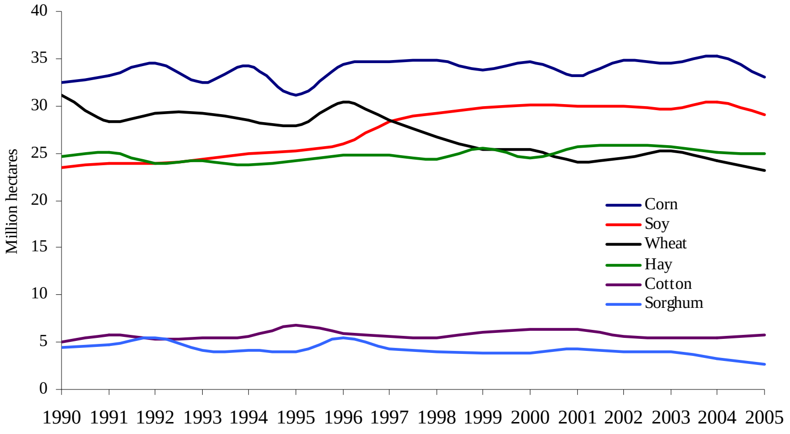
Chapter 3: Cropland Agriculture

3.1 Summary of U.S. Greenhouse Gas Emissions from Cropland Agriculture

In 2005, cropland agriculture resulted in total emissions of 219.5 Tg CO_2 eq. of greenhouse gases (GHG) (Table 3-1). Cropland agriculture is responsible for about half (53%) of all emissions from the agricultural sector (EPA 2007). Nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions from agricultural soils totaled 177, 34, and 8 Tg CO_2 eq., respectively, in 2005. However, that amount was offset by a storage, or carbon sequestration, of 66.5 Tg CO_2 eq. in agricultural soils in 2005. Thus, when this is taken into account, net emissions of GHG from cropland agriculture amount to approximately 153 Tg CO_2 eq. The 95% confidence interval for net emissions in 2005 is estimated to lie between 137 and 188 Tg CO_2 eq. (Table 3-1).

Figure 3-1

U.S. Planted Cropland Area by Crop Type, 1990-2005



Emissions in 2005 were only 4% higher than the baseline year (1990). Greenhouse gas emissions from agricultural soils fluctuated between 1990 and 2005 with no clear trend of increasing or decreasing (Table 3-2). Annual fluctuations are primarily a result of variability in weather patterns and land use changes.

Greenhouse gas emission from agricultural soils, primarily N_2O, were responsible for the majority of total emissions, while CH_4 and N_2O from residue burning and rice cultivation caused about 4% of emissions (Tables 3-1, 3-2). Soil CO_2 emissions from cultivation of organic soils (14%) and from liming (2%) are the remaining sources. Nitrous oxide emissions from soils

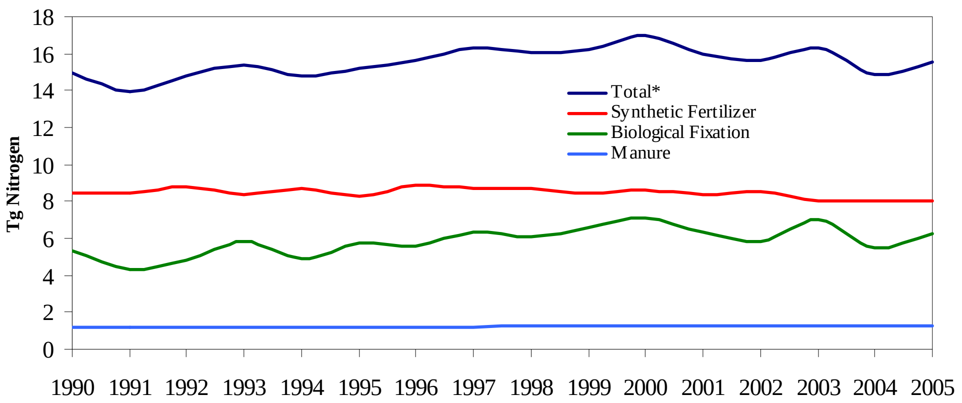
Table 3-1 Estimates and Uncertainties for Cropland Greenhouse Gas Emissions, 2005

	GHG Emissions	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Source		*Tg CO_2 eq.*			%
N_2O	**177.4**	**159.8**	**220.8**	**-10**	**24**
Soils	**168.4**	**151.8**	**205.8**	-10	22
Managed Manure [1]	8.5	2.6	30.6	-70	259
Residue Burning	0.50	0.45	0.57	-10	14
CH_4	**7.7**	**3.0**	**19.5**	**-61**	**152**
Residue Burning	0.90	0.75	0.97	-17	8
Rice Cultivation	6.90	2.10	18.60	-70	170
CO_2	**(32.2)**	**(49.7)**	**(16.9)**	**-55**	**47**
Mineral Soils [2]	(66.5)	(77.9)	(55.2)	-17	17
Organic Soils	30.3	18.4	39.6	-39	31
Liming of Soils	4.0	0.2	8.0	-96	98
Total Emissions	**219.5**	**197.4**	**265.6**	**-10**	**21**
Net Emissions [3]	**153.0**	**136.6**	**187.9**	**-11**	**23**

[1] Accounts for loss of manure N during transport, treatment and storage, including both volatilization and leaching/runoff.
[2] Soil carbon sequestration on land under the Conservation Reserve Program and soil carbon fluxes for land converted to cropland are included with mineral soils.
[3] Includes sources and sinks.

Figure 3-2

Annual Nitrogen Inputs to Cropland Soil



* Includes activated and other sludge, dried blood, compost, tankage, and other organics.

are the largest source in the U.S. due to the fact that N_2O is a potent greenhouse gas (see Chapter 1 Box 1-1) and due to the large amounts of nitrogen added to crops in fertilizer that stimulate N_2O production. Emissions from residue burning are minor because only ~3% of crop residue is assumed to be burned in the U.S. Cropped soils in the U.S. are a net CO_2 sink mainly because reduced tillage intensity has become more popular in recent years and more cropland has been enrolled in the Conservation Reserve Program (CRP).

Nitrous oxide emissions were largest in areas where a large portion of land is used for intensive agriculture (Map 3-1). For example, 90% or more of the land in many counties in the Corn Belt is intensively cropped (Map 3-2). Corn is the leading crop for N_2O emissions followed by soybean and wheat (Table 3-3). Emissions from corn cropping are high because large amounts of nitrogen (N) fertilizer are routinely applied and the land area used for corn production is the most extensive (Figure 3-1). Although little N fertilizer is applied for soybean cropping, N_2O emissions are high because

Table 3-2 Summary of Greenhouse Gas Emissions from Cropland Agriculture, 1990, 1998-2005

	1990	1998	1999	2000	2001	2002	2003	2004	2005
Source					*Tg CO_2 eq.*				
N_2O	**168.9**	**188.8**	**173.4**	**179.2**	**185.4**	**171.0**	**167.0**	**166.6**	**177.4**
Soils	161.0	180.1	164.7	170.4	176.5	161.9	158.0	157.7	168.4
Managed Manure[1]	7.5	8.2	8.3	8.4	8.5	8.7	8.5	8.5	8.5
Residue Burning	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5	0.5
CH_4	**7.8**	**8.7**	**9.1**	**8.3**	**8.4**	**7.5**	**7.7**	**8.4**	**7.7**
Residue Burning	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.9	0.9
Rice Cultivation	7.1	7.9	8.3	7.5	7.6	6.8	6.9	7.6	6.9
CO_2	**(19.5)**	**(28.0)**	**(28.0)**	**(29.3)**	**(30.8)**	**(30.6)**	**(31.1)**	**(32.2)**	**(32.2)**
Mineral Soils[2]	(54.0)	(63.0)	(62.8)	(64.0)	(65.6)	(65.8)	(66.0)	(66.4)	(66.5)
Organic Soils	29.8	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3
Liming of Soils	4.7	4.7	4.5	4.3	4.4	5.0	4.6	3.9	4.0
Total Emissions	**211.2**	**232.5**	**217.2**	**222.2**	**228.5**	**213.9**	**209.5**	**209.3**	**219.5**
Net Emissions	**157.2**	**169.5**	**154.5**	**158.2**	**163.0**	**148.0**	**143.6**	**142.9**	**153.0**

Note: Parenthesis indicate a net sequestration.

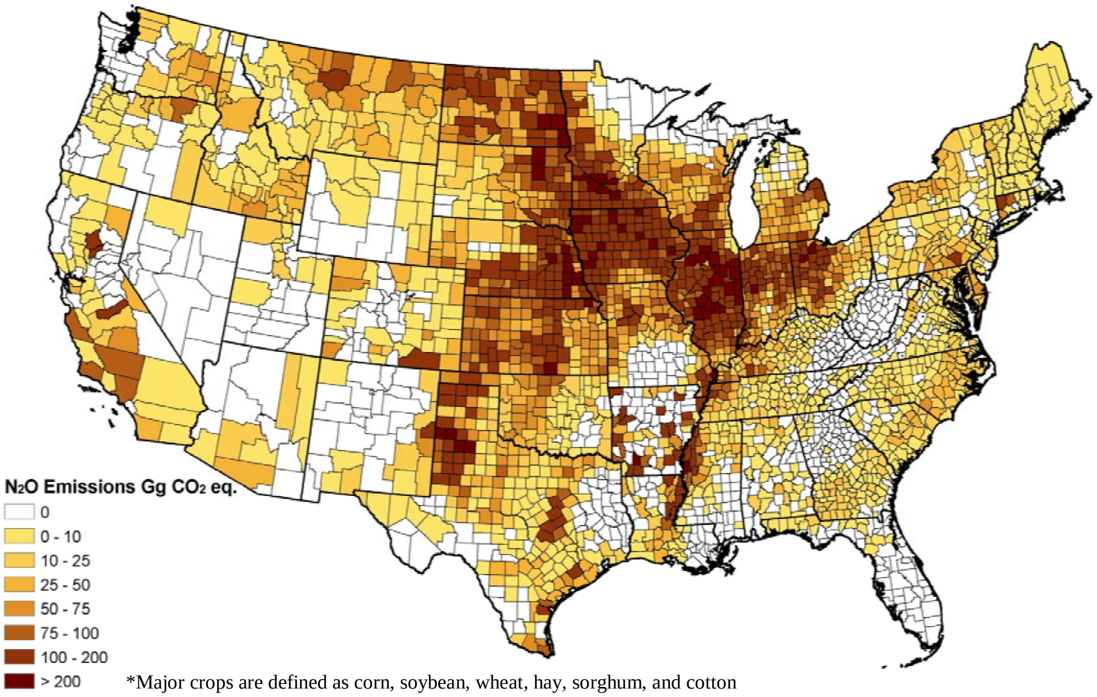
[1] Accounts for loss of manure N during transport, treatment and storage, including both volatilization and leaching/runoff.

[2] Soil C sequestration on CRP land and soil C fluxes for land converted to cropland are included with mineral soils.

soybeans supply large amounts of N to the soil from biological fixation of atmospheric nitrogen (N_2). In general, N_2O emissions are highly correlated with crop areas and nitrogen inputs. Synthetic fertilizer makes up about half of total N additions, followed by fixation and manure (Figure 3-2). Note that Map 3-1 does not include emissions from non-major crops, which make up a significant potion of total emissions in California and Florida. Soil N_2O emissions reported here are lower than those reported in EPA (2007) because a mistake was found in the calculations reported in EPA (2007). The cropped soil emissions reported here are consistent with those in EPA (2008).

Map 3-1

County-Level Nitrous Oxide Emissions from Major Cropped Soils in 2005 *



*Major crops are defined as corn, soybean, wheat, hay, sorghum, and cotton

Cropland agriculture results in GHG emissions from multiple sources, with the magnitude of emissions determined, in part, by land management practices. Application of synthetic and organic fertilizers, cultivation of N fixing crops and rice, cultivation and management of soils, and field burning of crop residues lead to emissions of N_2O, CH_4, and CO_2. However, agricultural soils can also mitigate GHG emissions through the biological uptake of organic carbon in soils resulting in CO_2 removals from the atmosphere. This chapter covers both GHG emissions from cropland agriculture and biological uptake of CO_2 in agricultural soils. National estimates of these sources, published in the U.S. GHG Inventory, are reported in this section and, where appropriate, county and State-level emissions estimates are provided.

Table 3-3 Nitrous Oxide Emissions from Differently Cropped Soils, 1990-2005[1]

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Source								*Tg CO_2 eq.*								
Corn	**56.6**	**55.0**	**54.6**	**59.2**	**54.1**	**50.3**	**61.5**	**57.2**	**63.9**	**56.6**	**61.1**	**63.4**	**58.2**	**51.9**	**54.1**	**56.5**
Direct	44.2	45.6	44.9	49.0	47.5	41.7	51.4	50.2	53.2	48.5	52.0	53.4	50.0	42.4	47.5	47.5
Volatilization	1.7	1.6	1.8	1.6	1.7	1.6	1.7	1.7	1.8	1.7	1.8	1.7	1.8	1.7	1.7	1.8
Leaching & Runoff	10.7	7.8	7.9	8.7	4.9	7.0	8.4	5.3	8.9	6.4	7.3	8.3	6.3	7.9	4.9	7.3
Soybean	**29.4**	**28.3**	**27.6**	**30.4**	**28.2**	**28.6**	**33.4**	**32.7**	**39.3**	**33.3**	**39.1**	**40.8**	**36.2**	**35.5**	**34.4**	**39.4**
Direct	22.9	22.4	22.0	24.8	23.5	23.3	27.1	27.4	31.9	28.3	32.0	32.7	29.9	27.9	29.2	31.4
Volatilization	1.1	1.0	1.1	1.2	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.4	1.3	1.5	1.3	1.4
Leaching & Runoff	5.4	5.0	4.6	4.4	3.6	4.1	5.2	4.1	6.0	3.6	5.6	6.7	5.1	6.1	3.9	6.5
Wheat	**27.8**	**24.6**	**26.1**	**34.1**	**23.8**	**25.1**	**30.6**	**27.5**	**24.6**	**19.8**	**21.7**	**20.1**	**19.6**	**19.3**	**19.2**	**19.9**
Direct	24.9	21.6	23.2	24.8	21.0	19.4	26.2	22.9	21.2	17.6	19.6	18.3	18.2	17.7	18.0	18.1
Volatilization	0.8	0.7	0.7	0.7	0.7	0.6	0.7	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.5
Leaching & Runoff	2.1	2.3	2.3	8.7	2.1	5.1	3.7	4.0	2.8	1.7	1.5	1.2	0.8	1.0	0.6	1.2
Hay	**8.6**	**7.9**	**8.2**	**4.4**	**7.9**	**8.1**	**8.9**	**7.7**	**8.9**	**8.5**	**4.5**	**9.1**	**8.4**	**7.9**	**7.7**	**8.3**
Direct	6.3	5.9	6.2	3.1	6.3	5.9	6.8	5.9	6.8	6.3	3.3	6.9	6.5	6.1	6.1	6.4
Volatilization	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Leaching & Runoff	1.9	1.6	1.6	1.0	1.3	1.8	1.7	1.4	1.7	1.8	0.7	1.8	1.4	1.5	1.2	1.4
Cotton	**5.6**	**6.5**	**6.0**	**6.4**	**6.3**	**7.3**	**6.8**	**6.4**	**6.5**	**6.8**	**7.8**	**7.5**	**6.9**	**5.4**	**5.7**	**6.3**
Direct	4.8	5.0	5.2	5.4	5.2	5.9	5.7	5.3	5.6	5.7	6.4	6.4	5.3	4.6	4.7	5.0
Volatilization	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Leaching & Runoff	0.7	1.3	0.7	0.8	0.9	1.3	0.9	1.0	0.8	0.9	1.2	0.9	1.4	0.7	0.8	1.1
Sorghum	**3.5**	**4.2**	**4.9**	**5.0**	**2.9**	**4.1**	**4.2**	**4.8**	**4.1**	**4.7**	**3.4**	**5.3**	**3.4**	**4.1**	**2.5**	**3.1**
Direct	2.9	3.9	3.8	4.5	2.6	3.8	3.9	4.2	3.5	3.9	2.9	5.0	3.1	3.8	2.3	2.9
Volatilization	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Leaching & Runoff	0.6	0.2	1.0	0.5	0.2	0.3	0.2	0.5	0.5	0.7	0.4	0.3	0.2	0.2	0.1	0.2
Non-major crops	**19.2**	**17.2**	**15.7**	**18.8**	**22.8**	**21.1**	**20.3**	**21.4**	**21.5**	**23.7**	**21.5**	**19.0**	**18.1**	**22.4**	**22.7**	**23.6**
Direct	14.4	15.2	14.2	16.0	19.9	18.1	17.8	18.6	18.6	20.4	18.8	16.4	15.4	18.4	18.3	19.4
Volatilization	1.6	0.5	0.3	0.7	0.8	0.8	0.7	0.8	0.8	0.9	0.7	0.7	0.7	1.1	1.3	1.2
Leaching & Runoff	3.2	1.5	1.2	2.0	2.1	2.2	1.9	2.1	2.2	2.4	2.0	1.9	2.0	2.9	3.2	3.0
Histosol Cultivation[2]	**2.8**	**2.8**	**2.8**	**2.8**	**2.8**	**2.8**	**2.8**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Managed Manure[3]	**7.5**	**7.7**	**7.7**	**7.9**	**7.9**	**8.0**	**7.9**	**8.2**	**8.2**	**8.3**	**8.4**	**8.5**	**8.7**	**8.5**	**8.5**	**8.5**
All Direct	130.5	130.1	129.8	138.2	136.8	128.9	149.7	145.4	152.0	141.9	146.2	150.5	140.0	132.3	137.5	142.3
All Volatilization	5.9	4.4	4.6	4.7	4.9	4.9	4.9	5.1	5.3	5.2	5.3	5.0	5.0	5.4	5.4	5.5
All Leaching & Runoff	24.6	19.7	19.3	26.0	15.1	21.8	21.8	18.3	22.8	17.5	18.8	21.1	17.3	20.2	14.8	20.7
Total	**161.0**	**154.3**	**153.7**	**168.9**	**156.8**	**155.6**	**176.4**	**168.7**	**180.0**	**164.6**	**170.4**	**176.6**	**162.3**	**158.0**	**157.7**	**168.4**

[1] Emissions from residue burning are not included.

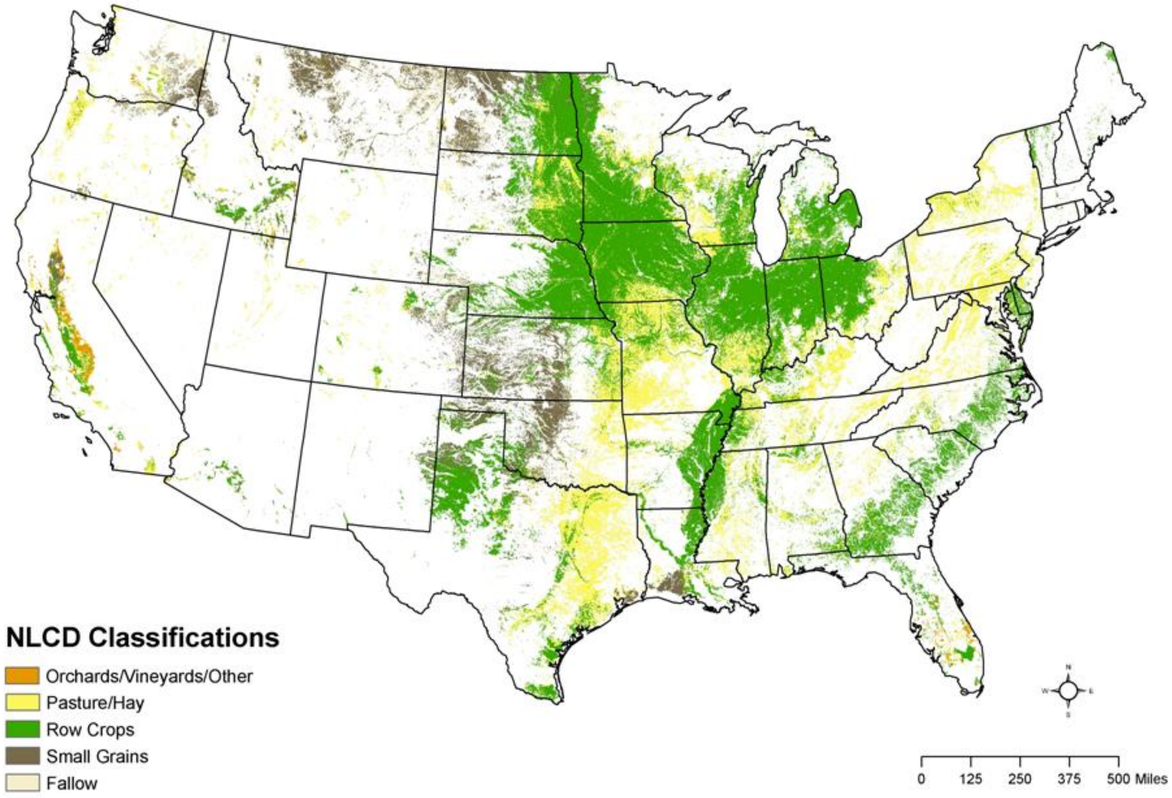
[2] Direct emissions.

[3] Accounts for loss of manure N during transport, treatment and storage, including both volatilization and leaching/runoff.

Sources and sinks of N_2O, CH_4, and CO_2 and the mechanisms that control fluxes are discussed in detail. Methodologies used to estimate emissions are summarized and mitigation opportunities are discussed and quantified where possible. In contrast to the first edition of the USDA GHG report (USDA 2004) that relied exclusively on IPCC (1997) methodology, this edition includes estimates for N_2O emissions and CO_2 fluxes from cropped soils obtained from the DAYCENT and CENTURY ecosystem models. Another change compared to the 1st edition is that CO_2 fluxes for grazed lands that were previously included in this chapter are now included in the Livestock and Grazed Land chapter.

Map 3-2

U.S. Cropped Land



3.2 Sources of Greenhouse Gas Emissions in Cropland Agriculture

3.2.1 Cropped Soils

Agricultural soils serve as both a source of GHG and a mechanism to remove CO_2 from the atmosphere. Nitrous oxide, CH_4, and CO_2 emissions and sinks are a function of underlying biochemical processes. Nitrous oxide is produced as an intermediate during nitrification and denitrification in soils (Firestone and Davidson, 1989). In nitrification, soil micro-organisms ("microbes") convert ammonium (NH_4) to nitrate (NO_3) through aerobic oxidation (IPCC 1996). In denitrification, microbes convert nitrate to nitrogen oxides (NO_x) and dinitrogen gas (N_2) by anaerobic reduction. During nitrification and denitrification, soil microbes release N_2O, which can diffuse from the soil and enter the Earth's atmosphere (IPCC 1996). Cropland soil amendments that add nitrogen to soils drive the production of N_2O by providing additional substrate for nitrification and denitrification. Commercial fertilizer, livestock manure, sewage sludge, cultivation of N-fixing crops, and incorporation of crop residues all add N to soils. In addition, cultivation, particularly of soils high in organic matter (i.e., histosols), enhances mineralization of nitrogen-rich organic matter, making more nitrogen available for nitrification and denitrification (EPA 2007). Compared to soil N_2O emissions, other GHG sources from croplands are relatively small. Methane gas is produced and emitted primarily from rice paddies. This, however, is responsible only for a small portion of total emissions from cropped soils in the U.S. due to the small land area cropped with rice in this country. Emissions from crop residue burning are also not a large source compared to soils due to the small portion of residues burned in the U.S.

Nitrous oxide is the major GHG emitted from cropland agriculture in the U.S. Nitrogen can be converted to N_2O and emitted directly from agricultural fields (direct emissions), or it can be transported from the field in a form other than N_2O and then converted to N_2O elsewhere (indirect emissions). A major source of indirect N_2O emissions is from nitrate that either leaches into the groundwater or runs off the soil surface and then is converted to N_2O via aquatic denitrification (Del Grosso et al. 2006). A second source of indirect N_2O emissions comes from N that is volatilized to the atmosphere, then is deposited back onto soils, and converted to N_2O (Del Grosso et al. 2006).

The size of CO_2 sources and sinks from soils is related to the amount of organic carbon stored in the soil (IPCC 1996). Changes in soil organic carbon (SOC) content are related to inputs, e.g., atmospheric CO_2 fixed as carbon in plants through photosynthesis, and losses from decomposition of soil organic matter which causes CO_2 emissions (IPCC 1996). The net balance of CO_2 uptake and loss in soils is driven in part by biological processes, which are affected by soil characteristics and climate. In addition, land use and management can affect the net balance of CO_2 through modifying inputs and rates of decomposition (IPCC 1996). Changes in agricultural practices such as clearing, drainage, tillage, crop selection, irrigation, grazing, crop residue management, fertilization, and flooding can modify both organic matter inputs and decomposition, and thereby result in a net flux of CO_2 to or from soils.

Most agricultural soils contain comparatively low amounts of organic carbon as a percentage of total soil mass, typically in the range of 0.5 to 5 % in the upper 20-30 cm and so they are classified as mineral soils. However, on an area basis this amount of carbon typically exceeds that stored in vegetation in most ecosystems (including forests). Historically, conversion of native ecosystems to agricultural uses resulted in large soil carbon losses, as much as 30-50 % or more of the C present in the native condition (Haas et al. 1957, Schlesinger 1986, Guo & Gifford 2002, Lal 2004). After many decades of cultivation, most soils have likely stabilized at lower carbon levels or are increasing their organic matter levels as a result of increasing crop productivity (providing more residues), less intensive tillage, and other improvements in agricultural management practices (Paustian et al. 1997, Allmaras et al. 2000, Follett 2001). Changes in land-use or management practices that result in increased organic inputs or decreased oxidation of organic matter (e.g., taking cropland out of production, improved crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) usually result in a net accumulation of SOC until a new equilibrium is achieved.

Cultivated organic soils, also referred to as histosols, contain more than 20 to 30 % organic matter by weight, and constitute a special case. Organic soils form as a result of water-logged conditions, in which decomposition of plant residue is retarded. When organic soils are drained and cultivated, the rate of decomposition, and hence CO_2 emissions, is greatly accelerated. Due to the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time.

In addition, lime, often added to mineral and organic agricultural soils to reduce acidic conditions, contains carbonate compounds (e.g., limestone and dolomite) that when added to soils release CO_2 through the bicarbonate equilibrium reaction (IPCC 1996).

3.2.2 Rice Cultivation

Rice cultivation is unique because it takes place almost universally on flooded fields, including in the U.S. where rice is grown exclusively on flooded fields (EPA 2007). This water regime causes CH_4 emissions as a result of waterlogged soils restricting oxygen diffusion and creating conditions for anaerobic decomposition of organic matter, facilitated by CH_4 emitting “methanogenic” bacteria (IPCC 1996, Le Mer & Roger 2001). Methane from rice fields reaches the atmosphere in three ways: bubbling up through the soil, diffusion losses from the water surface, and diffusion through the vascular elements of plants (IPCC 1996). Diffusion through plants is considered the primary pathway, with diffusion losses from surface water being the least important process (IPCC 1996). Soil composition, texture, and temperature are important variables affecting CH_4 emissions from rice cultivation, as are the availability of carbon substrate and other nutrients, soil pH, and partial pressure of CH_4 (IPCC 1996). Since U.S. rice acreage is relatively small compared to other crops, CH_4 emissions from rice cultivation are small compared to other cropland agriculture sources (EPA 2007).

3.2.3 Residue Burning

Crop residues are sometimes burned in fields to prepare for cultivation and control for pests, although this is not a common practice in the U.S. (EPA 2007). While CO_2 is a product of residue combustion, residue burning is not considered a net source of CO_2 to the atmosphere because CO_2 released from burning crop biomass is replaced by uptake of CO_2 in crops growing the following season (IPCC 1996). However, CH_4 and N_2O, also products of residue combustion, are not recycled into crop biomass through biological uptake the following season. Therefore, residue burning is considered a net source of CH_4 and N_2O to the atmosphere. Overall, GHG emissions from field burning of crop residues are comparatively small in the U.S. (EPA 2007).

3.2.4 Agroforestry

Agroforestry practices such as establishing windbreaks and riparian forest buffers represent another potential carbon sink in cropland agriculture. Comprehensive data on agroforestry practices are not available to estimate the current national levels of carbon sequestration from such practices. However, published research studies have estimated the potential agroforestry carbon sink in the U.S. In temperate systems, agroforestry practices store large amounts of carbon (Kort and Turlock 1999, Schroeder 1994), with the potential ranging from 15 to 198 metric tons of carbon per hectare (modal value of 34 metric tons of carbon per hectare) (Dixon 1995). Nair and Nair (2003) estimated that by the year 2025, the potential carbon sequestration of agroforestry in the United States will be 90 million metric tons of carbon per year. There is a need to better quantify and track agroforestry practices nationally, particularly to inform USDA programs like the Conservation Reserve Program, Environmental Quality

Incentives Program, and Forest Land Enhancement Program, which may provide incentives to land owners to implement agroforestry.

3.3 Nitrous Oxide Emissions from Cropped Soils

On average, ~85% of total cropland soil N_2O emissions are direct soil emissions (Table 3-3). Of the 15% of total emissions from indirect N_2O, 80% are from NO_3 leaching/runoff and the remainder are associated with volatilization. Corn cropland has the highest emissions, almost 40% of the total, followed by soybean and wheat (Table 3-3). Emissions are highest from corn because corn covers the largest land area (Figure 3-1) of all crops and synthetic nitrogen inputs with corn are high. Emissions from soybeans are high due to large crop area and high rates of nitrogen fixation. Although wheat area has tended to decline, it still covers an area comparable to soybean and is the third highest in emissions. Emissions from hay cropping are also substantial. Emissions from hay are lower than those from wheat even though the areas are similar because hay is not typically fertilized with N and a large portion of the N supplied by fixation by legumes (e.g., alfalfa) is removed during harvest. Emissions from cotton and sorghum are low as the cropland areas for these crops is small compared to the other major crops simulated by DAYCENT. Non-major crop types were responsible for ~14% of total emissions on average. Emissions from histosol cultivation are small (~2% of total) because histosols represent only ~750,000 ha, which is less than 1% of U.S. cropped land.

Nitrous oxide emissions are largely driven by nitrogen additions, weather, and soil physical properties. External nitrogen inputs to cropped soils varied between ~14 and 17 Tg N between 1990 and 2005 (Fig. 3-2) while N_2O emissions varied between 154 and 180 Tg CO_2 eq. (Table 3-3). However, variation in N inputs only explained about 38% of the variability in soil N_2O emissions. Also, the years with highest nitrogen inputs did not necessarily lead to the highest N_2O emissions. This indicates that other factors such as changes in weather patterns strongly influence the annual variability in estimated N_2O emissions.

3.3.1 Changes Compared to the 1st edition of the USDA GHG Report

In contrast to the first edition of the USDA GHG report, this edition uses the process-based model DACENT to estimate N_2O emissions from the majority of agricultural soils in the U.S. DAYCENT simulates major crops (corn, soybean, wheat, hay, sorghum, and cotton) at county level resolution. The model simulates corn and sorghum harvested for grain and silage, and alfalfa hay as well as non-alfalfa hay. The DAYCENT simulations accounted for ~90% of synthetic nitrogen fertilizer applied to cropland soils in the U.S. and ~86% of cropland area in the U.S. IPCC (2006) emissions factor methodology was used to estimate emissions from crops not accounted for by DAYCENT (e.g., oats, tobacco, sugarcane, orchards, cash crops) and emissions associated with cultivation of histosols. IPCC (2006) methodology assumes that N_2O emissions are solely a function of N inputs to the soil. The major advantage of using DAYCENT to compute emissions is that the model accounts for additional factors that influence emissions like weather, soil type, and previous land use history, making estimates more reliable. Comparisons of observed N_2O emissions from experimental plots throughout North America with emissions estimated using DAYCENT and IPCC methodologies showed that DAYCENT was closer to the observed values (Del Grosso et al. 2005).

Another change is due to the nature of how nitrogen cycling is represented in this process-based model. Emissions cannot be partitioned as they were in the first edition. In the first edition, emissions were partitioned based on the source of nitrogen inputs (synthetic fertilizer, fixed N, crop residue, manure, etc.) because the IPCC (1997) methodology was based on N inputs. With DAYCENT, once nitrogen enters the plant/soil system, it can be taken up by vegetation, metabolized by microbes, or stored in the soil, and also cycled among these components. Consequently, when the model simulates emission of a given amount of nitrogen gas, it is impossible to accurately distinguish the original source of the nitrogen. Instead of partitioning N_2O emissions by nitrogen input type, emissions are partitioned spatially and by crop type.

Another major change in this edition compared to the first relates to prior assumptions about synthetic nitrogen fertilizer. Instead of assuming that all of the synthetic nitrogen fertilizer sold in this country was applied to agricultural soils, this edition accounts for the portion of total fertilizer that was applied for non-farm use (e.g., golf courses, parks, lawns) based on data compiled by the USGS (Ruddy et al. 2006). The following sections present emission estimates obtained by summing DAYCENT estimates for the major crop listed above and IPCC (2006) estimates for other crops. Following this, the methodologies used to conduct the DAYCENT simulations for major crops and IPCC methodology for other crops are summarized. Lastly, a quantification of N_2O mitigation is included in this edition.

3.3.2 Methods for Estimating N_2O Emissions from Cropped Soils

Emissions of N_2O from nitrogen additions to cropland soils and cultivation of histosol soils are source categories analogous to those covered in Agricultural Soil Management in the U.S. GHG Inventory (EPA 2007), with some exceptions. The U.S. GHG Inventory includes in Agricultural Soils Management direct emissions of N_2O from livestock on grazed lands, while the USDA GHG Inventory includes this source under Livestock GHG Emissions. The methodology outlined below does not include the portion of N_2O emissions from grazed lands. Methods for this source are covered in Chapter 2 of this report. Also, the U.S. GHG Inventory includes in Agricultural Soils Management indirect emissions of N_2O from all sources, including indirect N_2O from livestock grazing and from urban areas. For this report, indirect N_2O from grazing is included in the livestock chapter while indirect emissions from urban areas and other non-agricultural sources are not covered at all.

Briefly, the DAYCENT ecosystem model was used to estimate direct soil N_2O emissions, NO_3 leaching, and nitrogen volatilization from major crop types. IPCC (2006) methodology was used to estimate direct and indirect emissions from cropped soils not included in the DAYCENT simulations and to calculate indirect emissions from DAYCENT estimates of NO_3 leaching and volatilization. IPCC (2006) methodology was also used to estimate emissions from cultivation of organic soils. Use of a process based model for inventories is known as a Tier 3 approach while use of IPCC (2006) methodology is referred to as a Tier 1 approach. The methodology described below shows how the Tier 1 and Tier 3 approaches can be combined to derive overall emission estimates. Refer to EPA (2007) for a complete description of the methodologies used to estimate N_2O emissions.

3.3.2.1 DAYCENT Simulations for Major Crop Types

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral soils producing major crops, (corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton) which represent approximately 86% of total cropland in the United States. DAYCENT simulated crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions. The simulations were driven by model input data generated from daily weather records, land management, and soil physical properties determined in national soil surveys.

DAYCENT simulations were conducted for each major crop at the county scale in the U.S. The county scale was selected because soil, weather, and crop area data were available for every county. However, land management data (e.g., timing of planting, harvesting, and fertilizer application; intensity of cultivation, rate of fertilizer application) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States; most States correspond to one region, except for those with greater heterogeneity in agricultural practices, which led to further subdivisions. Therefore, while several cropping systems were simulated for each county in an agricultural region, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested, amount of fertilizer added), did not differ among those counties.

Corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton are defined as major crops and were simulated in every county where they were grown. For rotations that include a cycle that repeats every two or more years (e.g., corn/soybeans, wheat/corn/fallow) different simulations were performed where each phase of the rotation was simulated every year. For example, in regions where wheat/corn/fallow cropping is used, three rotations were simulated: one with wheat grown the first year, a second with corn the first year, and a third with fallow the first year. This ensured that each crop was represented during each year in one of the three simulations. In cases where the same crop was grown in the same year in two or more distinct rotations for a region, N_2O emissions were averaged across the different rotations to obtain a value for that crop. Emissions from cultivated fallow land were also included. Fallow area was assumed to be equal to winter wheat area in regions where winter wheat/fallow rotations are the dominant land management for winter wheat.

The simulations reported here assumed conventional tillage cultivation, gradual improvement of cultivars, and gradual increases in fertilizer application until 1989. We accounted for improvements of cultivars (cultivated varieties) because it is unrealistic to assume that modern corn is identical, in terms of yield potential, nitrogen demand, etc., as corn grown in 1900. Realistic simulations of historical land management and vegetation type are important because they influence present day soil carbon and nitrogen levels, which influence present day nitrogen cycling and associated N_2O emissions.

Nitrous oxide emission estimates from DAYCENT include the influence of N additions, crop type, irrigation, and other factors in aggregate, and therefore it is not possible to reliably partition N_2O emissions by anthropogenic activity (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Consequently, emissions are not subdivided according to activity (e.g., N fertilization, manure amendments), as is suggested in the IPCC *Guidelines*, but the overall estimates are likely more accurate than the more simplistic IPCC method, which is not capable of addressing the broader set of driving variables influencing N_2O emissions. Thus DAYCENT forms the basis for a more complete estimation of N_2O emissions than is possible with the IPCC methodology.

Uncertainty in the three major model inputs (weather, soil class, and N addition) was addressed using Monte Carlo analysis. For example, although mean amounts of N fertilizer applied to different crops are known, the amounts of fertilizer applied by particular farmers are uncertain. Monte Carlo analysis provides a method to quantify how this type of uncertainty impacts N_2O emissions. There are three main steps in this analysis. First, a set of simulations was performed using mean N fertilizer additions, median weather, and the dominant soil texture class. These were designated the 0th simulations. Second, probability distribution functions were derived for N additions, weather, and soil texture class. Third, Monte Carlo simulations were performed for a subset of counties in each agricultural region.

In addition to uncertainty in model inputs, model structural error was also addressed. Model structural error stems from models not being perfect representations of reality. That is, models contain assumptions and imperfectly represent the processes that control crop growth and N_2O emissions. To quantify model structural error, N_2O emissions generated by DAYCENT were compared with emissions measured in field plots at various locations in North America.

3.3.2.2 0th Simulations

For each crop in each county, simulations were performed assuming the most common land management practice, the weather most representative of the land area in the county where each crop is grown, and the most common soil type for the land area where each crop is grown (0th simulations). Simulations included native vegetation (year one to plow out), historical agricultural practices (plow out to 1970) and modern agriculture (1971 through 2003). Plow out (the year when native soils were initially cropped) was assumed to occur between 1600 and 1850, depending on the State in which the county lies. Simulation of at least 1600 years of native vegetation was needed to initialize soil organic matter (SOM) pools in the model. Modern weather (1980-2003) was used to drive the simulations of native vegetation and historical cropping. Simulation of native vegetation and the historical cropping period was needed to establish modern-day SOM levels, which is important because N_2O emissions are sensitive to the amount of SOM. Annual model outputs for N_2O emissions, NO_3 leached/runoff, and N volatilized were compiled for the years 1990-2005.

3.3.2.3 Probability Distribution Functions

Probability distribution functions (PDFs) were derived for key model inputs, including weather, soil type, and N amendments. In each county selected for the Monte Carlo analysis, all of the 1 km^2 cells with daily weather that correspond to the land area where row crops and small grains dominate were identified and assigned an equal probability of being selected in an individual Monte Carlo simulation. Cells with daily weather were similarly identified for the areas cropped with hay. The three dominant soil map units were identified for the land area with row crops and small grains, and each was assigned a probability given their relative level of dominance. Three soil map units were similarly identified and assigned probabilities for the areas where hay predominates.

Mineral N fertilization rates were based on two sets of PDFs, which were specified for individual crop types and hay. The first PDF was the probability of a fertilization event and the second PDF was a log-normal distribution of fertilization rates. Both PDFs were derived from USDA surveys and supplemental information (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). Irrigated and rain-fed crops were treated separately due to significantly different fertilization rates. State-level PDFs were developed for crops and hay if a minimum of 15 survey data points existed in the State. Where data were insufficient at the State level, PDFs were developed for multi-State Farm Production Regions.

Uncertainty in manure amendments for crops and hay was incorporated in the analysis based on total manure available for application in each county, a weighted average amendment rate, and the crop-specific land area amended with manure for 1997 (Edmonds et al. 2003). Edmonds et al. (2003) provided county-level estimates of the proportion of specific crops and hay land amended with manure in 1997. EPA (2007) provided supplemental data on county-level variation in manure production across the time series from 1990 to 2005. We used the EPA data to scale the amended area in 1997 for each crop and hay under the assumption that more manure production would increase the area amended with manure, and vice versa. The estimated area was then divided by the respective total areas in the county for each crop and hay, yielding a probability of either including a manure amendment or not in the Monte Carlo analysis. If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., farmers usually reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from PDFs based on relationships between manure N application and fertilizer rates (ERS 1997).

3.3.2.4 Monte Carlo Simulations

In each agricultural region, two counties were randomly selected for Monte Carlo simulations. Additional counties were selected based on the variance in N_2O emissions across regions from previous simulations (Del Grosso et al. 2006) by using a Neyman allocation (Cochran 1977). Neyman's optimization apportions samples based on an estimated variance in soil N_2O emissions. Using this approach, greater variance leads to a higher sampling density within the respective region with the goal of optimally capturing variation across the croplands in the conterminous U.S. regions with greater variance in N_2O emissions were assumed to have more variability in weather, soil characteristics, and agronomic practices, suggesting that more counties needed to be included in the Monte Carlo analysis. In total, 300 counties were selected for the Monte Carlo simulations. As with the 0th simulations, simulations of pre-settlement native vegetation and historical cropping patterns were performed in each county using the median weather for the county in combination with the three most dominant soil types.

One hundred Monte Carlo simulations were performed for each crop and hay type in the 300 counties selected for the Monte Carlo analysis. Random draws were made to select a soil type and weather file for the simulation from their respective PDFs, and the appropriate historical simulation was identified based on the soil type. Random draws were made to determine if mineral N fertilizer would be applied and the rate, and if the crop would be amended with manure. If manure was added, synthetic fertilizer rates were reduced based on an additional draw from the PDF for the reduction factors. The DAYCENT simulation was executed following the PDF draws and the process was repeated for a total of 100 iterations.

3.3.2.5 Nitrous Oxide Emission Estimates

Nitrous oxide emissions from the 0th simulation for each crop in each county in each agricultural region were adjusted by comparing the 0th simulation emissions to the mean emissions from the Monte Carlo simulations for that agricultural region. DAYCENT emissions for each crop in units of g N_2O-N m^{-2} were multiplied by the county-level crop area based on NASS data. Lastly, emissions from all crops were summed to obtain county-level and national emissions from cropped soils.

3.3.2.6 Activity Data for DAYCENT Simulations

The activity data requirements for estimating N_2O emissions from major crop types include the following: daily weather, soil texture, native vegetation, crop rotation and land management information, N fertilizer rates and timing, manure amendment N rates and timing, and county-level crop areas. Unlike the IPCC approach, N inputs from crop residues are not considered activity data in the DAYCENT analysis because N availability from this source is internally generated by the model. That is, while the model accounts for the contribution of crop residues to the soil profile and subsequent N_2O emissions, this source of mineral soil N is not activity data in the sense that it is not a model input.

Daily Weather Data: Daily maximum/minimum temperature and precipitation were obtained from the DAYMET model, which generates daily surface precipitation, temperature, and other meteorological data at 1 km^2 resolution driven by weather station observations and an elevation model (Thornton et al. 2000, 1997, Thornton & Running, 1990). DAYMET weather data is available for the United States at 1 km^2 resolution for 1980 through 2003.

Soil Properties: Soil texture data required by DAYCENT was obtained from STATSGO (Soil Survey Staff, Natural Resources Conservation Service, 2005), and was based on observations. Observed data for soil hydraulic properties needed for model inputs were not available so they were calculated from STATSGO texture class and Saxton et al.'s (1986) hydraulic properties calculator.

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

Crop Rotation and Land Management Information by Agricultural Region: Data for the 63 agricultural regions were obtained for specific timing and type of cultivation, timing of planting/harvest, and crop rotation schedules (Hurd 1930, 1929, Latta 1938, Iowa State College Staff Members 1946, Bogue 1963, Hurt 1994, USDA 2000a, USDA 2000c, CTIC 1998, Piper et al. 1924, Hardies & 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, Elliot & Tapp 1928, Elliot 1933, Ellsworth 1929, Garey 1929, Hodges et al. 1930, Bonnen & Elliot 1931, Brenner et al. 2001, 2002, Smith et al. 2002).

Nitrogen Fertilizer Amendment Rates and Timing by Agricultural Region: Fertilizer application rates and timing of applications within each of the 63 agricultural regions were determined from regional, State, or sub-State estimates for different crops. Estimates 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). Prior to 1990, estimates for crop specific regional fertilizer rates were based largely on extrapolation/interpolation of fertilizer rates from the years with available data. For crops in some agricultural regions, little or no data were available, and therefore a geographic regional mean was used to simulate N fertilization rates.

Managed Livestock Manure[2] Nitrogen Amendment Rates and Timing by Agricultural Region: Data on managed manure N amendments to soils were available for 1997 (Kellogg et al. 2000), and demonstrated that less than half of manure N produced on an annual basis was applied to soils. Crop-specific manure N application rates between 1990 and 2005 were obtained by multiplying the amount of manure N produced in that year by the proportion of manure N applied to the same crop in 1997; the amount of land receiving manure (approximately 5 percent of total cropped land) was assumed to be constant during 1990 through 2005. Nitrogen available for application was estimated for managed systems based on the total amount of N produced in manure minus N losses and including the addition of N from bedding materials. Nitrogen losses include direct nitrous oxide emissions, volatilization of ammonia and NO_x, and runoff and leaching. The remaining manure N that was not applied to major crops and grassland was assumed to be applied to non-major crop types. Manure was applied during spring at the same time as synthetic N fertilizer. Prior to 1990, manure application rates and timing were based on various sources (Brooks 1901, Anonymous 1924, Fraps & Asbury 1931, Ross & Mehring 1938, Saltzer & Schollenberger 1938, Alexander & Smith 1990). As with mineral N fertilization, data for manure were incomplete so regional averages were used to fill spatial gaps in data and interpolation/extrapolation was used to fill temporal gaps. Manure N application rates during 1990 through 2004 were based on Kellogg et al. (2000).

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

Crop Areas by Crop Type and by County: County-level total crop area data were downloaded from the USDA NASS Web site for the years 1990 through 2005 (USDA 2005b), and this data formed the basis to scale emissions from individual crop types across the entire county.

3.3.3 IPCC Methodology for Non-Major Crop Types

3.3.3.1 Mineral Soils

For mineral agricultural soils producing non-major crop types, the Tier 1 IPCC methodology was used to estimate direct N_2O emissions. Estimates of direct N_2O emissions from N applications to non-major crop types were based on the annual increase in mineral soil N from the following practices: 1) the application of synthetic commercial fertilizers, 2) the retention of crop residues, and 3) manure and non-manure organic fertilizers.

IPCC methodology for emissions from mineral soils is based on nitrogen inputs. Nitrogen inputs from synthetic and organic fertilizer and above and below ground crop residues were added together. This sum was multiplied by the IPCC default emission factor (1.0%) to derive an estimate of cropland direct N_2O emissions from non-major crop types. Nitrate leached or runoff and N volatilized from non-major crop types are calculated by multiplying N fertilizer applied by the IPCC (2006) default factors (30% and 10%, respectively).

Annual synthetic fertilizer nitrogen additions to non-major crop types are calculated by process of elimination. For each year, fertilizer applied to major crops and grazed lands (as simulated by DAYCENT—approximately 80% of the U.S. total fertilizer used on farms) was subtracted from total fertilizer used on farms in the United States. The difference, approximately 20% of total synthetic fertilizer N used on farms in the U.S., was assumed to be applied to non-major crop types. Non-major crop types include fruits, nuts, and vegetables, which is estimated at approximately 5% of total U.S. N fertilizer use (TFI 2000), and other annual crops not simulated by DAYCENT, barley, oats, tobacco, sugarcane, sugar beets, sunflower, millet, peanuts, etc., which account for approximately 15% of total U.S. fertilizer used on farms. Manure N applied to non-major crops was estimated in a similar manner; manure applied to major crops and grazed lands as simulated by DAYCENT was subtracted from total manure available for soil application. This difference was assumed to be applied to non-major crops. In addition to synthetic fertilizer and manure N, nitrogen in soils due to the cultivation of non-major N-fixing crops (e.g., edible legumes) was included in these estimates. Finally, crop residue nitrogen was derived from information on crop production yields, residue management (retained vs. burned or removed), mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the residues (IPCC 2006). The activity data for these practices were obtained from the following sources:

- Annual production statistics for crops whose residues are left on the field: USDA (1994, 1998, 2000a, 2001, 2002, 2003), Schueneman (1999a, 1999b, 1999c, 2001), Deren (2002), Schueneman and Deren (2002), Cantens (2004), Lee (2003, 2004).

- 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, 2005b, 2006b), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

Annual Applications of Commercial Non-manure Organic Fertilizers by Agricultural Region: Estimates of total national annual N additions from land application of other organic fertilizers were derived from organic fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000a, 2000b, 2002, 2003, 2004, 2005, 2006). The organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of N by multiplying by the average organic fertilizer N contents provided in the annual fertilizer publications. These N contents are weighted average values, and vary from year to year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2004). Annual onfarm use of these organic fertilizers is very small, less than 0.03 Tg N.

3.3.3.2 Cultivation of Histosols

The IPCC Tier 1 method is used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions was obtained for 1982, 1992, and 1997 from the National Resources Inventory (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998). To estimate annual N_2O emissions from histosol cultivation, the temperate histosol area is multiplied by the IPCC default emission factor for temperate soils (8 kg N_2O-N/ha cultivated; IPCC 2000), and the sub-tropical histosol area is multiplied by the average of the temperate and tropical IPCC default emission factors (12 kg N_2O-N/ha cultivated; IPCC 2000).

3.3.3.3 Total N_2O Emissions

Total direct emissions were obtained by summing DAYCENT generated emissions from major crops on mineral soils, IPCC generated estimates for non-major crops on mineral soils, and IPCC estimates of emissions from organic soils. Total indirect emissions from NO_3 leaching or runoff were obtained by adding DAYCENT estimates for major crops on mineral soils to IPCC (2006) estimates for non-major crops on mineral soils and multiplying by the default emission factor (0.75% of N leached/runoff). Total indirect emissions from nitrogen volatilization were obtained by adding DAYCENT estimates for major crops on mineral soils to IPCC (2006) estimates for non-major crops on mineral soils and multiplying by the default emission factor (1% of N volatilized). Indirect emissions from NO_3 leaching or runoff were added to those from nitrogen volatilization to get total indirect emissions. Total direct and indirect emissions were then summed to get total N_2O emissions from cropped soils.

3.3.4 Uncertainty in N_2O Emissions

Uncertainty was estimated differently for each of the following components of N_2O emissions from cropped soils: direct emissions from major crops calculated by DAYCENT due to model input uncertainty, direct emissions from major crops calculated by DAYCENT due to model structure uncertainty, direct emissions from minor crops not calculated by DAYCENT; indirect emissions from all crops. For direct emissions calculated using DAYCENT, model input uncertainty was quantified using the Monte Carlo analysis described above in section 3.3.2. Model structure uncertainty was quantified by comparing DAYCENT estimates of N_2O emissions with measured values. Uncertainty for direct emissions from minor crops and indirect emissions from all crops were estimated using simple error propagation (IPCC 2006). Error propagation was used to combine uncertainties in the various components by taking the square root of the sum of the squares of the standard deviations of the components (IPCC 2006). The 95% confidence interval in N_2O emissions was estimated to lie between 137 and 188 Tg CO_2 eq. (Table 3-1).

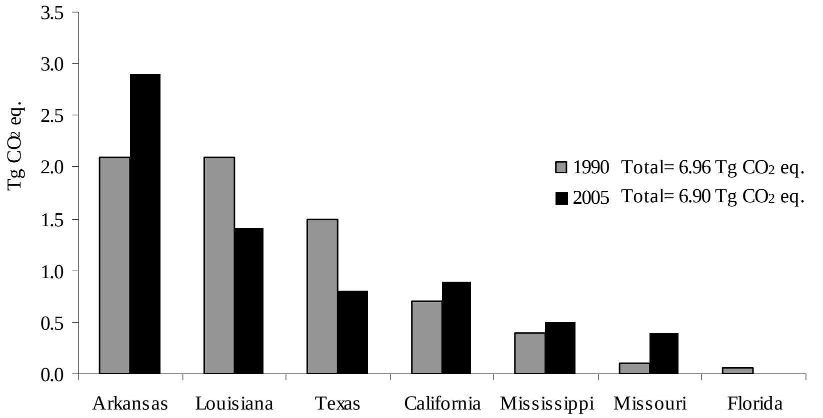
3.3.5 Mitigation of N_2O Emissions

Mitigation of N_2O emissions is based on optimizing the amount and timing of nitrogen fertilizer additions. Excess fertilizer applied to crops increases the nitrogen available for N_2O, N oxide and NH_3 emissions, and for NO_3 leaching. Using time-released fertilizers and applying fertilizer in multiple applications improves the synchrony between nitrogen supply and plant nitrogen demand. However, multiple applications of fertilizer require increased time and equipment usage by farmers and time-released fertilizers are more expensive than conventional fertilizers. Use of nitrification inhibitors has been shown to decrease N_2O emissions (Weiske et al. 2001, McTaggert et al. 1997). The capability to simulate their impact has been incorporated into the DAYCENT ecosystem model. National-scale DAYCENT simulations suggest that universal use of nitrification inhibitors could reduce total N_2O emissions by 10-20% while maintaining, or slightly increasing crop yields. The model showed lower direct N_2O and NO_x emissions because nitrification rates are decreased but also lower NO_3 leaching rates because reduced nitrification also reduces inputs to the soil NO_3 pool. Unfortunately, as with time-released fertilizer, fertilizer amended with nitrification inhibitors is more expensive. Further analyses of the environmental and economic costs and benefits of the different mitigation strategies needs to be performed before optimum mitigation strategies can be identified.

3.4 Methane Emissions from Rice Cultivation

Figure 3-3

Methane from Rice Cultivation by State, 1990 & 2005



Methane emissions from rice cultivation[3] are limited to seven U.S. States (Figure 3-3). In four States (Arkansas, Florida, Louisiana, and Texas), the climate allows for cultivation of two rice crops per season, the second of which is referred to as a ratoon crop (EPA 2007). Methane emissions from primary and ratoon crops are accounted for separately because emissions are higher from ratoon crops (EPA 2007). Overall, rice cultivation is a small source of CH_4 in the United States. In 2005, CH_4 emissions totaled 6.9 Tg CO_2 eq, of which 6.0 Tg CO_2 eq. were from primary crops in all seven States and 0.9 Tg CO_2 was from ratoon crops in four States (Table 3-4).

Arkansas and Louisiana had the highest CH_4 emissions from rice cultivation in 2005, followed by California and Texas. Missouri and Florida both had emissions of less than 0.5 Tg CO_2 eq. (Table 3-4). Overall since 1990, CH_4 emissions from rice cultivation have decreased almost 3% (Table 3-5). While small national-scale changes were seen between 1990 and 2005 (3% decrease), sizeable shifts occurred at State levels during that time period. For example, CH_4 emission in Missouri, Arkansas and California increased by 180%, 35% and 28%, respectively, while emissions in Florida declined by 68% (Table 3-5). Although CH_4 emissions from Missouri increased by 180% between 1990 and 2005, they remained small in magnitude relative to emissions from other states because of the small land area used for rice production in this State. State-level shifts in CH_4 emissions since 1990 are positively correlated with changes in area of rice cultivation (Appendix Table B-1). Appendix Table B-1 provides a complete time series of areas harvested for rice by State with primary versus ratoon crops from 1990-2005.

3.4.1 Methods for Estimating CH_4 Emissions from Rice Cultivation

The EPA provided estimates for CH_4 emissions from rice cultivation for this report. Details on the methods are provided below and are excerpted, with permission from EPA, from Chapter 6 of the U.S. GHG Inventory report (EPA 2007). The method used by EPA applies area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to harvested rice areas to estimate annual CH_4 emissions from rice cultivation. The EPA derives specific

Table 3-4 Methane from Rice Cultivation from Primary and Ratoon Operations by State, 1990-2005

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	Tg CO_2 eq.															
Primary	**5.1**	**5.0**	**5.6**	**5.1**	**6.0**	**5.6**	**5.0**	**5.6**	**5.8**	**6.3**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**	**6.0**
Arkansas	2.1	2.2	2.5	2.2	2.5	2.4	2.1	2.5	2.7	2.9	2.5	2.9	2.7	2.6	2.8	2.9
California	0.7	0.6	0.7	0.8	0.9	0.8	0.9	0.9	0.8	0.9	1.0	0.8	0.9	0.9	1.1	0.9
Florida	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Louisiana	1.0	0.9	1.1	0.9	1.1	1.0	1.0	1.0	1.1	1.1	0.9	1.0	1.0	0.8	1.0	0.9
Mississippi	0.4	0.4	0.5	0.4	0.6	0.5	0.4	0.4	0.5	0.6	0.4	0.5	0.5	0.4	0.4	0.5
Missouri	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.4
Texas	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.4	0.4
Ratoon	**2.1**	**2.0**	**2.2**	**1.9**	**2.3**	**2.1**	**1.9**	**1.9**	**2.1**	**2.0**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**	**0.9**
Arkansas	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Florida	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	+	+	+
Louisiana	1.1	1.0	1.2	1.1	1.2	1.1	1.1	1.2	1.2	1.2	1.3	1.1	0.5	1.0	1.1	0.5
Texas	0.9	0.9	0.9	0.8	0.9	0.8	0.8	0.7	0.8	0.7	0.7	0.6	0.5	0.5	0.6	0.4
Total	**7.1**	**7.0**	**7.9**	**7.0**	**8.2**	**7.6**	**7.0**	**7.5**	**7.9**	**8.3**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**	**6.9**

(+) Less than 0.05 Tg CO_2 Eq.

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[3] This source focuses on CH_4 emissions resulting from anaerobic decomposition, and does not include emissions from burning of rice residues. The later is covered in section 3.5.

CH_4 emission factors from published studies containing rice field measurements in the United States, with separate emissions factors for ratoon and primary crops to account for higher seasonal emissions in ratoon crops.

Table 3-5 Change In Methane Emissions from Rice Cultivation, 1990-2005

	1990	2005	% Change 1990-2005
State	*Tg CO_2 eq.*		
Arkansas	2.14	2.90	35%
California	0.70	0.90	28%
Florida	0.06	0.02	-68%
Louisiana	2.06	1.40	-32%
Mississippi	0.45	0.50	12%
Missouri	0.14	0.40	180%
Texas	1.57	0.80	-49%
Total	**7.12**	**6.92**	**-3%**

A review of published experiments was used to develop emissions factors for primary and ratoon crops. Experiments where nitrate or sulfate fertilizers or other substances believed to suppress CH_4 formation were applied, and experiments where measurements were not made over an entire flooding season or where floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results 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 synthetic and organic fertilizer added (Bossio et al. 1999, Cicerone et al. 1992, Sass et al. 1991a and 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with synthetic fertilizer added (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/ha per season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/ha per season.

The harvested rice areas for the primary and ratoon crops in each State are presented in Appendix Table B-1. Primary crop areas for 1990 through 2001 for all States except Florida were taken from USDA NASS Field Crops Final Estimates 1987-1992 (USDA 1994), Field Crops Final Estimates 1992-1997 (USDA 1998), Crop Production 2000 Summary (USDA 2001), and Crop Production 2001 Summary (USDA 2002). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001), a Florida agricultural extension agent, and Dr. Chris Deren (2002) of the Everglades Research and Education Center at the University of Florida. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each State.

In Arkansas, ratooning occurred only in 1998 and 1999, when the ratoon area was less than 1% of the primary area (Slaton 1999, 2000, 2001). In Florida, the ratoon area was 50% of the primary area from 1990 to 1998 (Schueneman 1999a), about 65% of the primary area in 1999 (Schueneman 2000), around 41% of the primary area in 2000 (Schueneman 2001a), and about 70% of the primary area in 2001(Deren 2002). In Louisiana, the percentage of the primary area in ratoon was constant at 30% over the 1990 to 1999 period, but increased to approximately 40% in 2000, before returning to 30% in 2001 (Linscombe 1999a, 2001, 2002 and Bollich 2000). In Texas, the percentage of the primary area in ratoon was constant at 40% over the entire 1990 to 1999 period and in 2001, but increased to 50% in 2000 due to an early primary crop (Klosterboer 1999a,1999b, 2000, 2001, 2002).

3.4.2 Uncertainty in Estimating Methane Emissions from Rice Cultivation

The following discussion of uncertainty in estimating GHG emissions from rice cultivation is modified from information provided in the U.S. GHG Inventory (EPA 2007). The information is reproduced here with permissions from the EPA.

Methane emissions factors are the largest source of uncertainty in estimates for rice cultivation. Seasonal emissions, derived from field measurements in the United States, vary by more than an order of magnitude, from variation in cultivation practices, fertilizer application, cultivar types, soil, and climatic conditions. Some variability is accounted for by separating primary from ratoon areas. However, even within a cropping season, measured emissions vary significantly. Of the experiments that were used to derive the emission factors used here, primary emissions ranged from 22 to 479 kg CH_4/ha per season and ratoon emissions ranged from 481 to 1,490 kg CH_4/ha per season.

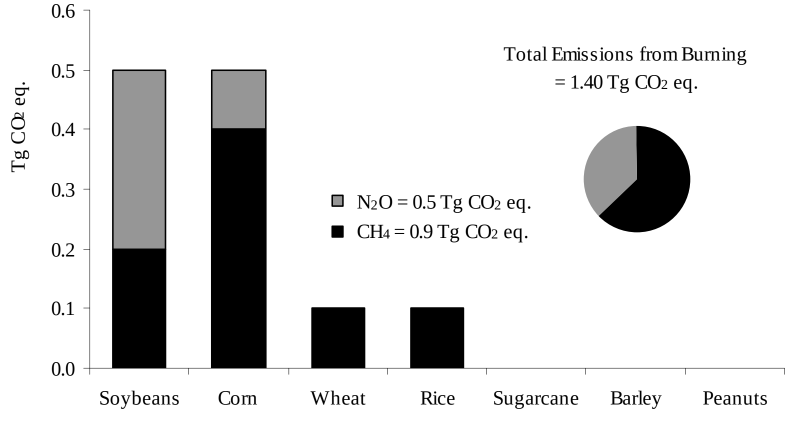
Data is not collected regularly on the area of rice crops in ratoon, creating another source of uncertainty. The area estimates are derived from expert opinion and account for less than 10% of the total area of rice cultivation. A final source of uncertainty is the practice of flooding outside of the normal rice season. According to agriculture extension agents, this occurs in all rice-growing States. Estimates of the area of off-season flooding range from five to 68% of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition.

A Monte Carlo analysis was performed to quantify the uncertainties mentioned above. The calculated 95% confidence interval was 2.1 to 18.6 Tg CO^2 eq. for CH_4 emissions from rice cultivation, or 70% below and 170% above the estimate of 6.9 Tg CO^2 eq. (Table 3-1).

3.5 Residue Burning

Figure 3-4

Greenhouse Gas Emissions from Field Burning by Crop Type, 2005



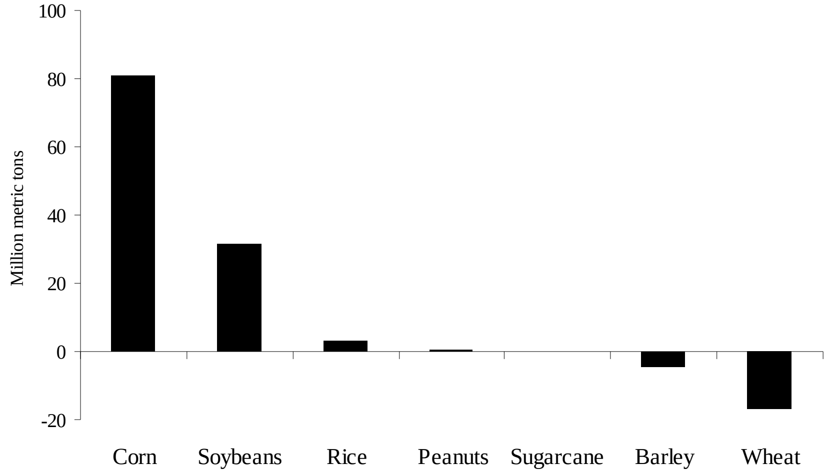
Greenhouse gas emissions from field burning of crop residues are a function of the amount and type of residues burned. In the U.S., crops burned include wheat, rice, sugarcane, corn, barley, soybeans, and peanuts (EPA 2007). For most crops, residues are burned per year, but a higher portion of rice residues is burned annually (EPA 2007). Consequently, emissions from residue burning are a small source of overall crop-related emissions in the U.S.

About three-fifths of GHG emissions from residue burning, across all crop types, consisted of CH_4 in 2005; the remaining was N_2O (Table 3-6, Figure 3-4). The highest GHG emissions were from burning of soybean and corn crop residues, at 40% each. Burning of wheat, rice, sugarcane, and barely crop residues each contributed 10% or less to overall GHG emissions; burning of peanut crop residues contributed almost nothing to this source of GHG due to the relatively small amount of land area planted with this crop.

Total GHG emissions from residue burning increased 33% from 1990 to 2005. Trends in relative GHG emissions were similar across crop types in 1990 compared to 2005 with a few exceptions. In 1990, burning of corn residues contributed the most to GHG emissions from residue burning, while burning of soybeans was the second largest source. By 2005, these crops had similar emissions form burning. Between 1990 and 2005, soybean and corn production both increased in absolute amounts (Figure 3-5). However, proportionally, soybean production increased more dramatically than corn (soybean production increased by 62% and corn by 50%) (Figure 3-6). In addition, soybeans have higher nitrogen content than corn, resulting in greater N_2O emission per unit of crop mass burned. Thus, while corn production was still greater than soybean production in 2005, GHG emissions from soybean residue burning were about equal to those from corn residue burning.

Figure 3-5

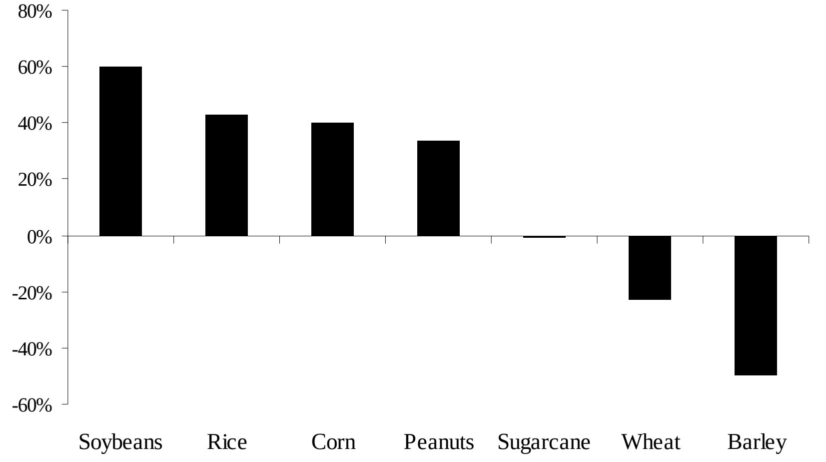
Change in Commodity Production, 1990-2005



Appendix Table B-2 provides the complete time series of crop production from 1990 to 2005 for crop types that contribute to GHG emissions from burning, Appendix Table B-3 provides crop production by State of crops managed with burning for 2005.

Figure 3-6

Percent Change in Commodity Production, 1990-2005



Illinois and Iowa had the highest State levels of GHG emissions from residue burning in 2005, emitting roughly 0.15 and 0.19 Tg CO_2 eq., respectively, of CH_4 and N_2O combined (Appendix

Table 3-6 Greenhouse Gas Emissions from Agriculture Burning by Crop, 1990-2005

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Source								*Tg CO_2 eq.*								
Methane	**0.7**	**0.6**	**0.8**	**0.6**	**0.8**	**0.7**	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**	**0.9**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Corn	0.3	0.3	0.3	0.2	0.4	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.3	0.4	0.4	0.4
Barley	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soybeans	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2
Peanuts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrous oxide	**0.4**	**0.4**	**0.4**	**0.3**	**0.5**	**0.4**	**0.4**	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**
Wheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rice	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soybeans	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3
Peanuts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**1.1**	**1.0**	**1.2**	**0.9**	**1.3**	**1.0**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.4**	**1.4**

Table B-5 and Appendix Table B-6). The next highest levels of GHG emissions from residue burning were in order Iowa, Illinois, Minnesota, Nebraska, Indiana, Arkansas, Kansas, and Ohio, with emissions between 0.06 and 0.11 Tg CO_2 eq. State-level GHG emissions from residue burning are strongly tied to crop production. State-level estimates of crop production are provided in Appendix Table B-3 for corn, soybeans, wheat, rice, sugarcane, barley, and peanuts.

3.5.1 Methods for Estimating CH_4 and N_2O Emissions from Residue Burning

EPA provided national-level estimates of GHG emissions from agricultural residue burning for all crop types, and State-level estimates for GHG emissions from rice residue burning for this report. In addition, State-level estimates were derived by USDA for all crop types (except rice) using the same method. Details on the methods used by EPA are provided below, including excerpts from Chapter 6 of the U.S. GHG Inventory report (EPA 2007). This information is reproduced with permission from EPA.

The equations below were used to estimate the amounts of carbon and nitrogen released during burning.

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio)
× (Fraction of Residues Burned in situ) × (Dry Matter Content of the Residue)
× (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio)
× (Fraction of Residues Burned in situ) × (Dry Matter Content of the Residue)
× (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

Values used in the above equations to estimate emissions from residue burning are summarized in Appendix Table B-4. National and State-level crop production statistics are provided in Appendix Table B-2 and Appendix Table B-3. The sources for developing these input data are described for each parameter below.

Annual Crop Production: kl
The crop residues that are burned in the United States were determined from various State-level GHG emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992). Crop production data for these crops, except rice in Florida, were taken from USDA's *Field Crops Final Estimates* 1987-1992, 1992-1997, 1997-2002 (USDA 1994, 1998, 2003b) and *Crop Production 2004 Summary* (USDA 2005a). Rice production data for Florida were estimated by applying average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005).

Residue-to-Crop Product Mass Ratios:
All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987) and Meisinger and Randall (1991). The ratio for sugarcane is from the University of California (1977).

Fraction of Residues Burned:
The percentage of crop residue burned was assumed to be three percent for all crops in all years, except rice, based on State inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, Cibrowski 1996). Estimates of the percentage of rice acreage on which residue burning took place were obtained on a State-by-State basis from agricultural extension agents in each of the seven rice-producing States (Bollich 2000; Deren 2002; Guethle 1999, 2000, 2001, 2002; Fife 1999; California Air Resources Board 1999; Klosterboer 1999a, 1999b, 2000, 2001, 2002; Linscombe 1999a, 1999b, 2001, 2002; Mutters 2002, Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Slaton 1999a, 1999b, 2000; Street 1999, 2000, 2001, 2002; Wilson 2004, 2005) (Appendix B-4).

The estimates provided for Florida remained constant over the entire 1990-2005 period, while the estimates for all other States varied over the time series. For California, it was assumed that the annual percent of rice acreage burned in Sacramento Valley is representative of burning in the entire State, because the Sacramento Valley accounts for over 95% of the rice acreage in California (Fife 1999). The annual percent of rice acreage burned in the Sacramento Valley was obtained from staff at the California Air Resources Board (CARB) (Najita, 2001), a report of the CARB (2001), and background data for future editions of the report (Lindberg 2002). These values declined over the period 1990 through 2005 because of a legislated reduction in rice straw burning.

Residue Dry-Matter Content:
Residue dry-matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry-matter content was obtained from Strehler and Stützle (1987). Peanut dry-matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System.

Burning Efficiency:
Burning efficiency refers to the fraction of dry biomass exposed to burning that actually burns. The burning efficiency was assumed to be 93%.

Carbon and Nitrogen Content:
The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999).

Combustion Efficiency:
Combustion efficiency refers to the fraction of carbon in the fire that is oxidized completely to CO_2. Combustion efficiency was assumed to be 88% for all crop types (EPA 1994).

State-level emissions estimates were calculated with the above equations, applying State-level production data to national-level coefficients. The State-level rice estimates were provided directly by EPA, using State-specific residue fractions (the fraction of residues burned varies among States), and State production data.

3.5.2 Uncertainty in Estimating Methane and Nitrous Oxide Emissions from Residue Burning

The following discussion of uncertainty in estimating GHG emissions from residue burning is modified from information provided in the U.S. GHG Inventory (EPA 2007). The information is reproduced here with permission from EPA.

Assumptions about the annual amount of residues burned by crop type are the largest source of uncertainty in estimating GHG emissions from field burning of agricultural residues. Data on the fraction burned, as well as the gross amount of residue burned each year, is not collected at either the national or State level. In addition, burning practices are highly variable among crops and States. The fractions of residue burned used in these calculations are based upon information collected by State agencies and in published literature. These emissions estimates may continue to change as more information becomes available in the future. Other sources of uncertainty include the residue/crop product mass ratios, residue dry matter contents, burning and combustion efficiencies, and emission ratios. Residue/crop product ratios for specific crops can vary among cultivars and, for all crops except sugarcane, generic global residue/crop product ratios were used rather than ratios specific to the United States. In addition, residue dry matter contents, burning and combustion efficiencies, and emission ratios can vary due to weather and other combustion conditions, such as fuel geometry. Values for these variables were taken from literature on agricultural biomass burning.

A Monte Carlo analysis was performed to quantify the uncertainties mentioned above. The calculated 95% confidence interval was 0.45 to 57 Tg CO^2 eq. for N_2O emissions from residue burning, or 10% below and 14% above the estimate of 0.5 Tg CO^2 eq. and 0.75 to 0.97 Tg CO^2 eq. for CH_4 emissions from residue burning, or 17% below and 8% above the estimate of 0.9 Tg CO^2 eq. (Table 3-1).

3.6 Carbon Stock Changes in Cropped Soils

In contrast to the first edition of the USDA GHG report, this edition uses the process-based model CENTURY to estimate CO_2 fluxes from the majority of agricultural soils in the U.S. CENTURY simulates most crops except vegetables, tobacco, horticultural crops, orchards, rice, and crops grown on organic soils. An IPCC (2006) Tier 2 approach was used to estimate fluxes from all crops not simulated by CENTURY. The IPCC (2006) methodology calculates soil C changes based on previous and current land use. The major advantage of using CENTURY to estimate soil C changes is that the model accounts for additional factors that influence C levels like weather, soil type, and fertilizer additions, making estimates more reliable.

3.6.1 Emissions by Land Use

Except for cultivated organic soils and liming practices, cropped soils in the U.S. were estimated to accumulate about 66.5 Tg CO_2 eq. in 2005 (Table 3-1)[4]. Much of the carbon change is attributable to the Conservation Reserve Program, land use conversions between annual croplands and perennial hay and grazing lands, and land management (Figure 3-7). Practices such as the adoption of conservation tillage, including no-till, which have taken place over the past two decades, and reduced frequency of summer-fallow are important drivers of carbon stock changes. Manure applications to cropland and pasture also impact the estimated carbon stock increase.

In contrast, the small area of cultivated organic soils—less than 1 million hectares of a total 386 million hectares of agricultural and forest land—concentrated in Florida, California, the Gulf and Southeastern coastal region and parts of the upper Midwest, was a net source of CO_2 emissions for all years covered by the inventory (1990-2005). About 30 Tg CO_2 eq. was emitted from cultivation of these soils in 2005 (Table 3-1). Liming of agricultural soils resulted in emissions of about 4 Tg CO_2 eq per year. Total net carbon sequestration in 2005 was about 32 Tg CO_2 eq. when all of the above components were taken into consideration. Carbon uptake on agricultural soils varied between 1990 and 2005 (Table 3-

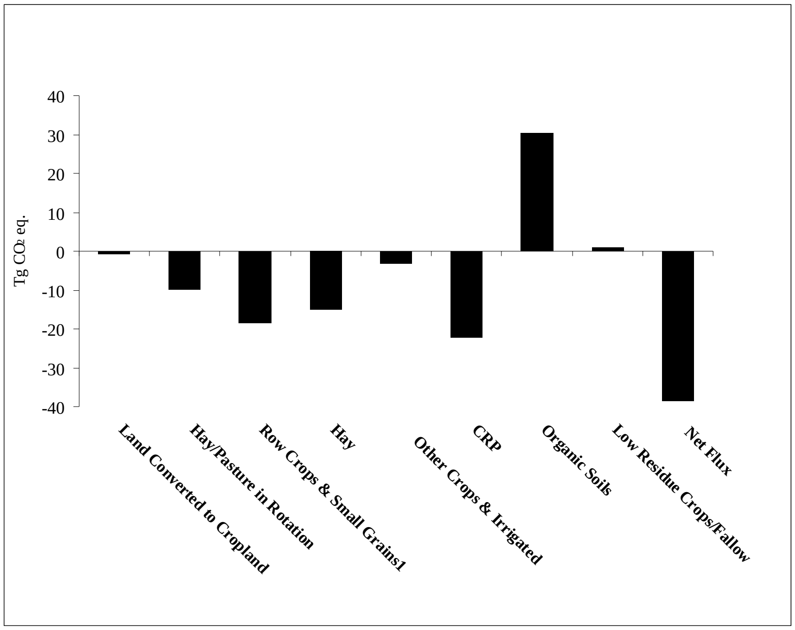


Figure 3-7. CO_2 Emissions and Sequestration from Cropland Soils, 2005

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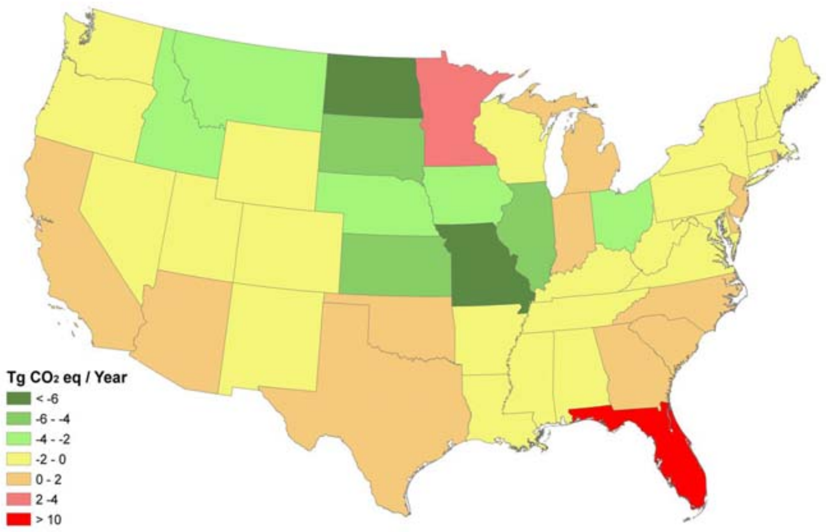
[4] Emissions and sinks of carbon in agricultural soils are expressed in terms of CO_2 equivalents; carbon sequestration is a result of changes in stocks of carbon in soils, from which CO_2 fluxes are inferred. Units of CO_2 equivalent can be converted to carbon using a multiplier of 0.272.

2), driven largely by land use changes and weather fluctuations.

Map 3-3

State Level Carbon Dioxide Fluxes from Cropped Soils in 2005



Most States in the Corn Belt are storing C in cropped soils due to adoption of reduced tillage practices (Map 3-3). The exception to this is Minnesota, which is losing C at the State level. Carbon losses from cropping of organic soils exceed C gains in mineral soil cropping for this State. Florida has the highest C losses, primarily due to sugarcane cropping on organic soils.

3.6.2 Methods for Estimating Carbon Stock Changes in Agricultural Soils

Two broad categories of cropland were considered, cropland remaining cropland and land converted to cropland. Within both of these categories, Tier 2 and Tier 3 methodologies were used. The Tier 2 approach is based on relatively simple equations used in IPCC (2003) methodology that have been modified to better represent nations or regions within nations. The Tier 3 approach (CENTURY model) uses a more complex ecosystem model to simulate carbon fluxes for cropped systems. Both tiers used land use and management data based primarily on the National Resources Inventory (NRI) (USDA 2000b). The NRI represents a robust statistical sampling of land use and management on all non-Federal land in the United States, and greater than 400,000 NRI survey points occurred in agricultural lands and were used in the inventory analysis. The methodology summarized below is described in detail in the U.S. GHG Gas Inventory (EPA 2007).

3.6.2.1 CENTURY Model Simulations for Most Cropped Mineral Soils

CENTURY simulates carbon and nitrogen dynamics, soil water content and temperature, and other ecosystem variables (Parton et al. 1994). Key submodels include: plant growth, senescence of biomass, decomposition of dead plant material and soil organic matter, and mineralization of nitrogen. Model inputs are monthly maximum/minimum air temperature and precipitation, surface soil texture class, soil hydric condition, vegetation type, and land management information (e.g., cultivation timing and intensity, timing and amount of fertilizer and organic matter amendments). Soil organic matter is simulated to a depth of 20 cm while water, temperature, and mineral nitrogen are simulated throughout the soil profile. Soil organic matter is divided into three pools based on decomposability: active (turns over in months to years), slow (turns over in decades), and passive (turns over in centuries). The model accounts for the effects of nutrient availability, water, and temperature on plant growth (CO_2 uptake) and the effects of these factors, as well as cultivation, on decomposition (CO_2 release). The ability of the model to integrate carbon gains and losses and simulate plant growth and soil carbon levels reliably has been demonstrated using data from many sites in the U.S. and around the world (Parton et al. 1994, Cerri et al. 2007, Ross et al. 2007). The model has been shown to work in all the major biomes of the Earth and can accurately reproduce the impacts of climate, soil texture, and land management on carbon fluxes (Parton et al. 1993, Kelly et al. 1997, Lugato 2007, Bricklemyer 2007). CENTURY has been parameterized to represent the major crops grown in the U.S. The major crops simulated by CENTURY for this analysis were corn, soybeans, small grains, hay, sorghum, millet, and cotton, which cover ~90 % of U.S. cropland. Crops not simulated by CENTURY include rice, sugarcane, tobacco, vegetables, orchards, and horticultural crops.

Three sets of simulations were performed; one to represent pre-settlement native vegetation, one to represent historical cropping, and one to represent modern cropping. This is important because previous vegetation types and land management activities influence the capacity of present-day soils to lose or sequester carbon. Native vegetation was represented at the MLRA (Major land Resource Area, USDA NRCS 1981) level. MLRA's represent geographical units with relatively similar soils, climate, water resources, and land use. Data on historical cropping practices for different regions were obtained form various sources including historical accounts and from NASS. Beginning in 1979, the first year of the NRI survey, simulations of crops and management practices were based on NRI data. Additional data for tillage practices used were from the Conservation Technology Information Center (CTIC 1998). Crop-specific N fertilization rates were from the USDA Economic Research Service survey (ERS 1997) and other sources, e.g., NASS. Manure application rates were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003). Monthly weather data required to run CENTURY were from the PRISM data base. PRISM (Daly et al. 1994) is based on observed weather and the resolution is 4x4 km grid cells. The data were area weighted to represent the agricultural land in each county in the U.S. Soil texture and drainage capacity (hydric vs. non-hydric) were derived from the NRI.

3.6.2.2 Tier 2 Approach for Remaining Cropped Mineral Soils, Organic Soils, and Liming

A Tier 2 approach was used to estimate soil carbon stock changes for crops not simulated by the CENTURY model, for non-agricultural lands that were converted to cropland, and for organic soils. Data on climate, soil type, and land use were used to classify land area and apply appropriate stock change factors. U.S. specific carbon stock change factors were derived from published literature to estimate the impact of management practices (e.g., changes in tillage or crop rotation) on soil carbon fluxes (Ogle et al. 2003; 2006b). Carbon stocks are listed in Appendix Table B-7, stock change rates are listed in Appendix Table B-8, areas of cropped organic soils are listed in Appendix Table B-9, and carbon loss rates from organic soils are listed in Appendix Table B-10.

Stock change factors and reference carbon stocks can vary for different climate regimes and soil types. The IPCC method defines eight climate types according to mean annual temperature, precipitation, and potential evapotranspiration. Six of these occur in the continental United States. The PRISM long-term monthly climate data set (Daly et al. 1998) was used to classify each of the 180 Major Land Resource Areas (MLRAs) in the United States into climate zones.

Reference soil carbon stocks were stratified by climate region and categorized into six major groupings, based on taxonomic orders that relate to soil development and physical characteristics that influence soil carbon contents. Estimates for carbon stocks under conventionally managed cropland (defined as the reference land use) were derived from the National Soil Survey Characterization Database (USDA NRCS 1997).

Based on the NRI, crop management systems were aggregated into 22 different categories. Land areas grouped by major land use and management system types are shown in Appendix Table B-11, carbon stock changes by State and land use/management in Appendix Table B-12, and by State on cropland by major activity in Appendix Table B-13. Tillage practices are not included in the NRI. Thus, supplemental data were used from the Conservation Technology Information Center (CTIC 1998),

Table 3-7 Tillage Percentages by Management Category and Climate Zones[1]

	1982			**1992**			**1997**		
Climate & System	No Till[2]	Red. Till[3]	Conv. Till[4]	No Till	Red. Till	Conv. Till	No Till	Red. Till	Conv. Till
STD									
Continuous Cropping Rotations[5]	0	3	97	0	4	96	0	15	85
Rotations with Fallow[6]	0	0	100	0	2	98	0	5	95
Low Residue Ag.[7]	0	3	97	0	4	96	0	10	90
STM									
Continuous Cropping Rotations	0	0	100	0	20	80	1	10	89
Rotations with Fallow	0	0	100	0	10	90	1	10	89
Low Residue Ag.	0	3	97	0	4	96	0	5	95
WTD									
Continuous Cropping Rotations	0	0	100	0	10	90	1	15	84
Rotations with Fallow	0	3	97	0	15	85	2	20	78
Low Residue Ag.	0	3	97	0	1	99	0	0	100
WTM									
Continuous Cropping Rotations	0	6	94	10	30	60	12	28	60
Rotations with Fallow	0	6	94	5	30	65	8	27	65
Low Residue Ag.	0	9	91	1	10	89	2	13	85
CTD									
Continuous Cropping Rotations	0	3	97	2	25	73	8	12	80
Rotations with Fallow	0	6	94	4	25	71	12	13	75
Low Residue Ag.	0	0	100	1	2	97	2	6	92
CTM									
Continuous Cropping Rotations	0	11	89	5	30	65	3	17	80
Rotations with Fallow	0	11	89	5	30	65	3	27	70
Low Residue Ag.	0	0	100	1	2	97	1	7	92

Climate regions: subtropical temperate dry (STD), subtropical temperate moist (STM), warm temperate dry (WTD), warm temperate moist (WTM), cold temperate dry (CTD), and cold temperate moist (CTM).

[1] Including Adjustments for Long-term Adoption of No-till Agriculture

[2] No-till includes CTIC survey data designated as no-tillage.

[3] Reduced-till includes CTIC survey data designated as ridge tillage, mulch tillage, and reduced tillage.

[4] Conventional till includes CTIC survey data designated as intensive tillage and conventional tillage.

[5] Medium and high input rotations (based on the IPCC categories) found in Table B-9. CTIC survey data for corn, soybeans, and sorghum were used in this category.

[6] Rotations with fallow found in Table B-9. CTIC survey data on fallow and small grain cropland were used in this category.

[7] Low input rotations found in Table 3, with the exception of rotations with fallow. CTIC survey data on cotton were used in this category; tillage rates are assumed to be the same for low residue crops and vegetables in rotation.

which reports tillage practices by major crops and county on an annual basis (Table 3-7). Data for wetland restoration under the CRP program were obtained from Euliss and Gleason (2002).

Organic soils (i.e., peat, mucks) that have been drained and converted to cropland or pasture use are subject to potentially high rates of carbon loss. Annual C losses were estimated using IPCC (1997) methodology except that U.S. specific carbon loss rates were used in the calculations instead of the default IPCC rates (Ogle et al. 2003).

Limestone and dolomite are often applied to acidic soils to raise the pH. However, CO_2 is emitted when these materials degrade. Emissions were estimated using a Tier 2 approach. Application rates were derived from estimates and industry sources (Minerals Yearbook, published by the Bureau of Mines through 1994 and by the U.S. Geological Survey from 1994 to present). The emission factors used, 0.059 ton CO_2-C/1 ton limestone and 0.064 ton CO_2-C/1 ton dolomite, are lower than the default IPCC emission factors because they account for a portion of limestone that may leach through soils and travel through waterways to the ocean (West and McBride 2005). The methodology summarized above is described in detail chapter 7 of the U.S. GHG Inventory (EPA 2007).

3.7 Uncertainty in Estimating Carbon Stock Changes in Agricultural Soils

Uncertainty was calculated separately for the Tier 3 and Tier 2 approaches used to estimate CO_2 fluxes. The methodologies summarized below are described in detail in Chapter 7 and Annex 3.13 of the U.S. GHG Inventory (EPA 2007).

3.7.1 Tier 3 Approach for Cropped Mineral Soils Simulated by CENTURY

As estimated by the CENTURY model, mineral soils on which major crops are grown sequestered ~66 Tg CO_2 eq. in 2005 with a 95 % confidence interval of +/- 16%. This uncertainty has three components: Monte Carlo approach to address uncertainties in CENTURY model inputs, an empirical approach to address structural uncertainty inherent in the model, and scaling uncertainty associated the NRI survey data. For model input uncertainty, probability distribution functions were developed for fertilizer rates, manure application, and tillage practices. A Monte Carlo analysis was conducted with 100 iterations in which input values were randomly drawn from the probability density functions to simulate the soil carbon stocks for each NRI cluster of points using CENTURY. An empirically based estimator was used to assess model structural error. This estimator was derived from a linear effects mixing model analysis of comparisons between modeled soil carbon stocks and measurements from 45 long-term experiments with over 800 treatments representing a variety of cropping, fertilizer, and tillage management practices (Ogle et al. 2006a). The model included variables that accounted for significant biases (alpha level of 0.05) in CENTURY model estimates. For each carbon stock estimate form the Monte Carlo simulations, the structural uncertainty estimator was applied to adjust the model output for bias and prediction error. Uncertainty in land use statistics from the NRI was incorporated based on the sampling variance of the cluster of NRI points.

3.7.2 Tier 2 Approach for Remaining Cropped Mineral Soils, Organic Soils, and Liming

As estimated by Tier 2 methodology, mineral soils not simulated by CENTURY sequestered ~0.5 Tg CO_2 eq. in 2005 with a 95 % confidence interval of –830 % and +832% and organic soils emitted 30.3 Tg CO_2 eq. in 2005 with a 95 % confidence interval of –39 % and +31 %. A Monte Carlo approach was used to simulate a range of values with 50,000 iterations by selecting values form probability distribution functions (Ogle et al. 2003). For mineral soils, probability distribution functions were derived form a synthesis of 91 published studies that addressed the impact of land management on soil carbon stock changes. For organic soils, probability distribution functions for emission factors were derived form a synthesis of 10 studies and combined with uncertainties in the NRI land use data for organic soils.

As estimated by Tier 2 methodology, liming of soils led to emissions of ~4.0 Tg CO_2 eq. in 2005 with a 95 % confidence interval of –94 % and +96 %. Uncertainty in the emissions factors and uncertainty in data for agricultural use of limestone and dolomite were included in the analysis.

3.7.3 Combined Uncertainties

Uncertainties for the above components were combined using simple error propagation (IPCC 2006). That is, the combined uncertainty was calculated by taking the square root of the sum of the squares of the standard deviations of the components. The combined 95 % confidence interval for CO_2 storage in cropped soils in 2005 ranged from 17 to 50 Tg CO_2 eq.around the estimate of 32.2 Tg CO_2 eq. (Table 3-1).

3.8 Mitigation of CO_2 Emissions

Currently, cropped soils in the U.S. are estimated to be storing carbon at the rate of approximately 30 Tg CO_2 per year. However, the potential to store carbon is thought to be much higher, e.g., Sperow et al. (2003) estimated a potential of 220 – 255 Tg CO_2 per year. To estimate mitigation potential for this report, the amount of land currently under different land management categories and land management changes were considered. Currently, the majority of cropped land in the U.S. is fully tilled (Table 3-7). Full tillage usually does not lead to carbon storage because tillage enhances decomposition of soil organic matter. Thus, reduction in tillage intensity provides on opportunity to store carbon. Other strategies to increase soil carbon considered here are: reduced cropping of organic soils, reduced summer fallow, increased land in CRP, and increased use of hay or pasture in crop rotations. Organic soils provide an opportunity to mitigate emissions because they make up less than 1 % of total cropped land in the U.S. (Table 3-8), but are a source of about 30 Tg CO_2 per year. Summer fallow tends to decrease soil carbon because during a large part of the growing season plants are not present to provide carbon inputs but decomposition of soil carbon by microbes continues. Cropped land converted to CRP stores carbon because the land is not cultivated and trees or grasses are planted to provide carbon inputs. Including hay or pasture in rotations also increases carbon inputs, and carbon losses are lower because the land is not tilled during the hay or pasture phase of the rotation.

Table 3-8 Cropland Area by Management Practice[1]

	Area	% of Total Cropland
Current Management	*million ha*	
Full Tillage	88.3	54.3 %
Reduced Tillage	28.0	17.2%
No Till	10.7	6.6%
Summer Fallow	19.0	11.7%
Hay/Pasture in Rotation	3.3	2%
Conservation Reserve Program	12.1	7.4%
Highly Erodable Lands	21.8	13.4%
Organic Soils	0.7	0.5%

[1] Categories are not mutually exclusive, e.g., land in summer fallow is also classified by tillage intensity.

CENTURY model simulations and IPCC Tier 2 methodologies were combined to estimate soil carbon stock changes for different land uses. NRI data were used to classify current land uses (Table 3-7). To estimate mitigation potential, 50% adoption with improved land use was assumed for the mitigation options considered. That is, 50% of the land in full tillage was assumed to be converted to minimum tillage, 50% of the land in minimum tillage was assumed to be converted to no till, 50% of land with summer fallow and 50% of land cropped on organic soils were assumed to be taken out of production, 50% of highly erodible lands were assumed to be converted to CRP, and 50% of crop rotations that currently do not include hay or pasture were assumed to be modified to include one or both of these in the rotation. All of these options stored large amounts of carbon except reduced summer fallow (Figure 3-8).

Together, adoption of these options could store ~104 Tg CO_2 per year; this is in addition to the ~32 Tg CO_2 per year stored currently in cropped soils. One hundred percent adoption would store a total of almost 240 Tg CO_2 per year. However, it must be pointed out that some of these strategies would affect the flux of other greenhouse gases and have other impacts. For example, taking organic soils out of production and allowing them to revert back to wetlands would store carbon but also increase methane emissions. Also, conversion to no till can increase N_2O emissions from some soils (Six et al. 2004) and sometimes lead to lower yields (Wilhelm & Wortmann 2004; Hammel et al. 1995; Lund et al. 1993), although these trends are far from universal and measures can be taken, e.g., improved nitrogen management and strip tillage, to eliminate or minimize these negative impacts. Also, it is probably not realistic to assume that 100% adoption of some strategies, such as including hay and pasture in rotations, is feasible because the extra hay produced would not necessarily be marketable.

Figure 3-8

Future Carbon Dioxide Mitigation Potential;
Adoption of Management Change by 50% of Farmers