14: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 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	8.6	3.0	21.8	-65%	+153%

[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 2010. 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.

Planned Improvements

A possible future improvement is to create region-specific emission factors for rice cultivation. The current methodology uses a nationwide average emission factor, derived from several studies done in a number of states. The prospective improvement would take the same studies and average them by region, presumably resulting in more spatially specific emission factors.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[175] A

---

[175] 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

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 and cultivation of organic cropland soils (i.e., soils with a high organic matter content, otherwise known as histosols).[176] Other 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,[177] and these processes are influenced by agricultural management through impacts on moisture and temperature regimes in soils. These additional sources of mineral N are included at the recommendation of 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,[178] and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water. Direct emissions from agricultural lands (i.e., cropland and grassland) 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.

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 2010 were 207.8 Tg CO_2 Eq. (670 Gg N_2O) (see Table 6-15 and Table 6-16). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2010, although overall emissions were almost 4 percent higher in 2010 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 70 percent of total direct emissions, while grassland accounted for approximately 30 percent. These percentages are about the same for indirect emissions since forest lands and settlements account for such a small percentage of total indirect emissions. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 6-17 and Table 6-6-18.

Table 6-15: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Direct	**155.8**	**169.1**	**165.6**	**166.8**	**168.5**	**162.2**	**162.3**
Cropland	103.0	118.0	115.7	117.8	118.0	112.4	112.4
Grassland	52.8	51.1	49.9	49.0	50.5	49.9	49.9
Indirect (All Land-Use Types)	**44.1**	**43.9**	**45.5**	**44.3**	**44.4**	**45.0**	**45.5**
Cropland	37.4	36.7	38.7	37.5	37.6	37.9	38.5
Grassland	6.4	6.5	6.0	6.1	6.1	6.4	6.4
Forest	+	0.1	0.1	0.1	0.1	0.1	0.1

---

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).

[176] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[177] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[178] 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.

Land							
Settlements	0.3	0.6	0.6	0.6	0.6	0.6	0.6
Total	**200.0**	**213.1**	**211.1**	**211.1**	**212.9**	**207.3**	**207.8**

+ Less than 0.05 Tg CO_2 Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two year, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.s.

Table 6-16: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990	2005	2006	2007	2008	2009	2010
Direct	**503**	**546**	**534**	**538**	**544**	**523**	**523**
Cropland	332	381	373	380	381	362	363
Grassland	170	165	161	158	163	161	161
Indirect (All Land-Use Types)	**142**	**142**	**147**	**143**	**143**	**145**	**147**
Cropland	121	118	125	121	121	122	124
Grassland	21	21	19	20	20	21	21
Forest Land	0	+	+	+	+	+	+
Settlements	1	2	2	2	2	2	2
Total	**645**	**687**	**681**	**681**	**687**	**669**	**670**

+ Less than 0.5 Gg N_2O

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Table 6-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	**103.0**	**118.0**	**115.7**	**117.8**	**118.0**	**112.4**	**112.4**
Mineral Soils	100.1	115.1	112.8	114.9	115.1	109.5	109.5
Mineralization and Asymbiotic Fixation	*44.6*	*50.5*	*49.7*	*50.9*	*50.9*	*47.1*	*47.1*
Synthetic Fertilizer	*32.5*	*38.8*	*36.8*	*37.6*	*37.6*	*37.1*	*37.2*
Residue N[a]	*12.4*	*13.7*	*13.8*	*13.9*	*14.3*	*13.1*	*13.1*
Organic Amendments[b]	*10.6*	*12.1*	*12.4*	*12.5*	*12.4*	*12.2*	*12.2*
Organic Soils	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Grassland	**52.8**	**51.1**	**49.9**	**49.0**	**50.5**	**49.9**	**49.9**
Residue N[c]	12.0	11.1	10.8	10.7	11.0	10.8	10.8
PRP Manure	21.6	21.6	21.2	20.6	21.0	20.6	20.6
Synthetic Fertilizer	2.7	2.8	2.8	2.7	2.8	2.8	2.8
Managed Manure[d]	+	+	+	+	+	+	+
Sewage Sludge	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Mineralization and Asymbiotic Fixation	16.3	15.1	14.6	14.5	15.1	15.1	15.1
Total	**155.8**	**169.1**	**165.6**	**166.8**	**168.5**	**162.2**	**162.3**

[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.

+ Less than 0.05 Tg CO_2 Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Table 6-6-18: Indirect N_2O Emissions from all Land-Use Types (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	**37.4**	**36.7**	**38.7**	**37.5**	**37.6**	**37.9**	**38.5**
Volatilization & Atm. Deposition	11.5	13.0	14.3	12.6	13.0	13.7	13.9
Surface Leaching & Run-Off	25.9	23.7	24.4	24.9	24.6	24.2	24.5
Grassland	**6.4**	**6.5**	**6.0**	**6.1**	**6.1**	**6.4**	**6.4**
Volatilization & Atm. Deposition	5.3	5.0	5.0	4.9	4.9	4.9	4.8
Surface Leaching & Run-Off	1.0	1.5	1.1	1.2	1.2	1.5	1.5
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	**0.3**	**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	**44.1**	**43.9**	**45.5**	**44.3**	**44.4**	**45.0**	**45.5**

+ Less than 0.05 Tg CO_2 Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Figure 6-3 through 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. Average annual emissions and N losses are shown for croplands that produce major crops and from grasslands in each state. Direct N_2O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern Minnesota, southern Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops. Direct emissions are also high in Missouri, Kansas, 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. Some areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grassland is much lower than in the central and western United States.

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: Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO_2 Eq./year)

Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO_2 Eq./year)

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide the Agricultural Soil Management source category into four 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 drainage and cultivation of organic cropland soils; (3) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (4) 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 (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with the 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; (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[179] (i.e., computing total emissions from managed land); and (6) reporting all emissions from managed lands, largely because management affects all processes leading to soil N_2O emissions. One recommendation from IPCC (2006) that has not been adopted is the accounting of emissions from pasture renewal, which involves occasional plowing to improve forage production. This practice is not common in the United States, and is not estimated.

The methodology used to estimate 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 major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. 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 6-1 for further elaboration). The Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from non-major crops on mineral soils (e.g., barley, oats, vegetables, and other crops); (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model (i.e., federal grasslands); and (3) direct emissions from drainage and cultivation of organic cropland soils. Indirect emissions were also estimated with a combination of DAYCENT and the IPCC Tier 1 method.

EPA considered subtracting "background" emissions that would presumably occur if the lands were not managed. However, this approach is not used since (1) it is likely to be inaccurate for estimating the anthropogenic influence on soil N_2O emissions, and (2) if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions, due to the high inputs of N to agricultural soils from fertilization and legume cropping. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N_2O emissions from soils in agricultural systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

[BEGIN BOX]

---

[179] 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.

Box 6-1. 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 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 is likely to produce 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 contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N added to soils is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

[END BOX]

Direct N_2O Emissions from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of major crops—specifically corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton—representing approximately 90 percent of total croplands in the United States. For these croplands, DAYCENT was used to simulate crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005). Note that the influence of land-use change on soil N_2O emissions was not addressed in this analysis, but is a planned improvement.

DAYCENT simulations were conducted for each major crop at the county scale in the United States. Simulating N_2O emissions at the county scale was facilitated by soil and weather data that were available for every county with more than 100 acres of agricultural land, and by land management data (e.g., timing of planting, harvesting, and intensity of cultivation) that were available at the agricultural-region level as defined by the Agricultural Sector Model (McCarl et al. 1993). ASM has 63 agricultural regions in the contiguous United States. Most regions correspond to one state, except for those states with greater heterogeneity in agricultural practices; in such cases, more than one region is assigned to a state. While cropping systems were simulated for each county, the results best represent emissions at regional (i.e., state) and national levels due to the regional scale of management data, which include model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested).

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.

DAYCENT was used to estimate direct N_2O emissions due to mineral N available from: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter and litter, 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. For the first two practices, annual changes in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), and USDA (1966, 1957, 1954, 1946). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA *Economic Research Service Cropping Practices Survey* (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).

- Managed manure production and application to croplands and grasslands: Manure N amendments and daily spread manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). Amendment data for 1997 were scaled to estimate values for other years based on the availability of managed manure N for application to soils in 1997 relative to other years. The amount of available N from managed manure for each livestock type was calculated as described in the Manure Management section (Section 6.2) and Annex 3.10.

- Retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: 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, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N_2O emissions, but these are not model inputs. The DAYCENT simulations also accounted for the approximately 3 percent of grain 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, and Cibrowski 1996), and therefore did not contribute to soil N_2O emissions.

- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2000a) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002).

DAYCENT simulations produced per-area estimates of N_2O emissions (g N_2O-N/m^2) for major crops in each county, which were multiplied by the cropland areas in each county to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2010a, 2010b). The emission estimates by reported crop areas in the county were scaled to the regions (and states for mapping purposes when there was more than one region in a state), and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to interannual variability in weather patterns and other controlling variables, so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions produces more accurate estimates of N_2O emissions than the Tier 1 method.

Non-Major Crop Types on 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 non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, rice, peanuts, and other crops that were not included in the DAYCENT simulations. Estimates of direct N_2O emissions from N applications to non-major crop types 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;[180] and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available. Consequently, non-manure organic amendments, as well as additional manure that was not added to major crops in the DAYCENT simulations, were included in the Tier 1 analysis. The influence of land-use change on soil N_2O emissions from non-major crops has not been addressed in this analysis, but is a planned improvement. The following sources were used to derive activity data:

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to non-major crops.
- A process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.
- Non-manure, non-sewage-sludge 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 2010). Manure and sewage sludge components were subtracted from total commercial organic fertilizers to avoid double counting.
- 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). Approximately 3 percent of the crop residues were burned and therefore did not contribute to soil N_2O emissions, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006)

---

[180] Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer have been excluded to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands.

default emission factor to derive an estimate of direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC (2006) Tier 1 methods were used to estimate direct N_2O emissions due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the *National Resources Inventory* (NRI) (USDA 2000a, as extracted by Eve 2001 and amended by Ogle 2002). Temperature data from Daly et al. (1994, 1998) were used to subdivide areas into temperate and sub-tropical climates using the climate classification from IPCC (2006). Data were available for 1982, 1992 and 1997. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and 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 grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native 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 county-scale N_2O emissions from 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), 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 section for Major Crop Types on Mineral Cropland Soils. 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 3.10. Biological N fixation is simulated within DAYCENT and therefore was not an input to the model.

Manure N deposition from grazing animals (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal and federal grasslands in each county were based on the proportion of non-federal to federal grassland area (See below for more information on area data). The amount of PRP manure applied on non-federal grasslands was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure. The remainder of the PRP manure N excretions in each county was assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for non-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. Data were obtained from the U.S. Department of Agriculture *National Resources Inventory* (USDA 2000a, Nusser and Goebel 1997) and the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD, Vogelman et al. 2001),[181] which were reconciled with the Forest Inventory and Analysis Data.[182] The area data for pastures and rangeland were aggregated to the county level to estimate non-federal and federal grassland areas.

DAYCENT simulations produced per-area estimates of N_2O emissions (g N_2O-N/m^2) for pasture and rangelands,

---

[181] Available online at <http://www.mrlc.gov>

[182] Available online at <http://fia.fs.us/tools-data/data>

which were multiplied by the non-federal grassland areas in each county. The county-scale N_2O emission estimates for non-federal grasslands were scaled to the 63 agricultural regions (and to the state level for mapping purposes if there was more than one region in a state), and the national estimate was calculated by summing results across all regions. Tier 1 estimates of N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N were produced by multiplying the N input by the appropriate emission factor. Tier 1 estimates for emissions from manure N were calculated at the state level and aggregated to the entire country but emission from sewage sludge N were calculated exclusively at the national scale.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from major and non-major crops on mineral cropland 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 6-15 and Table 6-16).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types

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 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 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., major croplands and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the sections on major crops and grasslands. 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 non-major croplands, PRP manure N excretion 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 6-6-18).

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 used to produce major crops and most grasslands. 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 produce non-major crops, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, and N inputs on settlements and forest lands. For both the DAYCENT 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 DAYCENT 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 6-6-18).

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 calculated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT; (3) direct emissions calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated with the IPCC (2006) Tier 1 method; and (5) indirect emissions calculated 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). Additional details on the uncertainty methods are provided in Annex 3.11.

Uncertainties from the Tier 1 and Tier 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006), and the results are summarized in Table 6-19. Agricultural direct soil N_2O emissions in 2010 were estimated to be between 120.2 and 255.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 26 percent below and 57 percent above the 2010 emission estimate of 162.3 Tg CO_2 Eq. The indirect soil N_2O emissions in 2010 were estimated to range from 23.3 to 113.9 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 49 percent below and 150 percent above the 2010 emission estimate of 45.5 Tg CO_2 Eq.

Table 6-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2010 (Tg CO_2 Eq. and Percent)

Source	Gas	2010 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	162.3	120.2	255.3	-26%	+57%
Indirect Soil N_2O Emissions	N_2O	45.5	23.3	113.9	-49%	+150%

Note: Due to lack of data, uncertainties in areas for major crops, managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.
Note: The estimates for 2010 are based on the emissions from 2009 due to limited changes in management of agricultural soils between the two years.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For quality control, 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 11 sites in the United States and one in Canada, representing 30 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at all sites compared to the IPCC Tier 1 estimate, except for Colorado dryland cropping (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 account for site-level factors (weather, soil type) that influence N_2O emissions and produce less biased emissions estimates. Nitrate leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.89 and 0.94 for annual N_2O emissions and NO_3^- leaching, respectively. This 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 (see additional information in Annex 3.11).

Figure 6-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model

Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as were the program scripts that were used to run the Monte Carlo uncertainty analysis. Several errors were identified following re-organization of the calculation spreadsheets, and corrective actions have been taken. In particular, some of the links between spreadsheets were missing or needed to be modified. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and no errors were found.

Recalculations Discussion

County-level animal populations were updated relative to the previous Inventory report based on 2007 USDA *Census of Agriculture* data (USDA 2007), which changed the animal population estimates for 2002 through 2009. The N excretion values for cattle changed for 1990 through 2009. Waste management system (WMS) distributions for dairy and swine were updated based on Census of Agriculture farm size data (USDA 2007). The result of these changes is that N_2O emissions increased by an average of 2.0 Tg CO_2 Eq.

Planned Improvements

A key improvement is underway for the Agricultural Soil Management source category to incorporate more land-use survey data from the NRI (USDA 2000a) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1979 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records, and there are three major disadvantages to this dataset. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, which is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI provides a complete history of cropland areas for four out of every five years from 1979 to 1997, and then every year after 1998. Third, the current inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil Management methods more consistent with the methods used to estimate C stock changes for agricultural soils. The structure of model input files that contain land management data are currently being extensively revised to facilitate use of the annualized NRI data.

Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 6.5). Estimates of crop residues burned used for the Field Burning of Agricultural Residues source category will be incorporated into the DAYCENT runs for the Agricultural Soil Management source category, and reconciled in the future.

Other planned improvements are minor but will lead to more accurate estimates, including updating DAYMET weather data for more recent years following the release of new data, and using a rice-crop-specific emission factor for N amendments to rice areas.

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; composted and then applied to soils; landfilled; or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. 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 is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). In 2010, CH_4 and N_2O emissions from field burning were 0.2 Tg CO_2 Eq. (11 Gg) and 0.1 Tg. CO_2 Eq. (0.3 Gg), respectively. Annual emissions from this source over the period 1990 to 2010 have remained relatively constant, averaging approximately 0.2 Tg CO_2 Eq. (10 Gg) of CH_4 and 0.1 Tg CO_2 Eq. (0.3 Gg) of N_2O (see Table 6-20 and Table 6-21).

Table 6-20: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CH_4	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
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	**0.3**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-21: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CH_4	**10**	**8**	**11**	**11**	**11**	**11**	**11**
Corn	1	1	2	1	1	1	1
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	2	2	2	3	3	3	3
Soybeans	1	1	1	1	1	1	1
Sugarcane	1	1	2	1	1	2	1
Wheat	5	3	3	4	4	4	4
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
CO	**206**	**166**	**223**	**226**	**224**	**226**	**228**

NO_x	**19**		**19**	**34**	**30**	**29**	**31**	**30**

+ 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 in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of C and N released during burning, the following equation was used:

C or N released = Σ over all crop types and states (Area Burned ÷ Crop Area Harvested × Crop Production × Residue/Crop Ratio × Dry Matter Fraction × Burning Efficiency × Combustion Efficiency × Fraction of C or N)

where,

Area Burned = Total area of crop burned, by state
Crop Area Harvested = Total area of crop harvested, by state
Crop Production = Annual production of crop in Gg, by state
Residue/Crop Ratio = Amount of residue produced per unit of crop production, by state
Dry Matter Fraction = Amount of dry matter per unit of biomass for a crop
Fraction of C or N = Amount of C or N per unit of dry matter for a crop
Burning Efficiency = The proportion of prefire fuel biomass consumed[183]
Combustion Efficiency = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively[183]

Crop production and area harvested were available by state and year from USDA (2010) 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 and CO, or N_2O and NO_x Emissions from Field Burning of Agricultural Residues = (C or N Released) × (Emissions Ratio for C or N) × (Conversion Factor)

where,

Emissions Ratio = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released
Conversion Factor = 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)

[BEGIN BOX]

Box 6-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

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

---

[183] 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).

comparison of the methods and factors used in (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990-2009 Inventory 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 emission factors for N_2O were not available for all crops. In order to maintain consistency of methodology, the IPCC/UNEP/OECD/IEA (1997) approach presented in the Methodology section 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.

[END BOX]

Crop production data for all crops except rice in Florida and Oklahoma were taken from USDA's QuickStats service (USDA 2011). Rice production and area data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon 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 2011), and crop yields for Arkansas (USDA 2011) were applied to Oklahoma acreages[184] (Lee 2003 through 2006; Anderson 2008 through 2011). The production data for the crop types whose residues are burned are presented in Table 6-22. 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[185] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[186] McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. National-level area burned data were divided by national-level crop area harvested data to estimate the percent of crop area burned by crop. The average fraction of area burned by crop across all states is shown in Table 6-23. All crop area harvested data were from USDA (2010), 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 2011; Lee 2003 through 2006; Anderson 2008 through 2011). 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 assumed to be equal to the average percent area burned from the 5 years for which data were available. This average was taken at the crop and national level. Table 6-23 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 6-24. 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

---

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

[185] Alaska and Hawaii were excluded.

[186] 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.

the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). Emission ratios and conversion factors for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-22: Agricultural Crop Production (Gg of Product)

Crop	1990	2005	2006	2007	2008	2009	2010
Corn[a]	201,534	282,263	267,503	331,177	307,142	333,011	316,165
Cotton	3,376	5,201	4,700	4,182	2,790	2,654	3,942
Lentils	40	238	147	166	109	266	393
Rice	7,114	10,132	8,843	9,033	9,272	9,972	11,027
Soybeans	52,416	83,507	87,001	72,859	80,749	91,417	90,610
Sugarcane	25,525	24,137	26,820	27,188	25,041	27,608	24,821
Wheat	74,292	57,243	49,217	55,821	68,016	60,366	60,103

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

Table 6-23: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2006	2007	2008	2009	2010
Corn	+	+	+	+	+	+	+
Cotton	1	1	1	1	1	1	1
Lentils	1	+	1	1	1	1	1
Rice	10	6	10	13	10	10	10
Soybeans	+	+	+	+	+	+	+
Sugarcane	32	18	47	21	32	32	32
Wheat	2	2	2	2	2	2	2

+ Less than 0.5 percent

Table 6-24: 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 6-25: 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 6-26. Methane emissions from field burning of agricultural residues in 2010 were estimated to be between 0.14 and 0.32 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 42 percent above the 2010 emission estimate of 0.23 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.07 and 0.13 Tg CO_2 Eq. (or approximately 29 percent below and 31 percent above the 2010 emission estimate of 0.10 Tg CO_2 Eq.).

Table 6-26: 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**	**2010 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	0.23	0.14	0.32	-40%	42%
Field Burning of Agricultural Residues	N_2O	0.10	0.07	0.13	-29%	31%

[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 2010. 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

For the current Inventory, the crop production data for 2009 and 2010 were updated relative to the previous report using data from USDA (2011). Rice cultivation data for Florida and Oklahoma, which are not reported by USDA, were updated for 2010 through communications with state experts. The methodology was revised to sum state-level crop area burned and state-level crop area harvested data to determine a national percentage of crop area burned. Previously, the percentage of crop area burned was determined at the state-level and then the state percentages were averaged. This update was made to improve accuracy and accommodate uncertainty calculations. These updates resulted in an 8.6 percent decrease in sector emissions in 2009, and an average decrease in emissions of 14.2 percent from 1990 to 2009.

Planned Improvements

Attempts will be made to incorporate state-level estimates of percentage of crop area burned into the uncertainty analysis next year to make the uncertainty analysis more robust. Further investigation will be also made into inconsistent 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.

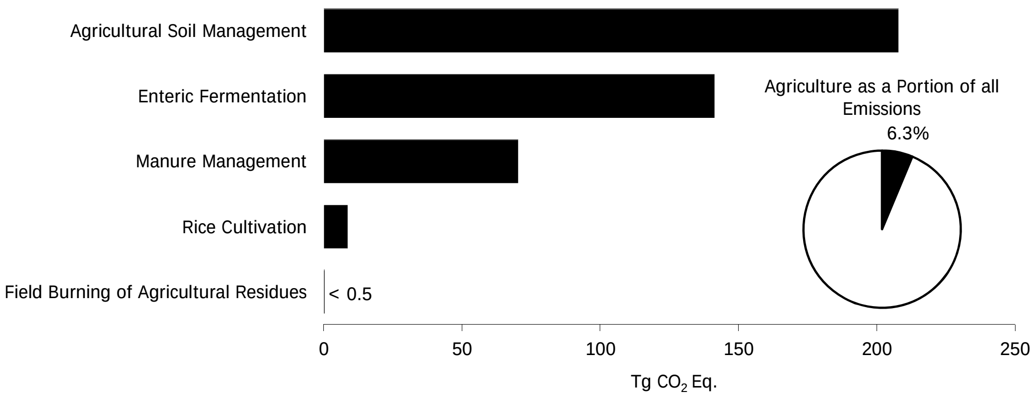
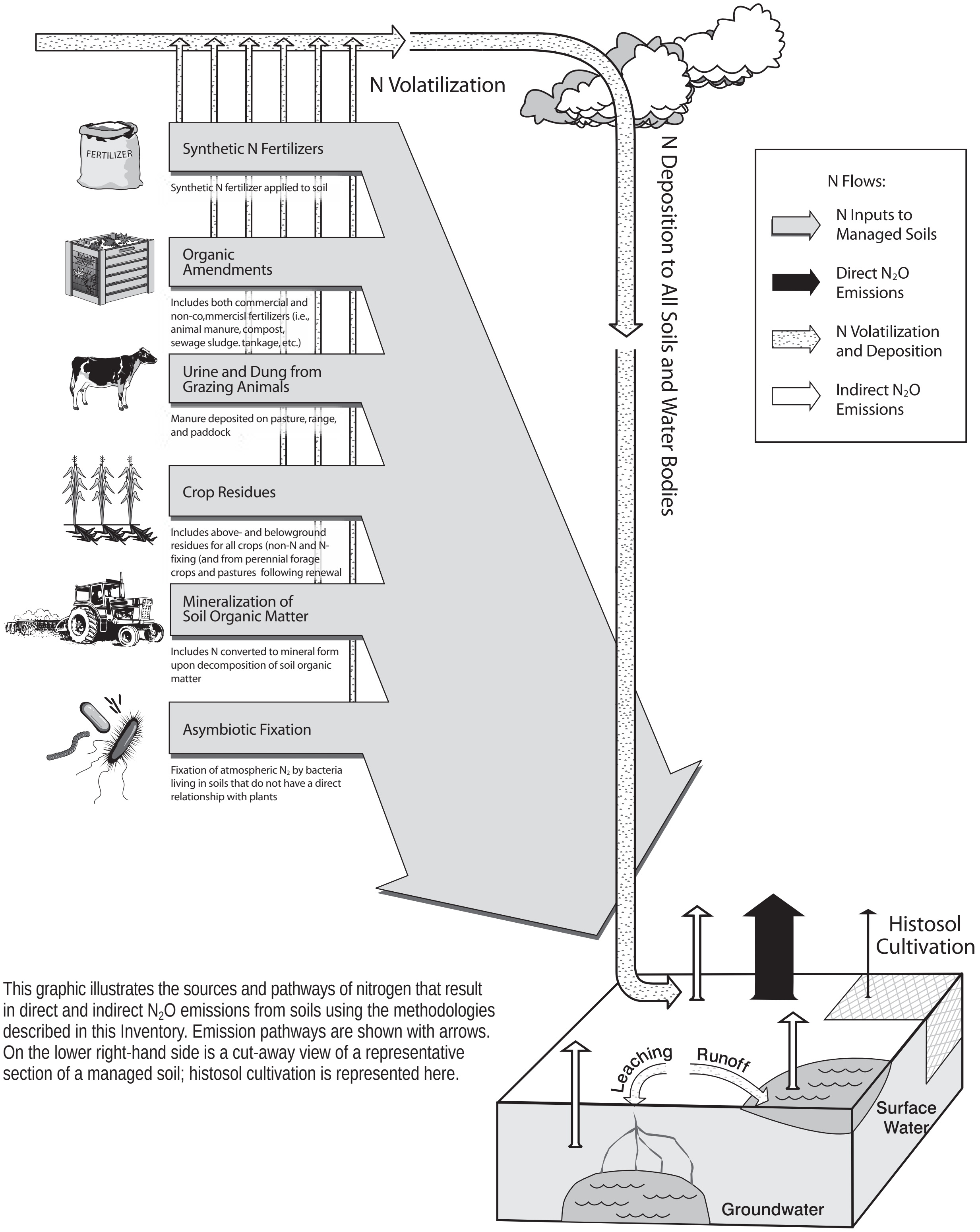


Figure 6-1: 2010 Agriculture Chapter Greenhouse Gas Sources

Figure 6-2

Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Figure 6-3

Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-20
(Tg CO_2 Eq/year)

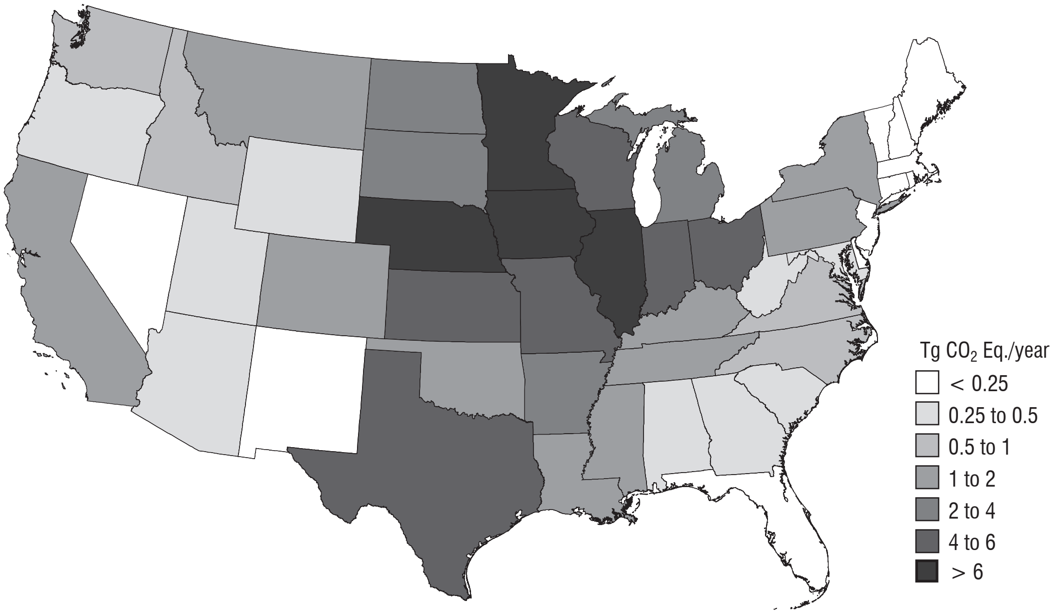


Figure 6-4

Grasslands, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO_2 Eq./year)

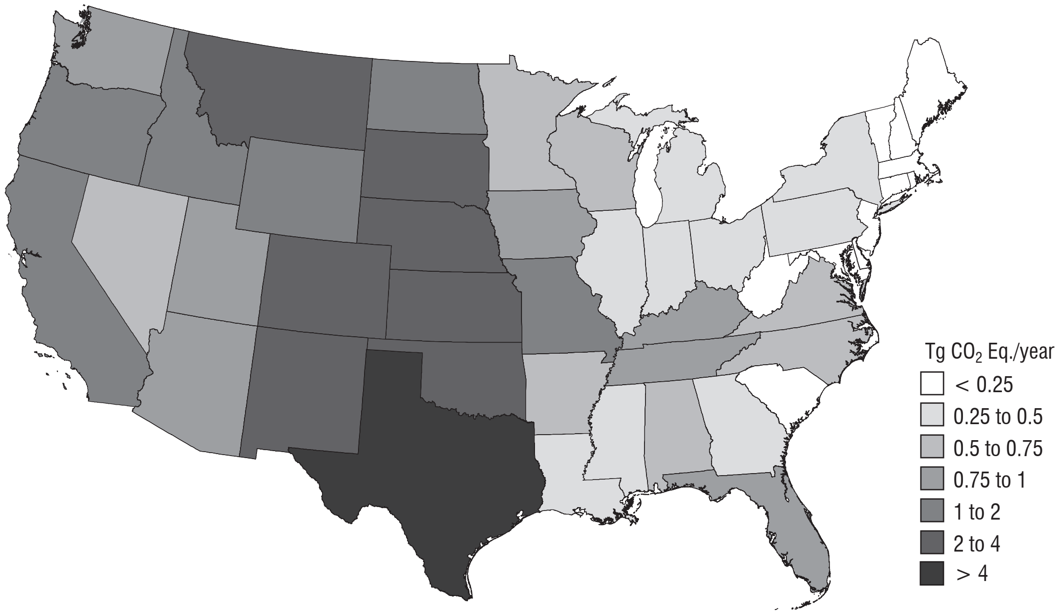


Figure 6-5

Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2010 (Gg N/year)

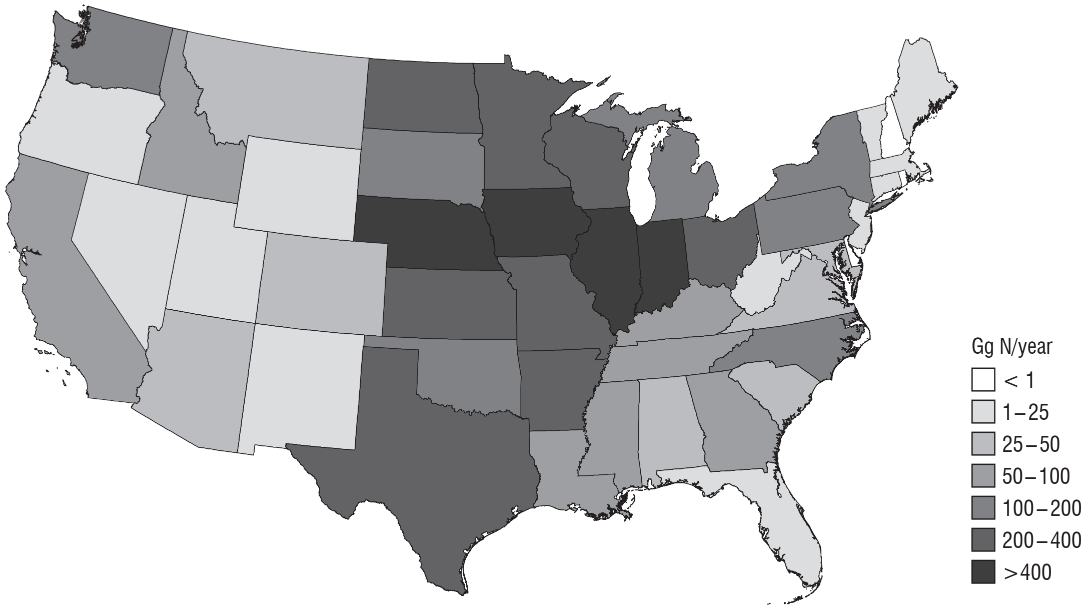


Figure 6-6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2010 (Gg N/year)

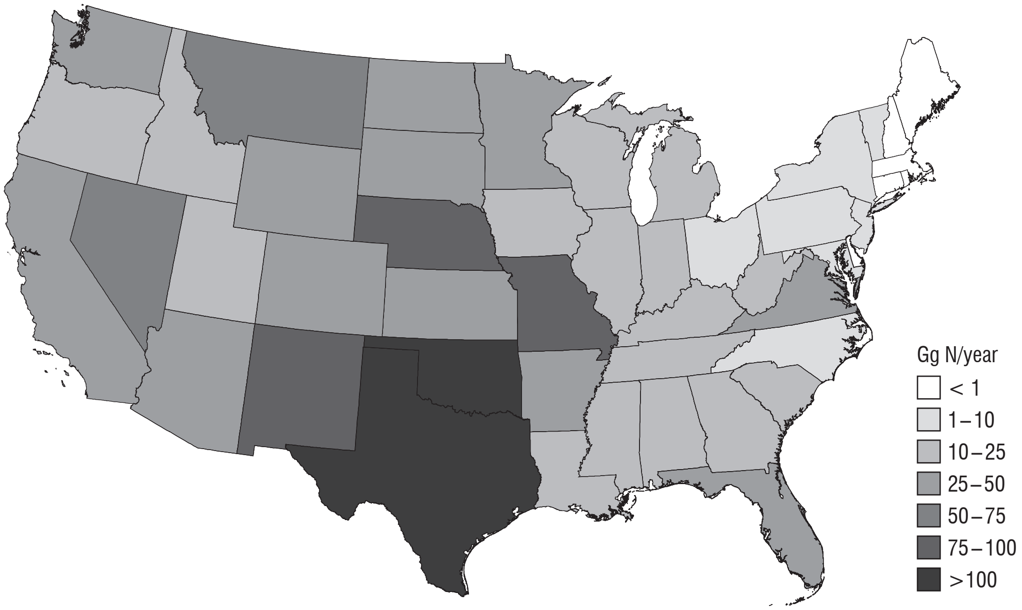


Figure 6-7

Comparison of Measured Emissions at Field Sites with Modeled Emissions Using the DAYCENT Simulation Model