7. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux[1] resulting from the uses and changes in land types and forests in the United States. The Intergovernmental Panel on Climate Change *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types, termed forest land, cropland, grassland, and settlements (as well as wetlands). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon (C) stocks, non-carbon dioxide (CO_2) emissions from forest fires, and the application of synthetic fertilizers to forest soils. The greenhouse gas flux reported in this chapter from agricultural lands (i.e., cropland and grassland) includes changes in organic C stocks in mineral and organic soils due to land use and management, and emissions of CO_2 due to the application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization. Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under *Other.*

The estimates in this chapter, with the exception of CO_2 fluxes from wood products and urban trees, and CO_2 emissions from liming and urea fertilization, are based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest C stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis from data collected in intervals ranging from 1 to 10 years. The resulting annual averages are applied to years between surveys. Calculations of non-CO_2 emissions from forest fires are based on forest CO_2 flux data. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. This flux has been applied to the entire time series, and periodic U.S. census data on changes in urban area have been used to develop annual estimates of CO_2 flux.

Land use, land-use change, and forestry activities in 2008 resulted in a net C sequestration of 940.3 Tg CO_2 Eq. (256.5 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 13.5 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net C sequestration[2] increased by approximately 3.4 percent between 1990 and 2008. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks. Net C accumulation in *Forest Land Remaining Forest Land*, *Land Converted to Grassland*, and *Settlements Remaining Settlements* increased, while net C

[1] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of C from the atmosphere. Removal of C from the atmosphere is also referred to as "carbon sequestration."

[2] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink. This is also referred to as net C sequestration.

Table 7-1: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	2000	2005	2006	2007	2008
Forest Land Remaining Forest Land[a]	(729.8)	(692.6)	(467.7)	(806.6)	(812.5)	(806.9)	(791.9)
Cropland Remaining Cropland	(29.4)	(22.9)	(30.2)	(18.3)	(19.1)	(19.7)	(18.1)
Land Converted to Cropland	2.2	2.9	2.4	5.9	5.9	5.9	5.9
Grassland Remaining Grassland	(52.0)	(26.7)	(52.6)	(9.0)	(8.9)	(8.8)	(8.7)
Land Converted to Grassland	(19.8)	(22.3)	(27.3)	(24.6)	(24.5)	(24.3)	(24.2)
Settlements Remaining Settlements[b]	(57.1)	(67.3)	(77.5)	(87.8)	(89.8)	(91.9)	(93.9)
Other (Landfilled Yard Trimmings and Food Scraps)	(23.5)	(13.9)	(11.3)	(10.1)	(10.3)	(9.8)	(9.5)
Total	**(909.4)**	**(842.9)**	**(664.2)**	**(950.4)**	**(959.2)**	**(955.4)**	**(940.3)**

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.
Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 7-2: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg C)

Sink Category	1990	1995	2000	2005	2006	2007	2008
Forest Land Remaining Forest Land[a]	(199.0)	(188.9)	(127.6)	(220.0)	(221.6)	(220.1)	(216.0)
Cropland Remaining Cropland	(8.0)	(6.3)	(8.2)	(5.0)	(5.2)	(5.4)	(4.9)
Land Converted to Cropland	0.6	0.8	0.6	1.6	1.6	1.6	1.6
Grassland Remaining Grassland	(14.2)	(7.3)	(14.3)	(2.5)	(2.4)	(2.4)	(2.4)
Land Converted to Grassland	(5.4)	(6.1)	(7.4)	(6.7)	(6.7)	(6.6)	(6.6)
Settlements Remaining Settlements[b]	(15.6)	(18.4)	(21.1)	(23.9)	(24.5)	(25.1)	(25.6)
Other (Landfilled Yard Trimmings and Food Scraps)	(6.4)	(3.8)	(3.1)	(2.8)	(2.8)	(2.7)	(2.6)
Total	**(248.0)**	**(229.9)**	**(181.2)**	**(259.2)**	**(261.6)**	**(260.6)**	**(256.5)**

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.
Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

accumulation in *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, and landfilled yard trimmings and food scraps slowed over this period. Emissions from *Land Converted to Cropland* increased between 1990 and 2008.

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. Liming of agricultural soils and urea fertilization in 2008 resulted in CO_2 emissions of 3.8 Tg CO_2 Eq. (3,831 Gg) and 3.8 Tg CO_2 Eq. (3,807 Gg), respectively. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 0.9 Tg CO_2 Eq. (941 Gg), and N_2O emissions of less than 0.01 Tg CO_2 Eq. The application of synthetic fertilizers to forest soils in 2008 resulted in direct N_2O emissions of 0.4 Tg CO_2 Eq. (1 Gg). Direct N_2O emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, direct N_2O emissions from fertilizer application to settlement soils in 2008 accounted for 1.6 Tg CO_2 Eq. (5 Gg) in 2008. This represents an increase of 61 percent since 1990. Forest fires in 2008 resulted in methane (CH_4) emissions of 11.9 Tg CO_2 Eq. (568 Gg), and in N_2O emissions of 9.7 Tg CO_2 Eq. (31 Gg).

Table 7-3: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	1990	1995	2000	2005	2006	2007	2008
CO_2	**8.1**	**8.1**	**8.8**	**8.9**	**8.8**	**9.3**	**8.6**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.4	4.3	4.3	4.2	4.5	3.8
Urea Fertilization	2.4	2.7	3.2	3.5	3.7	3.8	3.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.0	1.2	1.1	0.9	1.0	0.9
CH_4	**3.2**	**4.3**	**14.3**	**9.8**	**21.6**	**20.0**	**11.9**
Forest Land Remaining Forest Land: Forest Fires	3.2	4.3	14.3	9.8	21.6	20.0	11.9
N_2O	**3.7**	**4.9**	**13.2**	**9.8**	**19.5**	**18.3**	**11.7**
Forest Land Remaining Forest Land: Forest Fires	2.6	3.5	11.7	8.0	17.6	16.3	9.7
Forest Land Remaining Forest Land: Forest Soils[a]	0.1	0.2	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements: Settlement Soils[b]	1.0	1.2	1.1	1.5	1.5	1.6	1.6
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total	**15.0**	**17.2**	**36.3**	**28.6**	**49.8**	**47.6**	**32.2**

+ Less than 0.05 Tg CO_2 Eq.
[a] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land,* and *Land Converted to Forest Land,* but not from land-use conversion.
[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements,* and *Land Converted to Settlements,* but not from land-use conversion.
Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter.
Totals may not sum due to independent rounding.

Table 7-4: Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Source Category	1990	1995	2000	2005	2006	2007	2008
CO_2	**8,117**	**8,067**	**8,768**	**8,933**	**8,754**	**9,331**	**8,579**
Cropland Remaining Cropland: Liming of Agricultural Soils	4,667	4,392	4,328	4,349	4,220	4,512	3,831
Urea Fertilization	2,417	2,657	3,214	3,504	3,656	3,807	3,807
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,033	1,018	1,227	1,079	879	1,012	941
CH_4	**152**	**203**	**681**	**467**	**1,027**	**953**	**568**
Forest Land Remaining Forest Land: Forest Fires	152	203	681	467	1,027	953	568
N_2O	**12**	**16**	**43**	**32**	**63**	**59**	**38**
Forest Land Remaining Forest Land: Forest Fires	8	11	38	26	57	53	31
Forest Land Remaining Forest Land: Forest Soils[a]	+	1	1	1	1	1	1
Settlements Remaining Settlements: Settlement Soils[b]	3	4	4	5	5	5	5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

+ Less than 0.5 Gg.
[a] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land,* and *Land Converted to Forest Land,* but not from land-use conversion.
[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements,* and *Land Converted to Settlements,* but not from land-use conversion.
Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter.
Totals may not sum due to independent rounding.

7.1. Representation of the U.S. Land Base

A national land-use categorization system that is consistent and complete both temporally and spatially is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country; (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series associated with the greenhouse gas inventory, such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories; and (3) account for greenhouse gas fluxes on all managed lands. The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible. This section of the Inventory has been developed in order to comply with this guidance.

Multiple databases are used to track land management in the United States, are also used as the basis to classify U.S. land area into the six IPCC land-use categories (i.e., *Forest Land Remaining Forest Land*, *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, *Wetlands Remaining Wetlands*, *Settlements Remaining Settlements* and *Other Land Remaining Other Land*) and thirty land-use change categories (e.g., *Cropland Converted to Forest Land*, *Grassland Converted to Forest Land*, *Wetlands Converted to Forest Land*, *Settlements Converted to Forest Land*, *Other Land Converted to Forest Land*)[3] (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[4] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[5] Database. The U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD)[6] is also used to identify land uses in regions that were not included in the NRI or FIA. The total land area included in the U.S. Inventory is 786 million hectares, and this entire land base is considered managed.[7] In 2008 the United States had a total of 273 million hectares of Forest Land (a 4.1 percent increase since 1990), 163 million hectares of Cropland (down 4.4 percent since 1990), 259 million hectares of Grassland (down 4.3 percent since 1990), 27 million hectares of Wetlands (down 3.8 percent since 1990), 49 million hectares of Settlements (up 24.4 percent since 1990), and 14 million hectares of Other Land. It is important to note that the land base formally classified for the Inventory (see Table 7-5) is considered managed. Much of the unmanaged area in the United States (see definition later in this section) occurs in Alaska. Alaska is not formally included in the current land representation, but there is a planned improvement underway to include this portion of the United States in future Inventories. In addition, wetlands are not differentiated between managed and unmanaged, although some wetlands would be unmanaged according to the U.S. definition (see definition later in this section). Future improvements will include a differentiation between managed and unmanaged wetlands.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns, although all land-uses occur within each of the fifty states (Figure 7-1). Forest Land tends to be more common in the eastern states, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country. Settlements are more concentrated along the coastal margins and in the eastern states.

[3] Land-use category definitions are provided in the Methodology section.

[4] NRI data is available at <http://www.ncgc.nrcs.usda.gov/products/nri/index.html>.

[5] FIA data is available at <http://fia.fs.fed .us/tools-data/data/>.

[6] NLCD data is available at <http://www.mrlc.gov/>.

[7] The current land representation does not include areas from Alaska or U.S. territories, but there are planned improvements to include these regions in future reports.

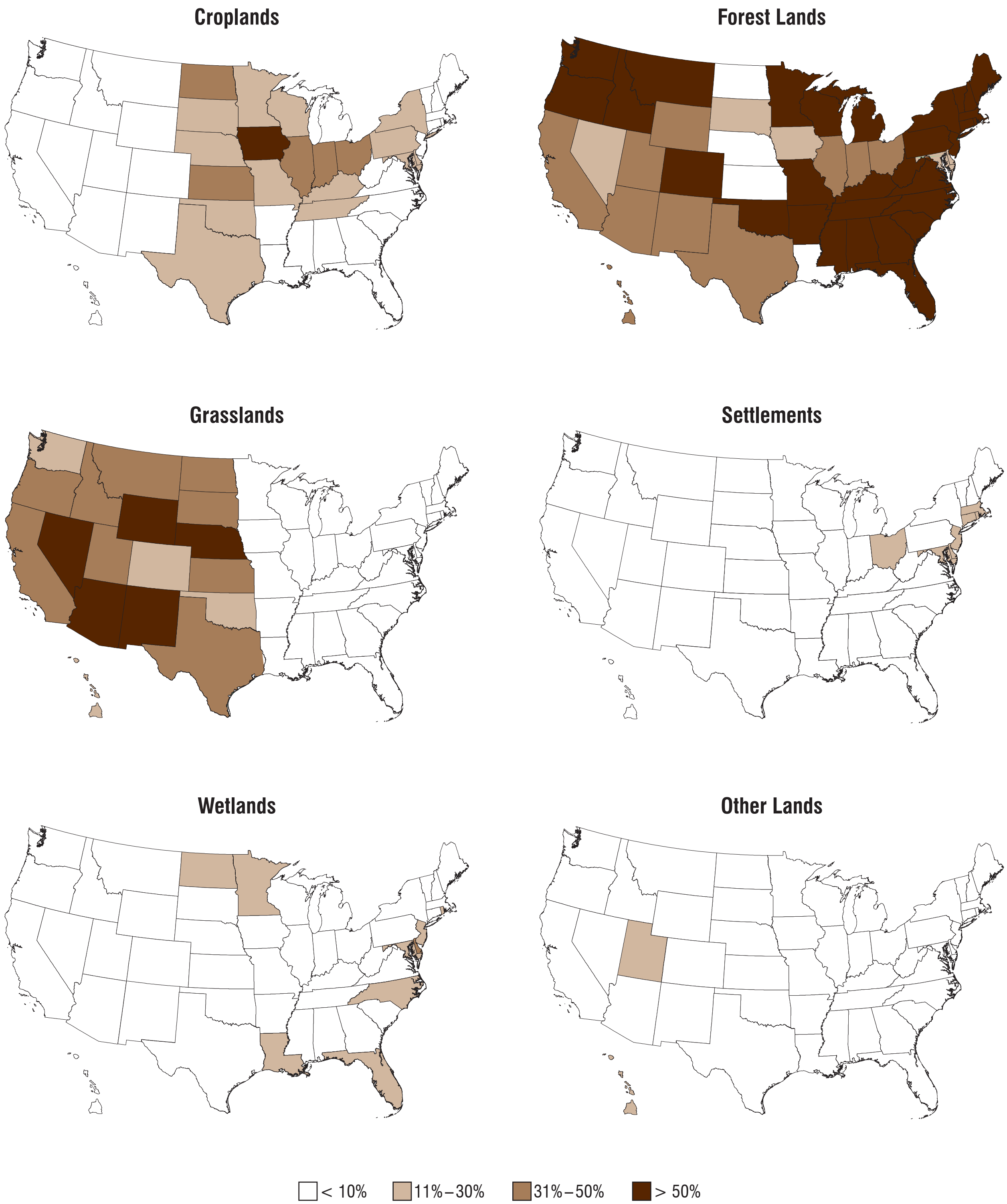
Table 7-5: Land Use, Land-Use Change, and Forestry on Managed Land (Thousands of Hectares)

Land Use, Land-Use Change Categories	1990	1995	2000	2005	2006	2007	2008
Total Forest Land	**262,625**	**265,753**	**268,247**	**271,169**	**271,889**	**272,609**	**273,329**
Forest Land Remaining Forest Land	255,922	254,772	252,529	255,309	255,997	256,686	257,375
Cropland Converted to Forest Land	1,267	1,890	2,793	2,975	2,981	2,986	2,992
Grassland Converted to Forest Land	4,883	8,056	11,354	11,111	11,136	11,160	11,184
Wetlands Converted to Forest Land	63	134	202	205	206	207	207
Settlements Converted to Forest Land	101	185	268	303	303	304	305
Other Lands Converted to Forest Land	390	716	1,101	1,266	1,266	1,266	1,266
Total Cropland	**170,661**	**168,484**	**164,391**	**163,182**	**163,170**	**163,159**	**163,147**
Cropland Remaining Cropland	155,462	149,337	143,995	145,521	145,510	145,500	145,489
Forest Land Converted to Cropland	1,105	1,289	1,101	805	805	804	804
Grassland Converted to Cropland	13,298	16,517	17,834	15,513	15,512	15,512	15,512
Wetlands Converted to Cropland	163	249	264	234	234	234	234
Settlements Converted to Cropland	470	869	886	825	825	825	825
Other Lands Converted to Cropland	162	223	311	283	283	283	283
Total Grassland	**270,658**	**266,081**	**263,601**	**260,694**	**260,173**	**259,653**	**259,132**
Grassland Remaining Grassland	261,096	253,167	245,932	243,862	243,411	242,960	242,509
Forest Land Converted to Grassland	1,459	2,067	3,057	2,802	2,794	2,786	2,778
Cropland Converted to Grassland	7,489	9,868	13,325	12,712	12,652	12,592	12,532
Wetlands Converted to Grassland	230	348	376	339	338	337	336
Settlements Converted to Grassland	129	227	255	255	254	253	252
Other Lands Converted to Grassland	255	404	657	724	724	724	724
Total Wetlands	**27,821**	**27,508**	**27,552**	**27,206**	**27,055**	**26,903**	**26,751**
Wetlands Remaining Wetlands	27,213	26,607	26,144	25,728	25,584	25,439	25,293
Forest Land Converted to Wetlands	137	249	380	403	401	399	397
Cropland Converted to Wetlands	134	225	347	352	350	348	345
Grassland Converted to Wetlands	286	401	635	675	673	671	669
Settlements Converted to Wetlands	+	+	3	3	3	3	3
Other Lands Converted to Wetlands	51	25	43	44	44	44	44
Total Settlements	**39,559**	**43,356**	**47,565**	**49,249**	**49,241**	**49,233**	**49,225**
Settlements Remaining Settlements	34,783	34,383	34,062	34,977	34,969	34,961	34,953
Forest Lands Converted to Settlements	1,842	3,561	5,480	5,872	5,872	5,872	5,872
Cropland Converted to Settlements	1,373	2,518	3,599	3,672	3,672	3,672	3,672
Grassland Converted to Settlements	1,498	2,756	4,183	4,479	4,479	4,479	4,478
Wetlands Converted to Settlements	3	9	29	32	32	32	32
Other Lands Converted to Settlements	60	128	212	217	217	217	217
Total Other Land	**14,519**	**14,663**	**14,489**	**14,345**	**14,317**	**14,289**	**14,261**
Other Lands Remaining Other Lands	13,531	12,974	12,331	12,103	12,076	12,049	12,022
Forest Land Converted to Other Lands	193	321	506	559	559	559	559
Cropland Converted to Other Lands	279	385	440	499	499	499	499
Grassland Converted to Other Lands	458	888	1,086	1,058	1,057	1,057	1,056
Wetlands Converted to Other Lands	55	88	115	114	114	114	113
Settlements Converted to Other Lands	3	7	11	12	12	12	12
Grand Total	**785,845**	**785,845**	**785,845**	**785,845**	**785,845**	**785,845**	**785,845**

+ Does not exceed one thousand hectares.
Note: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands which includes both managed and unmanaged lands based on the definitions for the current U.S. Land Representation Assessment. In addition, U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See Planned Improvements for discussion on plans to include Alaska and territories in future Inventories.

Figure 7-1

Percent of Total Land Area in the General Land Use Categories for 2008



Note: Land use/land-use change categories were aggregated into the 6 general land-use categories based on the current use in 2008.

Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, Grassland to Cropland, etc.), using surveys or other forms of data that do not provide location data on specific parcels of land. Approach 3 extends Approach 2 by providing location data on specific parcels of land, such as maps, along with the land-use history. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. All of these datasets have a spatially-explicit time series of land-use data, and therefore Approach 3 is used to provide a full representation of land use in the U.S. Inventory. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use-change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The U.S. definitions of managed and unmanaged lands are similar to the basic IPCC (2006) definition of managed land, but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community or societal objectives. Managed land also includes legal protection of lands (e.g., wilderness, preserves, parks, etc.) for conservation purposes (i.e., meets societal objectives).[8]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to human intervention due to the remoteness of the locations, or lands with essentially no development interest or protection due to limited personal, commercial or social value. Though these lands may be influenced indirectly by human actions such as atmospheric deposition of chemical species produced in industry, they are not influenced by a direct human intervention.[9]

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect U.S. circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition

[8] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands is difficult, however, due to limited data availability. Wetlands are not characterized by use within the NRI. Therefore, unless wetlands are managed for cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. See the Planned Improvements section of the Inventory for work being done to refine the Wetland area estimates.

[9] There will be some areas that qualify as Forest Land or Grassland according to the land use criteria, but are classified as unmanaged land due to the remoteness of their location.

of Forest Land is based on the FIA definition of forest,[10] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[11] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 36.6 m wide and 0.4 ha in size with at least 10 percent cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 36.6 m and continuous length of at least 110.6 m to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 36.6 m wide or 0.4 ha in size, otherwise they are excluded from Forest Land and classified as Settlements. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land (Smith et al. 2009). NOTE: This definition applies to all U.S. lands and territories. However, at this time, data may be limited or based solely on remote sensing in some areas, such as western Texas, western Oklahoma, and interior Alaska.
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest, this category includes both cultivated and non-cultivated lands.[12] Cultivated crops include row crops or close-grown crops and also hay or pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with alley cropping and windbreaks,[13] as well as lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides).[14] Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.
- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands.[15] This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Savannas, some wetlands and deserts, in addition to tundra are considered Grassland.[16] Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices such as silvipasture and windbreaks, assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland area estimates and are, instead, classified as Settlements.
- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are

[10] See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

[11] See <http://www.nrcs.usda.gov/technical/land/nri01/glossary.html>.

[12] A minor portion of Cropland occurs on federal lands, and is not currently included in the C stock change inventory. A planned improvement is underway to include these areas in future C inventories.

[13] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

[14] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees.

[15] Grasslands on federal lands are included in the managed land base, but C stock changes are not estimated on these lands. Federal grassland areas have been assumed to have negligible changes in C due to limited land use and management change, but planned improvements are underway to further investigate this issue and include these areas in future C inventories.

[16] IPCC (2006) guidelines do not include provisions to separate desert and tundra as land categories.

covered in other areas of the IPCC guidance and/or the inventory, including Cropland (e.g., rice cultivation), Grassland, and Forest Land (including drained or undrained forested wetlands).

- *Settlements*: A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the settlement category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, non-settlement transportation corridors, and all land areas that do not fall into any of the other five land-use categories. It allows the total of identified land areas to match the managed national area.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main data sources for land area and use data in the United States are the NRI, FIA, and the NLCD. For the Inventory, the NRI is the official source of data on all land uses on non-federal lands (except forest land), and is also used as the resource to determine the total land base for the conterminous United States and Hawaii. The NRI is conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160-acre (64.75 ha) square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands, and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. This Inventory incorporates data through 2003 from the NRI.

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for forest land. Historically, FIA inventory surveys had been conducted periodically, with all plots in a state being measured at a frequency of every 5 to 14 years. A new national plot design and annual sampling design was introduced by FIA about ten years ago. Most states, though, have only recently been brought into this system. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every 5 years. See Annex 3.12 to see the specific survey data available by state. The most recent year of available data varies state by state (2002 through 2008).

Though NRI provides land-area data for both federal and non-federal lands, it only includes land-use data on non-federal lands, and FIA only records data for forest land.[17] Consequently, major gaps exist when the datasets are combined, such as federal grassland operated by the Bureau of Land Management (BLM), USDA, and National Park Service, as well as most of Alaska.[18] Consequently, the NLCD is used as a supplementary database to account for land use on federal lands that are not included in the NRI and FIA databases. The NLCD is a land-cover classification scheme, available for 1992 and 2001, that has been applied over the conterminous United States. The 2001 product also provides land use data that has been used for Hawaii federal lands. For this analysis, the NLCD Retrofit Land Cover Change Product was used in order to represent both land use and land-use change for federal lands in the conterminous United States. It is based primarily on Landsat Thematic Mapper imagery. The NLCD contains 21 categories of land-cover information, which have been aggregated into the IPCC land-use categories, and the data are available at a spatial resolution of 30 meters. The federal land portion of the NLCD was extracted from the dataset using the federal land area boundary map from the National Atlas.[19] This map represents federal land boundaries in 2005, so as part of the analysis, the federal land area was adjusted annually based on the NRI federal land area estimates (i.e., land is periodically transferred between federal and non-federal ownership). Consequently, the portion of the land base categorized with NLCD data varied from year to year, corresponding to an increase or decrease in the federal land base. The NLCD is strictly a source of land-cover information, however, and does not provide the necessary site conditions, crop types, and management information from which to estimate C stock changes on those lands.

Another step in the analysis is to address gaps as well as overlaps in the representation of the U.S. land base between the Agricultural Carbon Stock Inventory (*Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*) and Forest Land Carbon Stock Inventory (*Forest Land Remaining Forest Land* and *Land Converted to Forest Land*), which are based on the NRI and FIA databases, respectively. NRI and FIA have different criteria for classifying forest land, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Moreover, dependence exists between the Forest Land area and the amount of land designated as other land uses in both the NRI and the NLCD, such as the amount of Grassland, Cropland, and Wetlands, relative to the Forest Land area. This results in inconsistencies among the three databases for estimated Forest Land area, as well as for the area estimates for other land-use categories. FIA is the main database for forest statistics, and consequently, the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. The adjustments were made at a state-scale, and it was assumed that the majority of the discrepancy in forest area was associated with an under- or over-prediction of Grassland and Wetland area in the NRI and NLCD due to differences in Forest Land definitions. Specifically, the Forest Land area for a given state according to the NRI and NLCD was adjusted to match the FIA estimates of Forest Land for non-federal and federal land, respectively. In a second step, corresponding increases or decreases were made in the area estimates of Grassland and Wetland from the NRI and NLCD, in order to balance the change in forest area, and therefore not change the overall amount of managed land within an individual state. The adjustments were based on the proportion of land within each of these land-use categories at the state-level. (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area and vice versa).

As part of Quality Assurance/Quality Control (QA/QC), the land base derived from the NRI, FIA and NLCD was compared to the U.S. Census Survey.[20] The U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The land area estimates from the U.S. Census Bureau differ from those provided by the land-use surveys used in the Inventory because of discrepancies in the reporting approach for the census and the methods used in the NRI, FIA, and NLCD. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey. More importantly, the U.S. Census Survey does not provide

[17] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[18] The survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for U.S. Territories.

[19] See <http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound>.

[20] See <http://www.census.gov/geo/www/tiger>.

a time series of land-use change data or land management information, which is critical for conducting emission inventories and is provided from the NRI and FIA surveys. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI data were adopted because this database provides full coverage of land area for the conterminous United States and Hawaii. Regardless, the total difference between the U.S. Census Survey and the data sources used in the Inventory is about 25 million hectares for the total land base of about 786 million hectares currently included in the Inventory, or a 3.1 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes. NRI does not include as much of the area of open waters in these regions as the U.S. Census Survey.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the six IPCC land-use categories using definitions[21] developed to meet national circumstances, while adhering to IPCC (2006). In practice, the land was initially classified into a variety of land-use categories using the NRI, FIA and NLCD, and then aggregated into the thirty-six broad land use and land-use-change categories identified in IPCC (2006). Details on the approach used to combine data sources for each land use are described below as are the gaps that will be reconciled as part of ongoing planned improvements:

- *Forest Land*: Both non-federal and federal forest lands in both the continental United States and coastal Alaska are covered by FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land. Interior Alaska is not currently surveyed by FIA, but NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports. Forest Lands in U.S. territories are currently excluded from the analysis, but FIA surveys are currently being conducted on U.S. territories and will become available in the future. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii. Currently, federal forest land in Hawaii is evaluated with the 2001 NLCD, but FIA data will be collected in Hawaii in the future.
- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate C stocks and fluxes on Cropland. Croplands in U.S. territories are excluded from both NRI data collection and the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate C stocks and fluxes on Grassland. U.S. territories are excluded from both NRI data collection and the current release of the NLCD product. Grassland on federal Bureau of Land Management lands, Department of Defense lands, National Parks and within USFS lands are covered by the NLCD In addition, federal and non-federal grasslands in Alaska are currently excluded from the analysis, but NLCD has a new product for Alaska that will be incorporated into the assessment for future reports.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands are covered by the NLCD. Alaska and U.S. territories are excluded. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See Planned Improvements for details.
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size,

[21] Definitions are provided in the previous section.

a forested area is classified as non-forest by FIA if it is located within an urban area. Settlements on federal lands are covered by NLCD. Settlements in U.S. territories are currently excluded from NRI and NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.

- *Other Land*: Any land not falling into the other five land categories and, therefore, categorized as Other Land is classified using the NRI for non-federal areas in the 49 states (excluding Alaska) and NLCD for the federal lands. Other land in U.S. territories is excluded from the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is initiated by distinguishing between managed and unmanaged lands. The managed lands are then assigned, from highest to lowest priority, in the following manner:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage or fiber. The consequence of this ranking is that crops in rotation with grass will be classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands that are used for rice production are considered Croplands. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a single land use. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a Wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, Wetlands are classified as Cropland if they are used to produce a crop, such as rice. In either case, emissions from Wetlands are included in the Inventory if human interventions are influencing emissions from Wetlands, in accordance with the guidance provided in IPCC (2006).

Recalculations Discussion

One major revision was made in the current Inventory for land representation; the time series for Forest Land was updated with a new release of data from the FIA. The updated time series also influenced the time series for Grassland and Wetlands, which are adjusted in the process of combining FIA data with NRI and NLCD (see previous section entitled "U.S. Land-Use Data Sources" for more information on the process of combining these datasets).

Planned Improvements

Area data by land-use category are not estimated for major portions of Alaska or any of the U.S. territories. A key planned improvement is to incorporate land-use data from these areas into the Inventory. For Alaska, a new NLCD 2001 data product will be used to cover those land areas presently omitted. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting is a key goal for the near future. Data sources will also be evaluated for representing land use on federal and non-federal lands in U.S. territories.

Additional work will be done to reconcile differences in Forest Land estimates between the NRI and FIA, evaluating the assumption that the majority of discrepancies in Forest Land areas are associated with an over- or under-estimation of Grassland and Wetland area. In some regions of the United

States, a discrepancy in Forest Land areas between NRI and FIA may be associated with an over- or under-prediction of other land uses.

There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements and Wetlands. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990 and 2000 U.S. Census data). Using the population statistics, "urban clusters" are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an urban forest inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas. For Wetlands, the Army Corps of Engineers National Inventory of Dams (NID) (ACE 2005) and the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI)[22] databases are being evaluated and will be compared against the NRI and NLCD. The NID and NWI may be used to refine Wetlands area estimates for the U.S. Land Representation assessment, including disaggregation of managed and unmanaged Wetlands.

7.2. Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating C stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2003):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the aboveground pools.

In addition, there are two harvested wood pools necessary for estimating C flux:

- Harvested wood products in use, and
- Harvested wood products in solid waste disposal sites (SWDS).

Carbon is continuously cycled among these storage pools and between forest ecosystems and the atmosphere as a result of biological processes in forests (e.g., photosynthesis, respiration, growth, mortality, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, clearing, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere or transferred to the soil by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of C of all vegetation C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 when the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately. Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS.

[22] See <http://www.fws.gov/nwi/>.

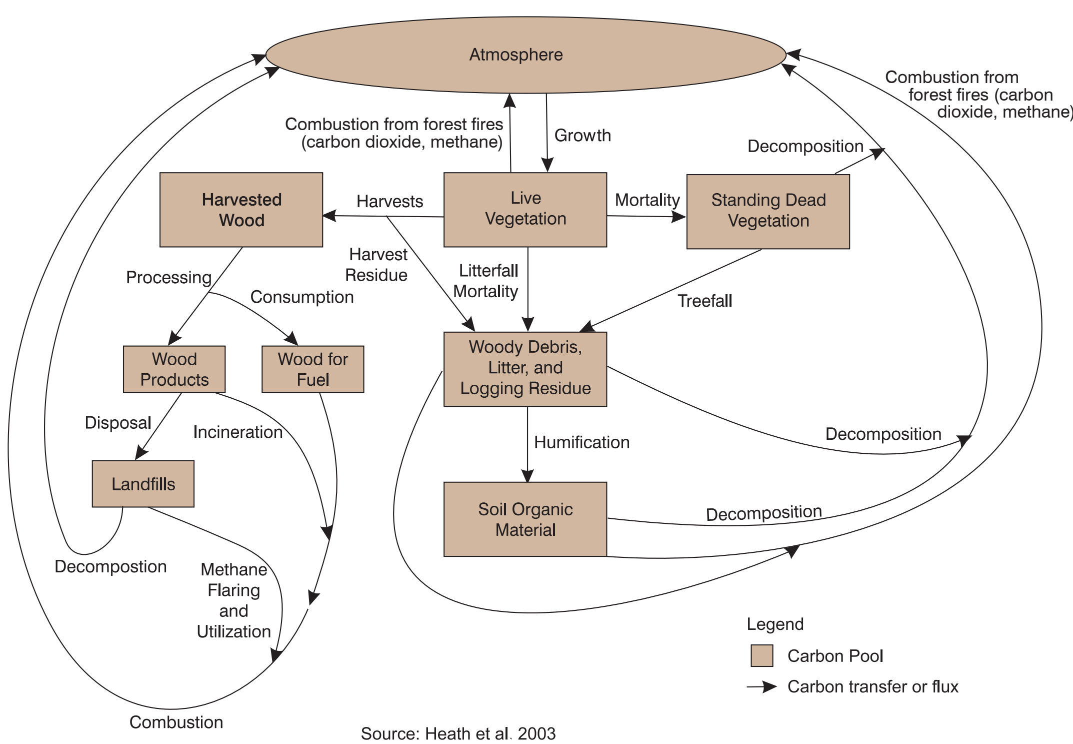
This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Disturbances from forest fires and pest outbreaks are implicitly included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. The change between inventories thus accounts for the C changes due to fires; however, it may not be possible to attribute the changes to the disturbance specifically. The IPCC (2003) recommends reporting C stocks according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Currently, consistent datasets are just becoming available for the conterminous United States to allow forest land conversions and forest land remaining forest land to be identified, and research is ongoing to properly use that information based on research results. Thus, net changes in all forest-related land, including non-forest land converted to forest and forests converted to non-forest, are reported here.

Forest C storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 7-2. In the figure, boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere. Note that the boxes are not identical to the storage pools identified in this chapter. The storage pools identified in this chapter have been refined in this graphic to better illustrate the processes that result in transfers of C from one pool to another, and emissions to as well as uptake from the atmosphere.

Approximately 33 percent (304 million hectares) of the U.S. land area is forested (Smith et al. 2009). The current forest inventory includes 270 million hectares in the conterminous 48 states (USDA Forest Service 2009a, 2009b) that are considered managed and are included in this Inventory. The additional 34 million hectares of forest land are located in Alaska and Hawaii. Of this forest area outside the conterminous United States, 6.2 million hectares of southeast and south central Alaskan forest are inventoried and are included here. Survey data are not yet available from

Figure 7-2

Forest Sector Carbon Pools and Flows



Source: Heath et al. 2003

Hawaii. While Hawaii and U.S. territories have relatively small areas of forest land and will thus probably not influence the overall C budget substantially, these regions will be added to the C budget as sufficient data become available. Agroforestry systems are also not currently accounted for in the Inventory, since they are not explicitly inventoried by either the Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service or the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

Sixty-eight percent of U.S. forests (208 million hectares) are classified as timberland, meaning they meet minimum levels of productivity. Nine percent of Alaska forests overall and 81 percent of forests in the conterminous United States are classified as timberlands. Of the remaining nontimberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 66 million hectares are lower productivity forest lands (Smith et al. 2009). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

Forest land area declined by approximately 10 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 12 million hectares. Current trends in forest area represent average annual change of less than 0.2 percent. Given the low rate of change in U.S. forest land area, the major influences on the current net C flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems. For example, intensified management of forests that leads to an increased rate of growth increases the eventual biomass density of the forest, thereby increasing the uptake of C.[23] Though harvesting forests removes much of the aboveground C, on average the volume of annual net growth nationwide is about 32 percent higher than the volume of annual removals (USDA Forest Service 2009d). The reversion of cropland to forest land increases C storage in biomass, forest floor, and soils. The net effects of forest management and the effects of land-use change involving forest land are captured in the estimates of C stocks and fluxes presented in this chapter.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2008. The rate of forest clearing begun in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes

Table 7-6: Net Annual Changes in C Stocks (Tg CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2005	2006	2007	2008
Forest	**(598.1)**	**(574.2)**	**(354.8)**	**(701.2)**	**(703.9)**	**(703.9)**	**(703.9)**
Aboveground Biomass	(377.7)	(398.3)	(309.3)	(397.2)	(397.2)	(397.2)	(397.2)
Belowground Biomass	(74.5)	(79.3)	(61.7)	(78.8)	(78.8)	(78.8)	(78.8)
Dead Wood	(29.4)	(31.0)	(15.8)	(23.4)	(26.2)	(26.2)	(26.2)
Litter	(46.5)	(28.3)	3.4	(55.9)	(55.9)	(55.9)	(55.9)
Soil Organic Carbon	(70.0)	(37.2)	28.7	(145.9)	(145.9)	(145.9)	(145.9)
Harvested Wood	**(131.8)**	**(118.4)**	**(112.9)**	**(105.4)**	**(108.6)**	**(103.0)**	**(88.0)**
Products in use	(64.8)	(55.2)	(47.0)	(45.4)	(45.1)	(39.1)	(24.4)
SWDS	(67.0)	(63.2)	(65.9)	(59.9)	(63.4)	(63.8)	(63.6)
Total Net Flux	**(729.8)**	**(692.6)**	**(467.7)**	**(806.6)**	**(812.5)**	**(806.9)**	**(791.9)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Forest area estimates are based on interpolation and extrapolation of inventory data as described in the text and in Annex 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

[23] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent C by weight.

Table 7-7: Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2005	2006	2007	2008
Forest	**(163.1)**	**(156.6)**	**(96.8)**	**(191.2)**	**(192.0)**	**(192.0)**	**(192.0)**
Aboveground Biomass	(103.0)	(108.6)	(84.4)	(108.3)	(108.3)	(108.3)	(108.3)
Belowground Biomass	(20.3)	(21.6)	(16.8)	(21.5)	(21.5)	(21.5)	(21.5)
Dead Wood	(8.0)	(8.5)	(4.3)	(6.4)	(7.1)	(7.1)	(7.1)
Litter	(12.7)	(7.7)	0.9	(15.2)	(15.2)	(15.2)	(15.2)
Soil Organic Carbon	(19.1)	(10.1)	7.8	(39.8)	(39.8)	(39.8)	(39.8)
Harvested Wood	**(35.9)**	**(32.3)**	**(30.8)**	**(28.7)**	**(29.6)**	**(28.1)**	**(24.0)**
Products in use	(17.7)	(15.1)	(12.8)	(12.4)	(12.3)	(10.7)	(6.7)
SWDS	(18.3)	(17.2)	(18.0)	(16.3)	(17.3)	(17.4)	(17.3)
Total Net Flux	**(199.0)**	**(188.9)**	**(127.6)**	**(220.0)**	**(221.6)**	**(220.1)**	**(216.0)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 7-8: Forest Area (1000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

	1990	1995	2000	2005	2006	2007	2008	2009
Forest Area (1000 ha)	**267,986**	**271,194**	**273,767**	**276,796**	**277,536**	**278,276**	**279,016**	**279,756**
Carbon Pools (Tg C) Forest	**42,540**	**43,332**	**43,973**	**44,762**	**44,953**	**45,145**	**45,337**	**45,529**
Aboveground Biomass	15,027	15,550	16,030	16,529	16,637	16,745	16,854	16,962
Belowground Biomass	2,986	3,089	3,185	3,284	3,305	3,327	3,348	3,370
Dead Wood	2,949	2,990	3,025	3,053	3,059	3,066	3,073	3,080
Litter	4,755	4,812	4,831	4,880	4,895	4,910	4,925	4,941
Soil Organic C	16,823	16,890	16,902	17,016	17,056	17,096	17,136	17,176
Harvested Wood	**1,859**	**2,029**	**2,187**	**2,325**	**2,354**	**2,383**	**2,412**	**2,436**
Products in Use	1,231	1,311	1,382	1,436	1,448	1,460	1,471	1,478
SWDS	628	718	805	890	906	923	941	958
Total C Stock	**44,399**	**45,361**	**46,161**	**47,087**	**47,307**	**47,528**	**47,748**	**47,964**

Note: Forest area estimates include portions of managed forests in Alaska for which survey data are available. Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest area estimates are based on interpolation and extrapolation of inventory data as described in Smith et al. (2010) and in Annex 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Inventories are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2006 requires estimates of C stocks for 2006 and 2007.

from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forests is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere (Skog and Nicholson 1998, Skog 2008). The size of these long-term C storage pools has increased during the last century.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 792 Tg CO_2 Eq. (216 Tg C) in 2008 (Table 7-6, Table 7-7, Table 7-8, and Figure 7-3). In addition to the net accumulation of C in harvested wood pools, sequestration is a reflection of net forest growth and increasing forest area over this period. Overall, average C in forest ecosystem biomass (aboveground and belowground) increased from 67 to 73 Mg

C/ha between 1990 and 2009 (see Annex 3-12 for average C densities by specific regions and forest types). Continuous, regular annual surveys are not available over the period for each state; therefore, estimates for non-survey years were derived by interpolation between known data points. Survey years vary from state to state, and national estimates are a composite of individual state surveys. Therefore, changes in sequestration over the interval 1990 to 2008 are the result of the sequences of new inventories for each state. C in forest ecosystem biomass had the greatest effect on total change through increases in C density and total forest land. Management practices that increase C stocks on forest land, as well as afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land in the United States.

Stock estimates for forest and harvested wood C storage pools are presented in Table 7-8. Together, the aboveground live and forest soil pools account for a large proportion of total forest C stocks. C stocks in all non-soil pools increased over time. Therefore, C sequestration was greater than C emissions from forests, as discussed above. Figure 7-4 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

Figure 7-3

Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools

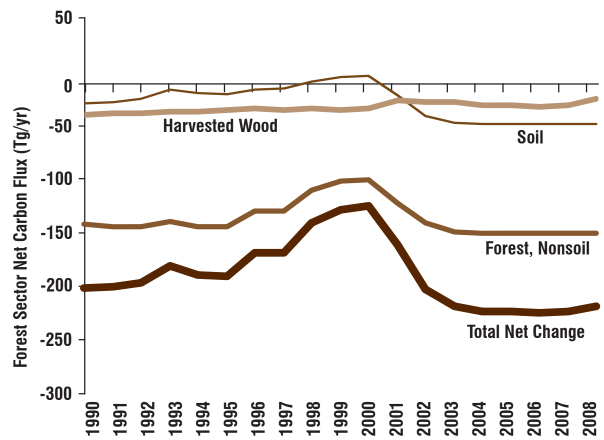
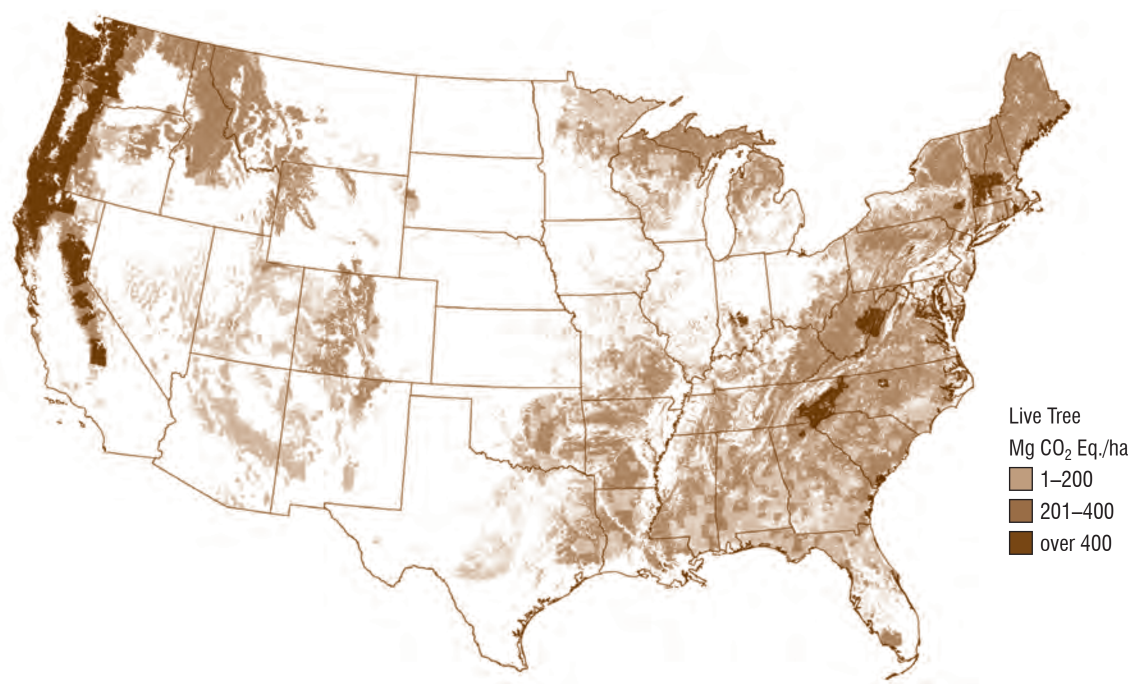


Figure 7-4

Average C Density in the Forest Tree Pool in the Conterminous United States, 2008



Box 7-1: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for emissions due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forestland already account for CO_2 emissions from forest fires occurring in the lower 48 states as well as in the proportion of Alaska's managed forest land captured in this Inventory. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these estimates are being highlighted here, using the full extent of available data. Non-CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

Table 7-9: Estimates of CO_2 (Tg/yr) Emissions for the Lower 48 States and Alaska[a]

Year	CO_2 Emitted from Wildfires in Lower 48 States (Tg/yr)	CO_2 Emitted from Prescribed Fires in Lower 48 States (Tg/yr)	CO_2 Emitted from Wildfires in Alaska (Tg/yr)	Total CO_2 Emitted (Tg/yr)
1990	42.1	8.5	+	50.7
1995	58.4	9.4	+	67.8
2000	225.1	2.1	+	227.3
2005	131.0	24.8	+	155.9
2006	313.6	29.3	+	342.9
2007	284.1	34.0	+	318.0
2008	168.9	20.8	+	189.7

\+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Note that these emissions have already been accounted for in the estimates of net annual changes in C stocks, which account for the amount sequestered minus any emissions.

The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate CO_2 emissions from forest fires. Carbon dioxide emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2008 were estimated to be 189.7 Tg CO_2/yr. This amount is masked in the estimate of net annual forest carbon stock change for 2008, however, because this net estimate accounts for the amount sequestered minus any emissions.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2003, 2006) and IPCC/UNEP/OECD/IEA (1997). Forest ecosystem C stocks and net annual C stock change are determined according to stock-difference methods, which involve applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. Harvested wood C estimates are based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems or harvested wood products is provided here. See Annex 3.12 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

Forest ecosystem stock and flux estimates are based on the stock-difference method and calculations for all estimates are in units of C. Separate estimates are made for the five IPCC C storage pools described above. All estimates are based on data collected from the extensive array of permanent forest inventory plots in the United States as well as models employed to fill gaps in field data. Carbon conversion factors are applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. A combination of tiers as outlined by IPCC (2006) is used. The Tier 3 biomass C values are from forest inventory tree-level data. The Tier 2 dead organic and soil C pools are based on empirical or process models from the inventory data. All carbon conversion factors are specific to regions or individual states within the United States, which are further classified according to characteristic forest types within each region.

The first step in developing forest ecosystem estimates is to identify useful inventory data and resolve any inconsistencies among datasets. Forest inventory data were obtained from the USDA Forest Service FIA program (Frayer and Furnival 1999, USDA Forest Service 2009b). Inventories include data collected on permanent inventory plots on forest lands[24] and are organized as a number of separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Some of the more recent annual inventories reported for some states include "moving averages" which means that a portion—but not all—of the previous year's Inventory is updated each year (USDA Forest Service 2009d). Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state. All available data sets are identified for each state starting with pre-1990 data, and all unique surveys are included.[25] Since C stock change is based on differences between successive surveys within each state, accurate estimates of net C flux thus depend on consistent representation of forest land between these successive inventories. In order to achieve this consistency from 1990 to the present, states are sometimes subdivided into sub-state areas where the sum of sub-state inventories produces the best whole-state representation of C change as discussed in Smith et al. (2007).

The principal FIA datasets employed are freely available for download at USDA Forest Service (2009b) as the Forest Inventory and Analysis Database (FIADB) Version 4.0. However, to achieve consistent representation (spatial and temporal), two other general sources of past FIA data are included as necessary. First, older FIA plot- and tree-level data—not in the current FIADB format—are used if available. Second, Resources Planning Act Assessment (RPA) databases, which are periodic, plot-level only, summaries of state inventories, are used mostly to provide the data at or before 1990. See USDA Forest Service (2009a) for information on current and older data as well as additional FIA Program features. A detailed list of the specific inventory data used in this Inventory is in Annex 3.12.

Forest C stocks are estimated from inventory data by a collection of conversion factors and models referred to as FORCARB2 (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004a), which have been formalized in an FIADB-to-carbon calculator (Smith et al. 2010). The conversion factors and model coefficients are categorized by region and forest type, and forest C stock estimates are calculated from application of these factors at the scale of FIA inventory plots. The results are estimates of C density (Mg C per hectare) for six forest ecosystem pools: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic matter. The six carbon pools used in the FIADB-to-carbon calculator are aggregated to the 5 carbon pools defined by IPCC (2006): aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. All non-soil pools except forest floor are separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass, and standing dead trees and down dead wood are pooled as dead wood, in accordance with IPCC (2006).

Once plot-level C stocks are calculated as C densities on *Forest Land Remaining Forest Land* for the five IPCC (2006) reporting pools, the stocks are expanded to population estimates according to methods appropriate to the respective inventory data (for example, see USDA Forest Service (2008)). These expanded C stock estimates are summed to state or sub-state total C stocks. Annualized estimates of C stocks are developed by using available FIA inventory data and interpolating or extrapolating to assign a C stock to each year in the 1990-2009 time series. Flux, or net annual stock change, is estimated by calculating the difference between two successive years and applying the appropriate sign convention; net increases in ecosystem C are identified as negative flux. By convention, inventories are assigned to represent stocks as of January 1 of the inventory year; an estimate of flux for 1996 requires estimates of C stocks for 1996 and 1997, for example. Additional discussion of the use of FIA inventory data and the C conversion process is in Annex 3.12.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for full-tree and aboveground-only biomass in order to estimate the belowground component. If inventory plots include data on individual trees, tree C is based on Jenkins et al. (2003) and is a function of species and diameter. Some inventory

[24] Forest land in the United States includes land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood.

[25] Accurate estimates of C stock change based on annual inventory data require that only one full cycle of inventory data (collected over a 5- to 10-year period) be included. This process ensures that each sample plot measurement is used only once in the estimates of net stock change (see recalculations section in this Chapter and detailed discussion in Annex 3.12).

data do not provide measurements of individual trees; tree C in these plots is estimated from plot-level volume of merchantable wood, or growing-stock volume, of live trees, which is calculated from updates of Smith et al. (2003). These biomass conversion and expansion factors (BCEFs) are applied to about 5 percent of the inventory records, all of which are pre-1998 data. Some inventory data, particularly some of the older datasets, may not include sufficient information to calculate tree C because of incomplete or missing tree or volume data; C estimates for these plots are based on averages from similar, but more complete, inventory data. This applies to an additional 3 percent of inventory records, which represent older (pre-1998) non-timberlands.

Understory vegetation is a minor component of biomass, which is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm d.b.h. In this Inventory, it is assumed that 10 percent of total understory C mass is belowground. Estimates of C density are based on information in Birdsey (1996). Understory frequently represents over 1 percent of C in biomass, but its contribution rarely exceeds 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter is initially calculated as three separate pools with C stocks modeled from inventory data. Estimates are specific to regions and forest types within each region, and stratification of forest land for dead organic matter calculations is identical to that used for biomass through the state and sub-state use of FIA data as discussed above. The two components of dead wood—standing dead trees and down dead wood—are estimated separately. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 2.54 cm d.b.h. Calculations are BCEF-like factors based on updates of Smith et al. (2003). Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. Down dead wood includes stumps and roots of harvested trees. Ratios of down dead wood to live tree are used to estimate this quantity. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates are based on equations of Smith and Heath (2002).

Carbon in Forest Soil

Soil organic C (SOC) includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC are based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. SOC determination is based on the general approach described by Amichev and Galbraith (2004). Links to FIA inventory data were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. This method produced mean SOC densities stratified by region and forest type group. It did not provide separate estimates for mineral or organic soils but instead weighted their contribution to the overall average based on the relative amount of each within forest land. Thus, forest SOC is a function of species and location, and net change also depends on these two factors as total forest area changes. In this respect, SOC provides a country-specific reference stock for 1990-present, but it does not reflect effects of past land use.

Harvested Wood Carbon

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP C. IPCC (2006) provides methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.12 for more details about each approach). The United States uses the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood is estimated as if it remains in the United States, and C in imported wood is not included in inventory estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.12). Annual estimates of change are calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end-uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census; 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a 2006b; Howard 2003, 2007). Estimates for disposal of products reflect the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that are in sanitary landfills versus dumps.

There are five annual HWP variables that are used in varying combinations to estimate HWP Contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States;

(1B) annual change of C in wood and paper products in SWDS in the United States;

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States;

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States;

(3) C in imports of wood, pulp, and paper to the United States,;

(4) C in exports of wood, pulp and paper from the United States; and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yields the estimate for HWP Contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty and Time-series consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems as well as carbon in harvested wood products through Monte Carlo simulation of the Methods described above and probabilistic sampling of carbon conversion factors and inventory data. See Annex 3.12 for additional information. The 2008 flux estimate for forest C stocks is estimated to be between -651 and -935 Tg CO_2 Eq. at a 95 percent confidence level (see Table 7-10). This includes a range of -567 to -845 Tg CO_2 Eq. in forest ecosystems and -67 to -110 Tg CO_2 Eq. for HWP. The smaller range of relative uncertainty (that is, in terms of percentage) for the total relative to the two separate components occurs in part simply because the mean total estimate is larger and in part because there is no correlation between the two which would cause the uncertainty range to change in a major way.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 7-10: Tier 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem	CO_2	(703.9)	(845.5)	(566.8)	-20%	+19%
Harvested Wood Products	CO_2	(88.0)	(109.8)	(67.2)	-25%	+24%
Total Forest	**CO_2**	**(791.9)**	**(934.7)**	**(651.2)**	**-18%**	**+18%**

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically based sampling of most of the forest land in the conterminous United States, dating back to 1952. The main purpose of the FIA program has been to estimate areas, volume of growing stock, and timber products output and utilization factors. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2009c).

Many key calculations for estimating current forest C stocks based on FIA data are based on coefficients from the FORCARB2 model (see additional discussion in the Methodology section above and in Annex 3.12). The model has been used for many years to produce national assessments of forest C stocks and stock changes. General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the derived C datasets, which include inventory variables such as areas and volumes, were compared with standard inventory summaries such as Resources Planning Act (RPA) Forest Resource Tables or selected population estimates generated from the FIA Database (FIADB), which are available at an FIA Internet site (USDA Forest Service 2009d). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. Finally, C stock estimates were compared with previous inventory report estimates to ensure that any differences could be explained by either new data or revised calculation methods (see the "Recalculations" discussion below).

Estimates of the HWP variables and the HWP contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper to units C are based on estimates by industry and Forest Service published sources. The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards each year over the period 1990 to 2000. These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by making sure that estimates of methane emissions from landfills based on EPA data are reasonable in comparison with methane estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

The basic models used to estimate forest ecosystem and HWP C stocks and change are largely unchanged from the previous Inventory (Smith et al. 2007, Skog 2008). Most of the state-level estimates for 1990-present are relatively similar to the values previously reported (EPA 2009). However, changes in methodology and additions to the underlying FIA data have driven some changes in estimates across the time series. Most states have added new inventory data or modified some of the information in previously existing surveys, and the FIADB format changed to version 4.0 (USDA Forest Service 2009b). In particular, western Texas forestlands were not previously included. This year we are able to include 19.5 million hectares of forest, of which 1.1 million hectares is timberland. Thus, 80 percent of Texas forests are included in carbon stock estimates, and 20 percent of the forest land is included in the stock change estimate.

The important change in methodology for this year's Inventory is in the selection and use of unique available surveys from the remeasured annual inventories for some states. Most eastern states have completed the first full cycle of annualized inventories and are providing annual updates to the state's forest inventory with each year's remeasurements, such that one plot's measurements are included in subsequent year's annual updates. Thus, annually updated estimates of forest C stocks are accurate because they give an accurate representation of the static C stock in that year. However, estimates of stock change cannot utilize all the annually updated inventory measurements as provided in the FIADB as there is redundancy in the data used to generate the annual updates of C stock (Smith and Heath in preparation). To remedy this situation, the C stock and stock change calculations used only the unique annual inventory data available for download in the FIADB. Specifically, the survey summaries included were the most recent version of the first full annualized inventory as well as the second annualized inventory cycle survey if it had at least 50 percent of the plots measured. Annex 3.12 provides a list of the specific surveys used here, and Smith et al. (2010) and Smith and Heath (in press) provide further details. In addition, an average estimate of logging residue was incorporated into the down dead wood carbon calculations to explicitly account for down dead wood following harvest on lands that were reforested. Specific documentation is given in Annex 3.12.

Planned Improvements

The ongoing annual surveys by the FIA Program will improve precision of forest C estimates as new state surveys become available (USDA Forest Service 2009a). The annual surveys will eventually include all states. To date, four states are not yet reporting any data from the annualized sampling design of FIA: Hawaii, Oklahoma, New Mexico and Wyoming. Estimates for these states are currently based on older, periodic data. Hawaii and U.S. territories will also be included when appropriate forest C data are available. In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent FIA plots continues and will substantially improve resolution of C pools at the plot level for all U.S. forest land when this information becomes available. Improved resolution, incorporating more of Alaska's forests, and using annualized sampling data as it becomes available for those states currently not reporting are planned for future reporting.

As more information becomes available about historical land use, the ongoing effects of changes in land use and forest management will be better accounted for in estimates of soil C (Birdsey and Lewis 2003, Woodbury et al. 2006, Woodbury et al. 2007). Currently, soil C estimates are based on the assumption that soil C density depends only on broad forest type group, not on land-use history, but long-term residual effects on soil and forest floor C stocks are likely after land-use change. Estimates of such effects depend on identifying past land use changes associated with forest lands.

Similarly, agroforestry practices, such as windbreaks or riparian forest buffers along waterways, are not currently accounted for in the Inventory. In order to properly account for the C stocks and fluxes associated with agroforestry, research will be needed that provides the basis and tools for including these plantings in a nation-wide inventory, as well as the means for entity-level reporting.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology incorporating default IPCC (2006) emissions factors and combustion factor for wildfires. Emissions from this source

Table 7-11: Estimated Non-CO_2 Emissions from Forest Fires (Tg CO_2 Eq.) for U.S. Forests[a]

Gas	1990	1995	2000	2005	2006	2007	2008
CH_4	3.2	4.3	14.3	9.8	21.6	20.0	11.9
N_2O	2.6	3.5	11.7	8.0	17.6	16.3	9.7
Total	**5.8**	**7.7**	**26.0**	**17.8**	**39.2**	**36.3**	**21.7**

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Table 7-12: Estimated Non-CO_2 Emissions from Forest Fires (Gg) for U.S. Forests[a]

Gas	1990	1995	2000	2005	2006	2007	2008
CH_4	152	203	681	467	1,027	953	568
N_2O	8	11	38	26	57	53	31

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

in 2008 were estimated to be 11.9 Tg CO_2 Eq. of CH_4 and 9.7 Tg CO_2 Eq. of N_2O, as shown in Table 7-11 and Table 7-12. The estimates of non-CO_2 emissions from forest fires account for wildfires in the lower 48 states and Alaska as well as prescribed fires in the lower 48 states.

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate non-CO_2 emissions from forest fires. However, more up-to-date default emission factors from IPCC (2006) were incorporated into the methodology and were converted into gas-specific emission ratios. Estimates for CH_4 and N_2O emissions were calculated by multiplying the total estimated CO_2 emitted from forest burned by the gas-specific emissions ratios. CO_2 emitted was estimated by multiplying total carbon emitted (Table 7-13) by the C to CO_2 conversion factor of 44/12 and by 92.8 percent which is the estimated proportion of C emitted as CO_2 (Smith 2008a). The equations used were:

$$CH_4 \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

Estimates for C emitted from forest fires are the same estimates used to generate estimates of CO_2 presented earlier in Box 7-1. Estimates for C emitted include emissions from wildfires in both Alaska and the lower 48 states as well as emissions from prescribed fires in the lower 48 states only (based on expert judgment that prescribed fires only occur in the lower 48 states) (Smith 2008a). The IPCC (2006) default combustion factor of 0.45 for "all 'other' temperate forests" was applied in estimating C emitted from both wildfires and prescribed fires. See the explanation in Annex 3.12 for more details on the methodology used to estimate C emitted from forest fires.

Table 7-13: Estimated Carbon Released from Forest Fires for U.S. Forests

Year	C Emitted (Tg/yr)
1990	14.9
1995	19.9
2000	66.8
2005	45.8
2006	100.8
2007	93.5
2008	55.8

Uncertainty and Time-Series Consistency

Non-CO_2 gases emitted from forest fires depend on several variables, including: forest area for Alaska and the lower 48 states; average carbon densities for wildfires in Alaska, wildfires in the lower 48, and prescribed fires in the lower 48; emission ratios; and combustion factor values (proportion of biomass consumed by fire). To quantify the uncertainties for emissions from forest fires, a Monte Carlo (Tier 2) uncertainty analysis was performed using information about the uncertainty surrounding each of these variables. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-14.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 7-14: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	11.9	3.3	30.2	-73%	+153%
Non-CO_2 Emissions from Forest Fires	N_2O	9.7	2.8	24.7	-71%	+154%

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

Non-CO_2 emissions were recalculated using the 2006 IPCC default emission factors for CH_4 and N_2O relative to the previous Inventory. These default emission factors were converted to CH_4 to CO_2 and N_2O to CO_2 emission ratios and then multiplied by CO_2 emissions to estimate CH_4 and N_2O emissions. The previous 2003 IPCC methodology provides emission ratios that are multiplied by total carbon emitted. Updating to the 2006 IPCC emission factors results in estimates for CH_4 emissions decreasing by a factor of approximately one third between methods (from 18.7 with 2003 factors to 11.9 Tg CO_2 Eq. with 2006 factors for 2008). In contrast, the update causes the estimated values for N_2O emissions to increase by a factor of approximately four (from 1.9 with 2003 factors to 9.7 Tg CO_2 Eq. with 2006 factors for 2008). Due to the similar magnitudes of the decrease in the CH_4 estimates and the increase in the N_2O estimates, the total estimates for non-CO_2 emissions from forest fire remain relatively consistent between methods.

Planned Improvements

The default combustion factor of 0.45 from IPCC (2006) was applied in estimating C emitted from both wildfires and prescribed fires. Additional research into the availability of a combustion factor specific to prescribed fires will be conducted.

Direct N_2O Fluxes from Forest Soils (IPCC Source Category 5A1)

Of the synthetic N fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropped soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once approximately 20 years later). Thus, although the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, average annual applications, inferred by dividing all forest land that may undergo N fertilization at some point during its growing cycle by the amount of N fertilizer added to these forests in a given year, is quite low. Direct N_2O emissions from forest soils in 2008 were 0.4 Tg CO_2 Eq. (1 Gg). Emissions have increased by 455 percent from 1990 to 2008 as a result of an increase in the area of N fertilized pine plantations in the southeastern United States and Douglas-fir timberland in western Washington and Oregon. Total forest soil N_2O emissions are summarized in Table 7-15.

Table 7-15: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	0.1	0.2
1995	0.2	0.6
2000	0.4	1.3
2005	0.4	1.2
2006	0.4	1.2
2007	0.4	1.2
2008	0.4	1.2

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions both from *Forest Land Remaining Forest Land* and from *Land Converted to Forest Land*.

Methodology

The IPCC Tier 1 approach was used to estimate N_2O from soils within *Forest Land Remaining Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted were for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also accounted for N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests were based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al., 2007).

Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer was multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast were not available for 2005, 2006, 2007 and 2008, so data from 2004 were used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir was accounted for, because the vast majority (~95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs, 2007). Estimates of total Douglas-fir area and the portion of fertilized area were multiplied to obtain annual area estimates of fertilized Douglas-fir stands and these were multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate annual N additions (Briggs 2007). The total N applied to forests was multiplied by the IPCC (2006) default emission factor of 1 percent to estimate direct N_2O emissions. The volatilization and leaching/runoff fractions, calculated according to the IPCC default factors of 10 percent and 30 percent, respectively, were included with all sources of indirect emissions in the Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from forests depends not only on N inputs, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology and only accounts for variations in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils is included in the Agricultural Soil Management and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates were assigned a default level[26] of uncertainty at ±50 percent, and area receiving fertilizer was assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct N_2O emission factor for synthetic N fertilizer application to soils. Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2008 emissions estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-16. N_2O fluxes from soils were estimated to be between 0.1 and 1.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2008 emission estimate of 0.4 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 7-16: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Land Remaining Forest Land: N_2O Fluxes from Soils	N_2O	0.4	0.1	1.1	-59%	+211%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[26] Uncertainty is unknown for the fertilization rates so a conservative value of ±50% was used in the analysis.

Recalculations Discussion

The improvement in this Inventory was to account for N fertilizer applications to commercial Douglas-fir forests in western Oregon and Washington, requiring a recalculation for the time series. This resulted in an annual increase in emissions of approximately 24 percent compared to the previous Inventory.

Planned Improvements

State-level area data will be acquired for southeastern pine plantations and northwestern Douglas-fir forests receiving fertilizer to estimate soil N_2O emission by state and provide information about regional variation in emission patterns.

7.3. Land Converted to Forest Land (IPCC Source Category 5A2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to forest each year, just as forest land is converted to other uses. However, the magnitude of these changes is not currently known. Given the paucity of available land-use information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Forest Land* from fluxes on *Forest Land Remaining Forest Land* at this time.

7.4. Cropland Remaining Cropland (IPCC Source Category 5B1)

Mineral and Organic Soil Carbon Stock Changes

Soils contain both organic and inorganic forms of C, but soil organic C (SOC) stocks are the main source and sink for atmospheric CO_2 in most soils. Changes in inorganic C stocks are typically minor. In addition, soil organic C is the dominant organic C pool in cropland ecosystems, because biomass and dead organic matter have considerably less C and those pools are relatively ephemeral. IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities on mineral and organic soils.[27]

Typical well-drained mineral soils contain from 1 to 6 percent organic C by weight, although mineral soils that are saturated with water for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural uses can cause as much as half of the SOC to be decomposed and the C lost to the atmosphere. The rate and ultimate magnitude of C loss will depend on pre-conversion conditions, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the C loss generally occurs within the first 10 years following conversion; C stocks continue to decline in subsequent decades but at a much slower rate. In temperate regions, C loss can continue for several decades, reducing stocks by 20 to 40 percent of native C levels. Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter. However, land use, management, and other conditions may change before the new equilibrium is reached. The quantity and quality of organic matter inputs and their rate of decomposition are determined by the combined interaction of climate, soil properties, and land use. Land use and agricultural practices such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding can modify both organic matter inputs and decomposition, and thereby result in a net flux of C to or from the pool of soil C.

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999, Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), forming under inundated conditions in which minimal decomposition of plant residue occurs. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil, which accelerates the rate of decomposition and CO_2 emissions. Because of the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time. The rate of CO_2 emissions varies depending on climate and composition (i.e., decomposability) of the organic matter.

[27] Carbon dioxide emissions associated with liming are also estimated but are included in a separate section of the report.

Table 7-17: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(56.8)	(50.6)	(57.9)	(45.9)	(46.8)	(47.3)	(45.7)
Organic Soils	27.4	27.7	27.7	27.7	27.7	27.7	27.7
Total Net Flux	**(29.4)**	**(22.9)**	**(30.2)**	**(18.3)**	**(19.1)**	**(19.7)**	**(18.1)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-18: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(15.5)	(13.8)	(15.8)	(12.5)	(12.8)	(12.9)	(12.5)
Organic Soils	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Total Net Flux	**(8.0)**	**(6.3)**	**(8.2)**	**(5.0)**	**(5.2)**	**(5.4)**	**(4.9)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Also, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests, due to deeper drainage and more intensive management practices in cropland (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997). Carbon losses are estimated from drained organic soils under both grassland and cropland management in this Inventory.

Cropland Remaining Cropland includes all cropland in an inventory year that had been cropland for the last 20 years[28] according to the USDA NRI land-use survey (USDA-NRCS 2000). The Inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands, which is not currently included in the estimation of C stock changes. It is important to note that these areas are part of the managed land base for the United States, as described in Section 7.1, and plans are being made to include federal croplands in future C inventories.

The area of *Cropland Remaining Cropland* changes through time as land is converted to or from cropland management. CO_2 emissions and removals[29] due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops. A Tier 2 IPCC method is used for the remaining crops (vegetables, tobacco, perennial/horticultural crops, and rice) not included in the Tier 3 method. In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale) and for additional changes in mineral soil C stocks that were not addressed with the Tier 2 or 3 approaches (i.e., change in C stocks after 2003 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Of the two sub-source categories, land-use and land management of mineral soils was the most important component of total net C stock change between 1990 and 2008 (see Table 7-17 and Table 7-18). In 2008, mineral soils were estimated to remove 45.7 Tg CO_2 Eq. (12.5 Tg C). This rate of C storage in mineral soils represented about a 20 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils were 27.7 Tg CO_2 Eq. (7.5 Tg C) in 2008. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 18.1 Tg CO_2 Eq. (4.9 Tg C) in 2008.

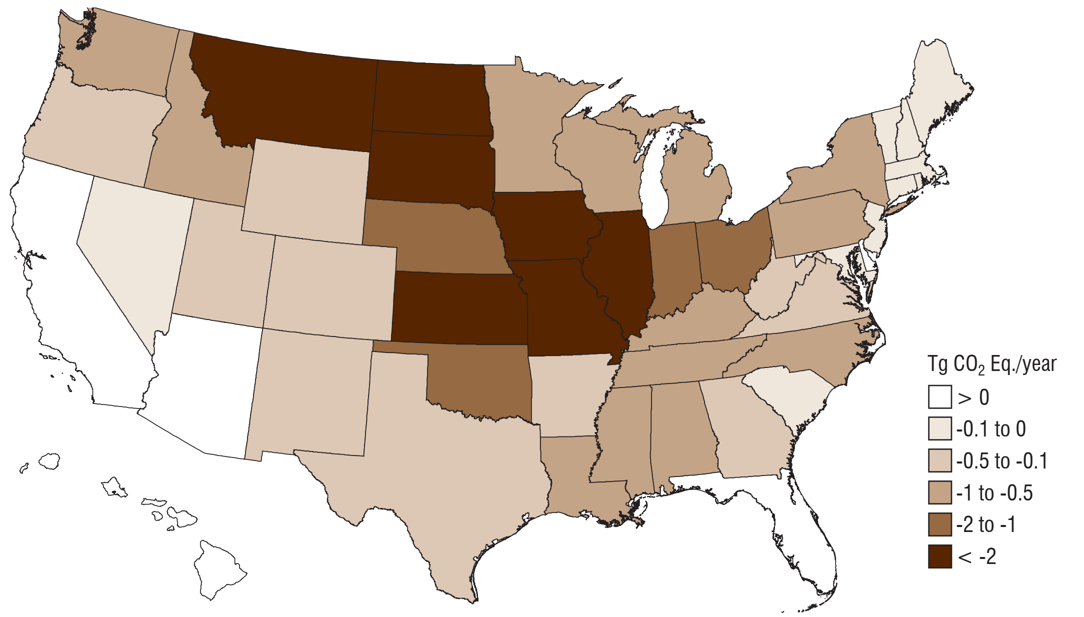
The net reduction in soil C accumulation over the time series (39 percent for 2008, relative to 1990) was largely due to the declining influence of annual cropland enrolled in the Conservation Reserve Program, which began in the late 1980s. However, there were still positive increases in C stocks from land enrolled in the reserve program, as well as intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased

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

[29] Note that removals occur through crop and forage uptake of CO_2

Figure 7-5

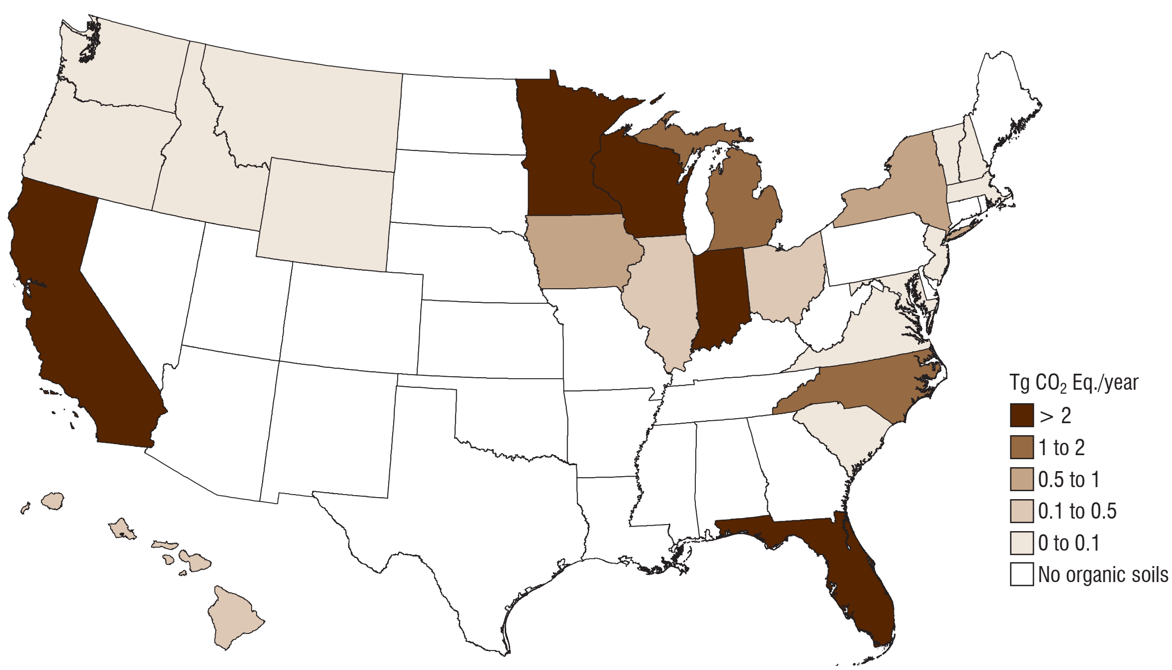
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2008, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure 7-6

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2008, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions.

hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-5 and Figure 7-6. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the area with the largest amounts of cropland managed with conservation tillage. Rates were also high in the Great Plains due to enrollment in the Conservation Reserve Program. Emission rates from drained organic soils were highest along the southeastern coastal region, in the northeast central United States surrounding the Great Lakes, and along the central and northern portions of the West Coast.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks due to: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils for *Cropland Remaining Cropland*.

Soil C stock changes were estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA *National Resources Inventory* (NRI) survey (USDA-NRCS 2000). The NRI is a statistically-based sample of all non-federal land, and includes approximately 260,000 points in agricultural land for the conterminous United States and Hawaii.[30] Each point is associated with an "expansion factor" that allows scaling of C stock changes from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected for 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992, and 1994-1997). However, the NRI program began collecting annual data in 1998, and data are currently available through 2003. NRI points were classified as *Cropland Remaining Cropland* in a given year between 1990 and 2008 if the land use had been cropland for 20 years.[31] Cropland includes all land used to produce food and fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was applied to estimate C stock changes for mineral soils used to produce a majority of annual crops in the United States (Ogle et al. 2009). The remaining crops on mineral soils were estimated using an IPCC Tier 2 method (Ogle et al. 2003), including vegetables, tobacco, perennial/horticultural crops, rice, and crops rotated with these crops. The Tier 2 method was also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). Mineral SOC stocks were estimated using a Tier 2 method for these areas, because the Century model used for the Tier 3 method has not been fully tested to address its adequacy for estimating C stock changes associated with certain crops and rotations, as well as cobbly, gravelly, or shaley soils. An additional stock change calculation was made for mineral soils using Tier 2 emission factors, accounting for enrollment patterns in the Conservation Reserve Program after 2003, which was not addressed by the Tier 3 methods.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.13.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), which simulates the dynamics of C and other elements in cropland, grassland, forest, and savanna ecosystems. It uses monthly weather data as an input, along with information about soil physical properties. Input data on land use and management are specified at monthly resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, residue removal, grazing, and fire). The model computes net primary productivity and C additions to soil, soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic

[30] NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2003.

[31] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

Box 7-2: Tier 3 Inventory for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to inventory soil C stock changes on the majority of agricultural land with mineral soils. This approach entails several fundamental differences compared to the IPCC Tier 1 or 2 methods, which are based on a classification of land areas into a number of discrete classes based on a highly aggregated classification of climate, soil, and management (i.e., only six climate regions, seven soil types and eleven management systems occur in U.S. agricultural land under the IPCC classification). Input variables to the Tier 3 model, including climate, soils, and management activities (e.g., fertilization, crop species, tillage, etc.), are represented in considerably more detail both temporally and spatially, and exhibit multi-dimensional interactions through the more complex model structure compared with the IPCC Tier 1 or 2 approach. The spatial resolution of the analysis is also finer in the Tier 3 method compared to the lower tier methods as implemented in the United States for previous Inventories (e.g., 3,037 counties versus 181 Major Land Resource Areas (MLRAs), respectively).

In the Century model, soil C dynamics (and CO_2 emissions and uptake) are treated as continuous variables, which change on a monthly time step. Carbon emissions and removals are an outcome of plant production and decomposition processes, which are simulated in the model structure. Thus, changes in soil C stocks are influenced by not only changes in land use and management but also inter-annual climate variability and secondary feedbacks between management activities, climate, and soils as they affect primary production and decomposition. This latter characteristic constitutes one of the greatest differences between the methods, and forms the basis for a more complete accounting of soil C stock changes in the Tier 3 approach compared with Tier 2 methodology.

Because the Tier 3 model simulates a continuous time period rather than the equilibrium step change used in the IPCC methodology (Tier 1 and 2), the Tier 3 model addresses the delayed response of soils to management and land-use changes. Delayed responses can occur due to variable weather patterns and other environmental constraints that interact with land use and management and affect the time frame over which stock changes occur. Moreover, the Tier 3 method also accounts for the overall effect of increasing yields and, hence, C input to soils that have taken place across management systems and crop types within the United States. Productivity has increased by 1 to 2 percent annually over the past 4 to 5 decades for most major crops in the United States (Reilly and Fuglie 1998), which is believed to have led to increases in cropland soil C stocks (e.g., Allmaras et al. 2000). This is a major difference from the IPCC-based Tier 1 and 2 approaches, in which trends in soil C stocks only capture discrete changes in management and/or land use, rather than a longer term trend such as gradual increases in crop productivity.

matter C and nutrient (N, K, S) elements. This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC, because the simulation model treats changes as continuous over time rather than the simplified discrete changes represented in the default method (see Box 7-2 for additional information). National estimates were obtained by simulating historical land-use and management patterns as recorded in the USDA National Resources Inventory (NRI) survey.

Additional sources of activity data were used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 1998) provided annual data on tillage activity at the county level since 1989, with adjustments for long-term adoption of no-till agriculture (Towery 2001). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management section (Section 6.2) and annex (Annex 3.10).

Manure amendments were an input to the Century Model based on manure N available for application from all managed or unmanaged systems except pasture/range/

paddock.[32] Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct nitrous oxide emissions, volatilization of ammonia and NOx, runoff and leaching, and poultry manure used as a feed supplement. More information on these losses is available in the description of the Manure Management source category. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil.

Monthly weather data were used as an input in the model simulations, based on an aggregation of gridded weather data to the county scale from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) database (Daly et al. 1994). Soil attributes, which were obtained from an NRI database, were assigned based on field visits and soil series descriptions. Each NRI point was run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Carbon stock estimates from Century were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2009). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2003, but C stock changes from 2004 to 2008 were assumed to be similar to 2003 because no additional activity data are currently available from the NRI for the latter years.

Tier 2 Approach

In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity were used to classify land area to apply appropriate stock change factors. MLRAs formed the base spatial unit for mapping climate regions in the United States; each MLRA represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981). MLRAs were classified into climate regions according to the IPCC categories using the PRISM climate database of Daly et al. (1994).

Reference C stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2003, 2006). Changing the reference condition was necessary because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than those that are not considered cultivated cropland.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, and land-use change between cultivated and uncultivated conditions (Ogle et al. 2003, Ogle et al. 2006). U.S. factors associated with organic matter amendments were not estimated because there were an insufficient number of studies to analyze those impacts. Instead, factors from IPCC (2003) were used to estimate the effect of those activities. Euliss and Gleason (2002) provided the data for computing the change in SOC storage resulting from restoration of wetland enrolled in the Conservation Reserve Program.

Activity data were primarily based on the historical land-use/management patterns recorded in the NRI. Each NRI point was classified by land use, soil type, climate region (using PRISM data, Daly et al. 1994) and management condition. Classification of cropland area by tillage practice was based on data from the Conservation Tillage Information Center (CTIC 1998, Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land were obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period were based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the previous methodology subsection on the Tier 3 analysis for mineral soils.

Combining information from these data sources, SOC stocks for mineral soils were estimated 50,000 times for 1982, 1992, and 1997, using a Monte Carlo simulation approach and the probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002, Ogle et al. 2003). The annual C flux for 1990 through 1992 was determined by calculating the average annual change in stocks between 1982 and 1992; annual C flux for 1993 through 2008 was determined by calculating the average annual change in stocks between 1992 and 1997.

[32] Pasture/Range/Paddock manure additions to soils are addressed in the *Grassland Remaining Grassland and Land Converted to Grassland categories.*

Additional Mineral C Stock Change

Annual C flux estimates for mineral soils between 1990 and 2008 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 2003 due to changes in Conservation Reserve Program enrollment. The change in enrollment acreage relative to 2003 was based on data from USDA-FSA (2007) for 2004 through 2008, and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. The stock change rate is based on estimations using the IPCC method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Cropland Remaining Cropland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2008.

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category was addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 7-19 for mineral soil C stocks and organic soil C stocks disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with IPCC (2006). The combined uncertainty was calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. More details on how the individual uncertainties were developed are in Annex 3.13. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 166 percent below to 161 percent above the 2008 stock change estimate of -18.1 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 7-19: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO_2 Eq. and Percent)

Source	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(42.3)	(69.6)	(15.1)	-64%	+64%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.0)	(6.9)	0.8	-127%	+128%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	(0.4)	(0.6)	(0.2)	-50%	+50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	27.7	15.8	36.9	-43%	+33%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(18.1)**	**(48.0)**	**11.0**	**-166%**	**+161%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled throughout the inventory process. As discussed in the uncertainty section, results were compared to field measurements, and a statistical relationship was developed to assess uncertainties in the model's predictive capability. The comparisons included over 40 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007). Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors.

Planned Improvements

The first improvement is to update the Tier 2 inventory analysis with the latest annual *National Resources Inventory* (NRI) data. While the land base for the Tier 3 approach uses the latest available data from the NRI, the Tier 2 portion of the Inventory has not updated and is based on the Revised 1997 NRI data product (USDA-NRCS 2000). This improvement will extend the time series of the land use data from 1997 through 2003 for the Tier 2 portion of the Inventory.

The second improvement is to incorporate remote sensing in the analysis for estimation of crop and forage production. Specifically, the Enhanced Vegetation Index (EVI) product that is derived from MODIS satellite imagery is being used to refine the production estimation for the Tier 3 assessment framework. EVI reflects changes in plant "greenness" over the growing season and can be used to compute production based on the light use efficiency of the crop or forage (Potter et al. 1993). In the current framework, production is simulated based on the weather data, soil characteristics, and the genetic potential of the crop. While this method produces reasonable results, remote sensing can be used to refine the productivity estimates and reduce biases in crop production and subsequent C input to soil systems. It is anticipated that precision in the Tier 3 assessment framework will be increased by 25 percent or more with the new method.

CO_2 Emissions from Agricultural Liming

IPCC (2006) recommends reporting CO_2 emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Limestone and dolomite are added by land managers to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, climate regime, and the type of mineral applied. Emissions from liming have

Table 7-20: CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq.)

Source	1990	1995	2000	2005	2006	2007	2008
Liming of Agricultural Soils[a]	4.7	4.4	4.3	4.3	4.2	4.5	3.8

[a] Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-21: CO_2 Emissions from Liming of Agricultural Soils (Tg C)

Source	1990	1995	2000	2005	2006	2007	2008
Liming of Agricultural Soils[a]	1.3	1.2	1.2	1.2	1.2	1.2	1.0

[a] Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

fluctuated over the past sixteen years, ranging from 3.8 Tg CO_2 Eq. to 5.0 Tg CO_2 Eq. In 2008, liming of agricultural soils in the United States resulted in emissions of 3.8 Tg CO_2 Eq. (1.0 Tg C), representing about a 18 percent decrease in emissions since 1990 (see Table 7-20 and Table 7-21). The trend is driven entirely by the amount of lime and dolomite estimated to have been applied to soils over the time period.

Methodology

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 7-22) were multiplied by CO_2 emission factors from West and McBride (2005). These emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of agricultural lime that may leach through the soil and travel by rivers to the ocean (West and McBride 2005). This analysis of lime dissolution is based on liming occurring in the Mississippi River basin, where the vast majority of all U.S. liming takes place (West 2008). U.S. liming that does not occur in the Mississippi River basin tends to occur under similar soil and rainfall regimes, and, thus, the emission factor is appropriate for use across the United States (West 2008). The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, b; USGS 2007, 2008). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

The "unspecified" and "estimated" amounts of crushed limestone and dolomite applied to agricultural soils were calculated by multiplying the percentage of total "specified" limestone and dolomite production applied to agricultural soils by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to agricultural soils (as opposed to other uses of the stone) was assumed to be proportionate to the amount of "specified" crushed limestone and dolomite that was applied to agricultural soils. In addition, data were not available for 1990, 1992, and 2008 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2008 data, the previous year's fractions were applied to a 2008 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2009* (USGS 2009).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each

Table 7-22: Applied Minerals (Million Metric Tons)

Source	1990	1995	2000	2005	2006	2007	2008
Limestone	19.01	17.30	15.86	18.09	16.54	17.77	15.09
Dolomite	2.36	2.77	3.81	1.85	2.73	2.84	2.41

Note: These numbers represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland,* and *Settlements Remaining Settlements*. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations. Since limestone and dolomite activity data are also available at the state level, the national-level estimates reported here were broken out by state, although state-level estimates are not reported here.

Uncertainty and Time-Series Consistency

Uncertainty regarding limestone and dolomite activity data inputs was estimated at ±15 percent and assumed to be uniformly distributed around the inventory estimate (Tepordei 2003b). Analysis of the uncertainty associated with the emission factors included the following: the fraction of agricultural lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not accounted for, but should not change the uncertainty associated with CO_2 emissions (West 2005). The uncertainties associated with the fraction of agricultural lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were each modeled as a smoothed triangular distribution between ranges of zero percent to 100 percent. The uncertainty surrounding these two components largely drives the overall uncertainty estimates reported below. More information on the uncertainty estimates for Liming of Agricultural Soils is contained within the Uncertainty Annex.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-23. CO_2 emissions from Liming of Agricultural Soils in 2008 were estimated to be between 0.1 and 7.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 97 percent below to 102 percent above the 2008 emission estimate of 3.8 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

Several adjustments were made in the current Inventory to improve the results. The quantity of applied minerals reported in the previous Inventory for 2007 has been revised; the updated activity data for 2007 are approximately 1,570 thousand metric tons greater than the data used last year. Consequently, the reported emissions resulting from liming in 2007 increased by about 11 percent. In the previous Inventory, to estimate 2007 data, the previous year's fractions were applied to a 2007 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2008* (USGS 2008). Since publication of the previous Inventory, the *Minerals Yearbook* has published actual quantities of crushed stone sold or used by producers in the United States in 2007. These values have replaced those used in the previous Inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

Table 7-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming of Agricultural Soils[b]	CO_2	3.8	0.1	7.7	-97%	+102%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland,* and *Settlements Remaining Settlements*.

Table 7-24: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Source	1990	1995	2000	2005	2006	2007	2008
Urea Fertilization[a]	2.4	2.7	3.2	3.5	3.7	3.8	3.8

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-25: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg C)

Source	1990	1995	2000	2005	2006	2007	2008
Urea Fertilization[a]	0.7	0.7	0.9	1.0	1.0	1.0	1.0

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as fertilizer leads to emissions of CO_2 that was fixed during the industrial production process. Urea in the presence of water and urease enzymes is converted into ammonium (NH_4^+), hydroxyl ion (OH^-), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States totaled 3.8 Tg CO_2 Eq. (1.0 Tg C) in 2008 (Table 7-24 and Table 7-25). Emissions from urea

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea fertilizer applied (see Table 7-26) were derived from state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2008) and were multiplied by the default IPCC (2006) emission factor of 0.20, which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July through June), a calculation was performed to convert the data to calendar years (January through December). According to historic monthly fertilizer use data (TVA 1992b), 65 percent of total fertilizer used in any fertilizer year is applied between January through June of that calendar year, and 35 percent of total fertilizer used in any fertilizer year is applied between July through December of the previous calendar year. Fertilizer sales data for the 2008 and 2009 fertilizer years were not available in time for publication. Accordingly, urea application in the 2008 fertilizer year was assumed to be equal to that of the 2007 fertilizer year. Since 2009 fertilizer year data were not available, July through December 2008 fertilizer consumption was assumed to be equal to July through December 2007 fertilizer consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-27 for Urea Fertilization. A Tier 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil. The emission

Table 7-26: Applied Urea (Million Metric Tons)

	1990	1995	2000	2005	2006	2007	2008
Urea Fertilization[a]	3.30	3.62	4.38	4.78	4.98	5.19	5.19

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-27: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	3.8	2.2	3.9	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.

estimate is, thus, likely to be high. In addition, each urea consumption data point has an associated uncertainty. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals; it was determined through personal communication with Fertilizer Regulatory Program Coordinator, David L. Terry (2007), however, that this amount is most likely very small. Research into aircraft deicing practices also confirmed that urea is used minimally in the industry; a 1992 survey found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 MT per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). Lastly, there is uncertainty surrounding the assumptions behind the calculation that converts fertilizer years to calendar years. CO_2 emissions from urea fertilization of agricultural soils in 2008 were estimated to be between 2.2 and 3.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2008 emission estimate of 3.8 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. Inventory reporting forms and text were reviewed. No errors were found.

Recalculations Discussion

July to December 2007 urea application data were updated with assumptions for fertilizer year 2008, and the 2007 emission estimate was revised accordingly. The activity data decreased about 200,000 metric tons for this year and this change resulted in an approximately 4 percent decrease in emissions in 2007 relative to the previous Inventory. In the previous Inventory, the application for this period was calculated based on application during July to December 2006.

Planned Improvements

The primary planned improvement is to investigate using a Tier 2 or Tier 3 approach, which would utilize country-specific information to estimate a more precise emission factor.

7.5. Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all cropland in an inventory year that had been another land use at any point during the previous 20 years[33] according to the USDA NRI land-use survey (USDA-NRCS 2000). Consequently, lands are retained in this category for 20 years as recommended by the IPCC guidelines (IPCC 2006) unless there is another land-use change. The Inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands, which is not currently included in the estimation of C stock

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

Table 7-28: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(0.3)	0.3	(0.3)	3.3	3.3	3.3	3.3
Organic Soils	2.4	2.6	2.6	2.6	2.6	2.6	2.6
Total Net Flux	**2.2**	**2.9**	**2.4**	**5.9**	**5.9**	**5.9**	**5.9**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-29: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(0.1)	0.1	(0.1)	0.9	0.9	0.9	0.9
Organic Soils	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total Net Flux	**0.6**	**0.8**	**0.6**	**1.6**	**1.6**	**1.6**	**1.6**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

changes. It is important to note that these areas are part of the managed land base for the United States, as described in Section 7.1, and plans are being made to include these areas in future C inventories.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Cropland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. The IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[34]

Land-use and management of mineral soils in *Land Converted to Cropland* generally led to relatively small increases in soil C during the 1990s but the pattern changed to small losses of C through the latter part of the time series (Table 7-28 and Table 7-29). The total rate of change in soil C stocks was 5.9 Tg CO_2 Eq. (1.6 Tg C) in 2008. Mineral soils were estimated to lose 3.3 Tg CO_2 Eq. (0.9 Tg C) in 2008, while drainage and cultivation of organic soils led to annual losses of 2.6 Tg CO_2 Eq. (0.7 Tg C) in 2008.

[34] Carbon dioxide emissions associated with liming are also estimated but included in a separate section of the report.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils for *Land Converted to Cropland* is displayed in Figure 7-7 and Figure 7-8. While a large portion of the United States had net losses of soil C for *Land Converted to Cropland*, there were some notable areas with net C accumulation in the Great Plains, Midwest, mid-Atlantic states. These areas were gaining C following conversion, because the land had been brought into hay production, including grass and legume hay, leading to enhanced plant production relative to the previous land use, and thus higher C input to the soil. Emissions from organic soils were largest in California, Florida, and the upper Midwest, which coincided with largest concentrations of cultivated organic soils in the United States.

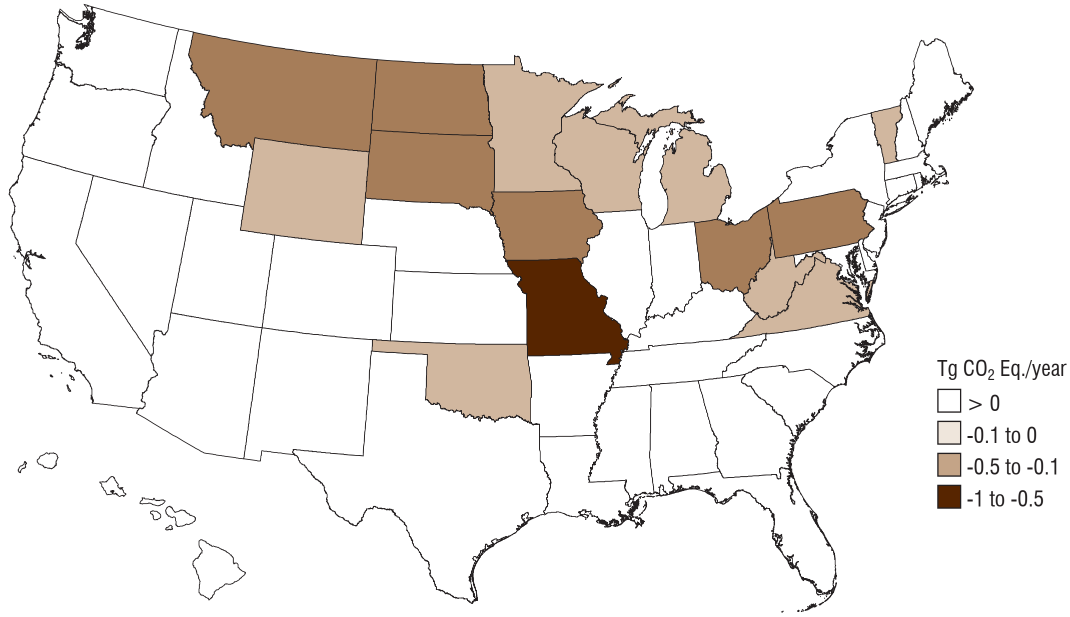
Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Land Converted to Cropland*. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.13.

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). Land-use and some management information (e.g., crop type, soil

Figure 7-7

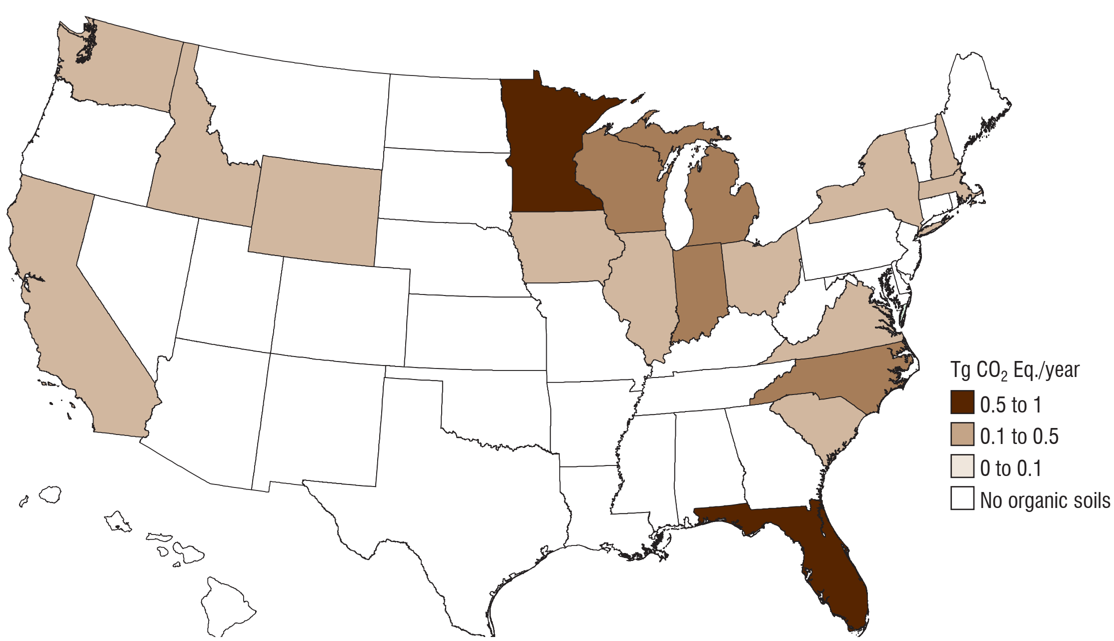
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2008, *Land Converted to Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-8

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2008, *Land Converted to Cropland*



Note: Values greater than zero represent emissions.

attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Land Converted to Cropland* in a given year between 1990 and 2008 if the land use was cropland but had been another use during the previous 20 years. Cropland includes all land used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

A Tier 3 model-based approach was applied to estimate C stock changes for soils on *Land Converted to Cropland* used to produce a majority of all crops (Ogle et al. 2009). Soil C stock changes on the remaining soils were estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce vegetable, tobacco, perennial/horticultural crops, and rice; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[35]

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model for the Tier 3 methods. National estimates were obtained by using the model to simulate historical land-use change patterns as recorded in the USDA *National Resources Inventory* (USDA-NRCS 2000). The methods used for *Land Converted to Cropland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 3 methods section and Annex 3.13 for additional information).

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes were estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section for additional information).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Land Converted to Cropland* areas from the 1997 *National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2008.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-30 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Land Converted to Cropland* was estimated to be 40 percent below and 36 percent above the inventory estimate of 5.9 Tg CO_2 Eq.

[35] Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2000).

Table 7-30: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (Tg CO_2 Eq. and Percent)

Source	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Cropland, Tier 3 Inventory Methodology	(0.8)	(1.5)	(0.1)	-84%	+84%
Mineral Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	4.1	2.3	5.8	-44%	+41%
Organic Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	2.6	1.2	3.7	-53%	+41%
Combined Uncertainty for Flux Associated with Soil Carbon Stock Change in Land Converted to Cropland	**5.9**	**3.5**	**8.1**	**-40%**	**+36%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland*.

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties related to the structure of the Century model for *Land Converted to Cropland,* but this is a planned improvement. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6. Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all grassland in an inventory year that had been grassland for the previous 20 years[36] according to the USDA NRI land use survey (USDA-NRCS 2000). The Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands. It is important to note that these areas are part of the managed land base for the United States, as described in Section 7.1. While federal grasslands probably have minimal changes in land management and C stocks, plans are being made to further evaluate and potentially include these areas in future C inventories.

Background on agricultural C stock changes is provided in the *Cropland Remaining Cropland* section and will only be summarized here for *Grassland Remaining Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared to soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[37]

Land-use and management of mineral soils in *Grassland Remaining Grassland* increased soil C, while organic soils lost relatively small amounts of C in each year 1990 through 2008. Due to the pattern for mineral soils, the overall trend was a gain in soil C over the time series although the rates varied from year to year, with a net removal of 8.7 Tg CO_2 Eq. (1.3 Tg C) in 2008 (Table 7-31 and Table 7-32). There

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

[37] Carbon dioxide missions associated with liming are also estimated but included in a separate section of the report.

Table 7-31: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(55.9)	(30.4)	(56.3)	(12.7)	(12.6)	(12.5)	(12.4)
Organic Soils	3.9	3.7	3.7	3.7	3.7	3.7	3.7
Total Net Flux	**(52.0)**	**(26.7)**	**(52.6)**	**(9.0)**	**(8.9)**	**(8.8)**	**(8.7)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-32: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils	(15.2)	(8.3)	(15.4)	(3.5)	(3.4)	(3.4)	(3.4)
Organic Soils	1.1	1.0	1.0	1.0	1.0	1.0	1.0
Total Net Flux	**(14.2)**	**(7.3)**	**(14.3)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

was considerable variation over the time series driven by variability in weather patterns and associated interaction with land management activity. The change rates on per hectare basis were small, however, even in the years with larger total changes in stocks. Overall, flux rates declined by 43.3 Tg CO_2 Eq. (11.9 Tg C) when comparing the net change in soil C for 1990 and 2008.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-9 and Figure 7-10.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Grassland Remaining Grassland*. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.13.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Grassland Remaining Grassland* in a given year between 1990 and 2008 if the land use had been grassland for 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

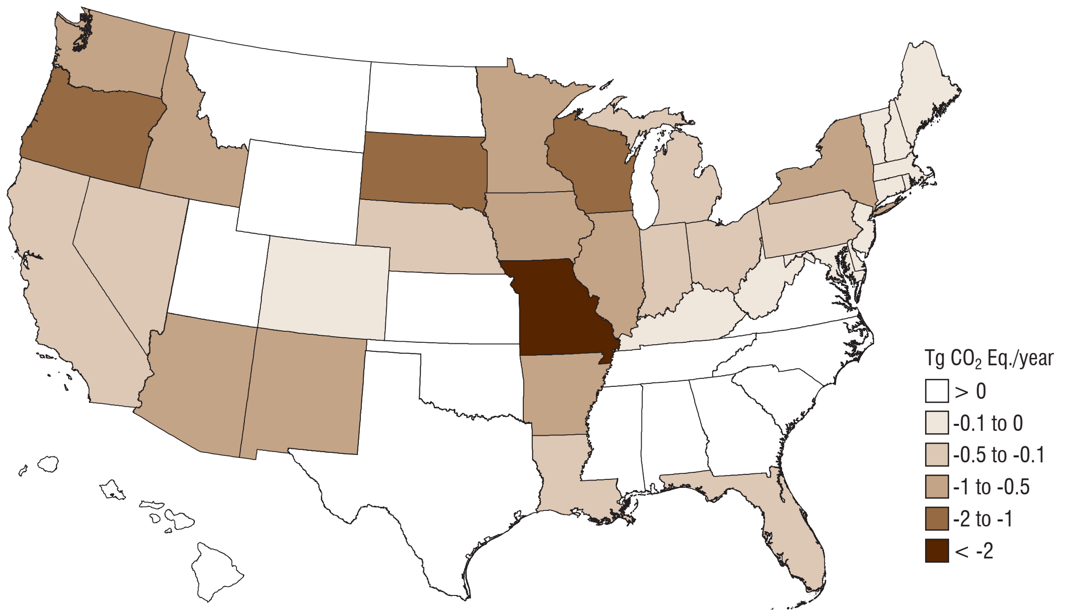
An IPCC Tier 3 model-based approach was applied to estimate C stock changes for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils were estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral soil organic C stocks and stock changes for *Grassland Remaining Grassland* were estimated using the Century biogeochemical model, as described in *Cropland Remaining Cropland*. Historical land-use and management patterns were used in the Century simulations as recorded in the USDA *National Resources Inventory* (NRI) survey, with

Figure 7-9

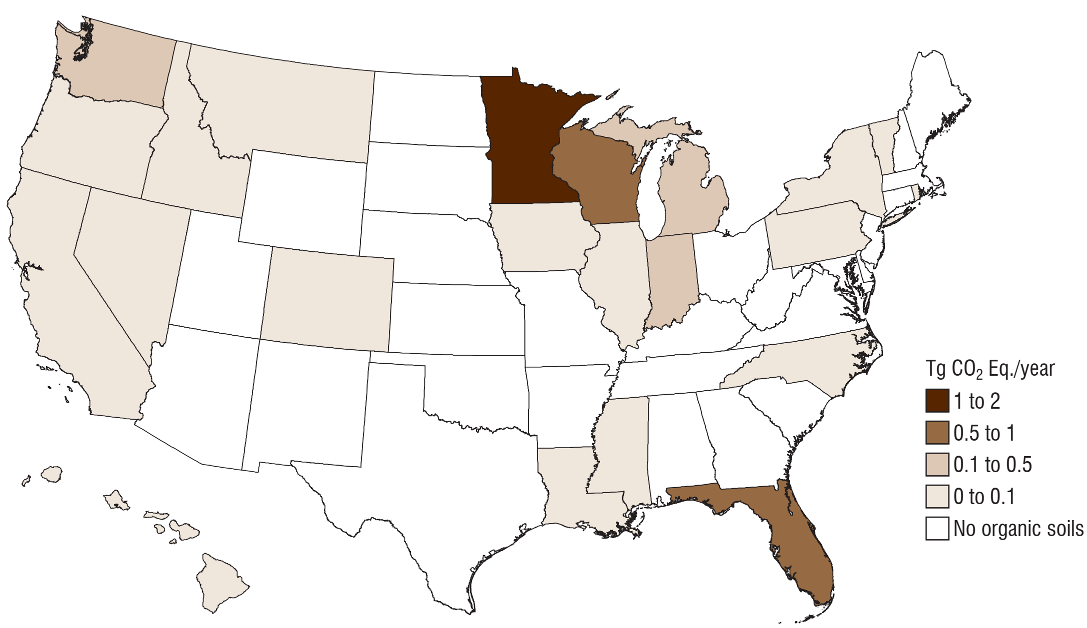
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2008, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure 7-10

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2008, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions.

supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to grassland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management Section (Section 6.2) and Annex (Annex 3.10). In contrast to manure amendments, pasture/range/paddock (PRP) manure N deposition was estimated internally in the Century model, as part of the grassland system simulations (i.e., PRP manure deposition was not an external input into the model). See the Tier 3 methods in *Cropland Remaining Cropland* section for additional discussion on the Tier 3 methodology for mineral soils.

Tier 2 Approach

The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section and Annex 3.13 for additional information).

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2008 were adjusted to account for additional C stock changes associated with sewage sludge amendments using a Tier 2 method. Estimates of the amounts of sewage sludge N applied to agricultural land were derived from national data on sewage sludge generation, disposition, and nitrogen content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. N application rates from Kellogg et al. (2000) were used to determine the amount of area receiving sludge amendments. Although sewage sludge can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is assumed to rarely be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at 0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Grassland Remaining Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2008.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-33 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* was estimated to be 29

Table 7-33: Tier 2 Quantitative Uncertainty Estimates for C Stock Changes occurring within *Grassland Remaining Grassland* (Tg CO_2 Eq. and Percent)

Source	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(11.0)	(11.2)	(10.8)	-2%	+2%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.2)	(0.3)	0.0	-89%	+127%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.2)	(1.8)	(0.6)	-50%	+50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	3.7	1.2	5.5	-66%	+49%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**(8.7)**	**(11.2)**	**(6.8)**	**-29%**	**+22%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

percent below and 22 percent above the inventory estimate of -8.7 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Uncertainties in Mineral Soil Carbon Stock Changes

The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 3 approach and Tier 2 approach were based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. See the Tier 3 approach for mineral soils under the *Cropland Remaining Cropland* section for additional discussion.

A ±50 percent uncertainty was assumed for additional adjustments to the soil C stocks between 1990 and 2008 to account for additional C stock changes associated with amending grassland soils with sewage sludge.

Uncertainties in Soil Carbon Stock Changes for Organic Soils

Uncertainty in C emissions from organic soils was estimated using country-specific factors and a Monte Carlo analysis. Probability distribution functions for emission factors were derived from a synthesis of 10 studies, and combined with uncertainties in the NRI land use and management data for organic soils in the Monte Carlo analysis. See the Tier 2 section under minerals soils of *Cropland Remaining Cropland* for additional discussion.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled through the inventory process. No additional errors were found in this Inventory.

Recalculations Discussion

The estimated area of grasslands changed across the time series relative to the previous Inventory due to revisions in the forest land definition. This adjustment reduced the area of grassland in the United States because woodlands previously designated as grassland are now considered forest land. The revised areas altered the estimated soil C stock changes in *Grassland Remaining Grassland* by an average of 1.2 Tg CO_2 eq. or 3 percent over the time series from 1990 to 2007, relative to the previous Inventory.

Planned Improvements

The empirically based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties in Century model results for *Grassland Remaining Grassland*, but this is a planned improvement for the Inventory. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.7. Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all grassland in an inventory year that had been in another land use at any point during the previous 20 years[38] according to the USDA *NRI land-use survey* (USDA-NRCS 2000). Consequently, lands are retained in this category for 20 years as recommended by IPCC (2006) unless there is another land use change. The Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands. It is important to note that these areas are part of the managed land base for the United States, as described in Section 7.1. Land use can lead to significant changes in C stocks, and plans are being made to include these areas in future C inventories.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. IPCC (2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[39]

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks from 1990 through 2008, which was largely due to annual cropland conversion to pasture (see Table 7-34 and Table 7-35). For example, the stock change rates were estimated to remove 20.3 Tg CO_2 Eq./yr (5.5 Tg C) and 25.1 Tg CO_2 Eq./yr (6.8 Tg C) from mineral soils in 1990 and 2008, respectively. Drainage of organic soils for grazing management led to losses varying from 0.5 to 0.9 Tg CO_2 Eq./yr (0.1 to 0.2 Tg C).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils is displayed in Figure 7-11 and Figure 7-12. Soil C stock increased in most states for *Land Converted to Grassland*. The largest gains were in the South-Central region, Midwest, and northern Great Plains. The patterns were driven by conversion of annual cropland into continuous pasture. Emissions from organic soils were largest in California, Florida, and the upper Midwest, coinciding with largest concentrations of organic soils in the United States that are used for agricultural production.

Methodology

This section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Grassland*. Biomass C stock changes are not explicitly included in this category but losses of associated with conversion of forest to grassland are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.13.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2008 if the land use was grassland, but had been another use in the previous 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland typically includes extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree

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

[39] Carbon dioxide emissions associated with liming are also estimated but included in a separate section of the report.

Table 7-34: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils[a, b]	(20.3)	(23.2)	(28.1)	(25.5)	(25.4)	(25.2)	(25.1)
Organic Soils	0.5	0.9	0.9	0.9	0.9	0.9	0.9
Total Net Flux[b]	**(19.8)**	**(22.3)**	**(27.3)**	**(24.6)**	**(24.5)**	**(24.3)**	**(24.2)**

[a] Stock changes due to application of sewage sludge are reported in *Grassland Remaining Grassland*.
[b] Preliminary estimates that will be finalized after public review period following completion of quality control measures.
Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-35: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007	2008
Mineral Soils[a, b]	(5.5)	(6.3)	(7.7)	(7.0)	(6.9)	(6.9)	(6.8)
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total Net Flux[b]	**(5.4)**	**(6.1)**	**(7.4)**	**(6.7)**	**(6.7)**	**(6.6)**	**(6.6)**

[a] Stock changes due to application of sewage sludge are reported in *Grassland Remaining Grassland*.
[b] Preliminary estimates that will be finalized after public review period following completion of quality control measures.
Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was applied to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils were estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[40] A Tier 2 approach was also used to estimate additional changes in mineral soil C stocks due to sewage sludge amendments. However, stock changes associated with sewage sludge amendments are reported in the *Grassland Remaining Grassland* section.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model as described for *Grassland Remaining Grassland*. Historical land-use and management patterns were used in the Century simulations as recorded in the NRI survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and the National Agricultural Statistics Service (NASS 1992, 1999, 2004) (see *Grassland Remaining Grassland* Tier 3 methods section for additional information).

Tier 2 Approach

The Tier 2 approach used for *Land Converted to Grassland* on mineral soils is the same as described for *Cropland Remaining Cropland* (See *Cropland Remaining Cropland* Tier 2 Approach and Annex 3.13 for additional information).

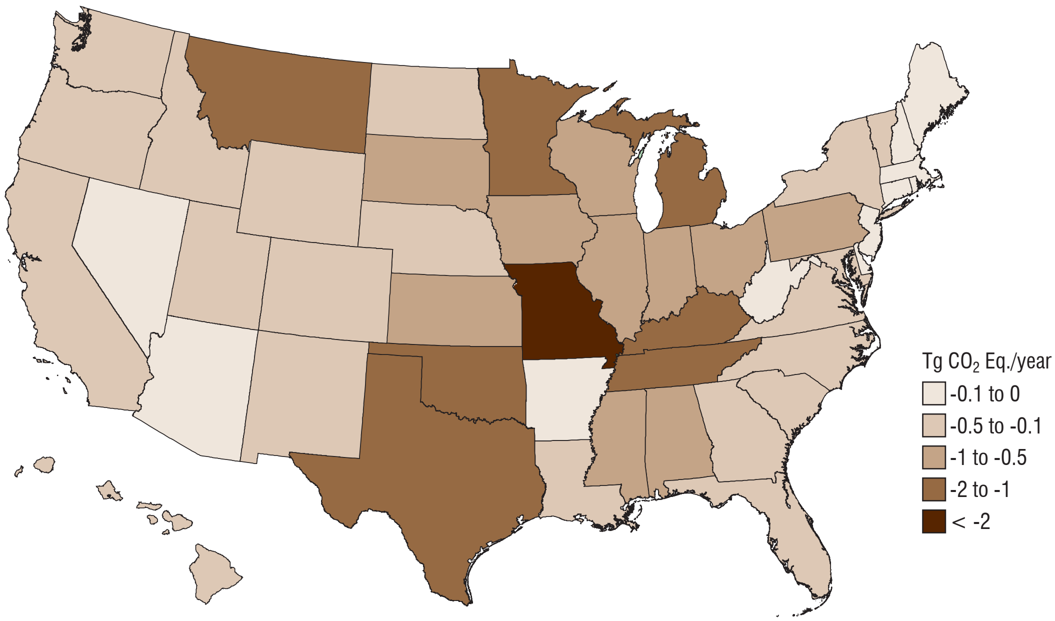
Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Land Converted to Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992,

[40] Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2000).

Figure 7-11

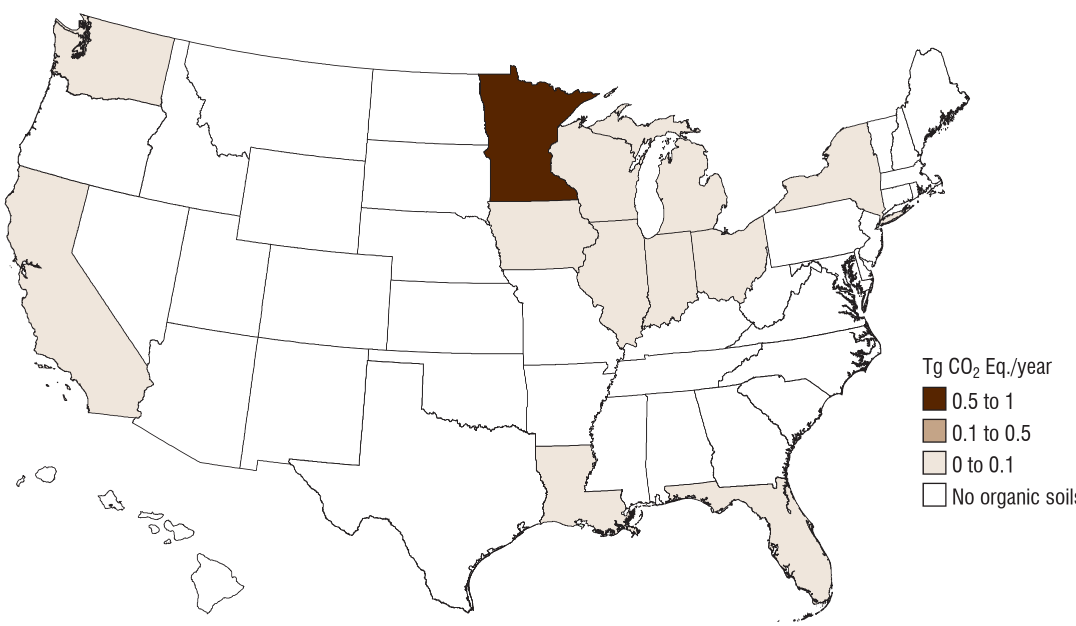
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2008, *Land Converted to Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure 7-12

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2008, *Land Converted to Grassland*



Note: Values greater than zero represent emissions.

and the annual flux estimated for 1997 was applied to 1993 through 2008.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described in *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty or annual C emission estimates from drained organic soils in *Land Converted to Grassland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-36 for each subsource (i.e., mineral soil C stocks and organic soil C stocks), disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with IPCC (2006), (i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities). The combined uncertainty for soil C stocks in *Land Converted to Grassland* ranged from 9 percent below to 10 percent above the 2008 estimate of -24.2 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See the QA/QC and Verification section under *Grassland Remaining Grassland*.

Recalculations Discussion

The estimated area of grasslands changed across the time series relative to the previous Inventory due to revisions in the forest land definition. This adjustment reduced the area of grassland in the United States because woodlands previously designated as grassland are now considered forest land. The revised areas altered the estimated soil C stock changes in *Land Converted to Grassland* by an average of 2.0 Tg CO_2 eq. or 8 percent over the time series from 1990 to 2007, relative to the previous Inventory.

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties in Century model results for *Land Converted to Grassland*, but this is a planned improvement for the Inventory. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvement.

Table 7-36: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (Tg CO_2 Eq. and Percent)

Source	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Grassland, Tier 3 Inventory Methodology	(20.1)	(20.7)	(19.5)	-3%	+3%
Mineral Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	(5.0)	(7.0)	(2.8)	-39%	+43%
Organic Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	0.9	0.2	1.8	-76%	+104%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stocks in Land Converted to Grassland	**(24.2)**	**(26.4)**	**(21.8)**	**-9%**	**+10%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

7.8. Wetlands Remaining Wetlands

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands which have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., draining, and clearing surface biomass), extraction (which results in the emissions reported under *Peatlands Remaining Peatlands*), and abandonment, restoration or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al., 2004); however, methane emissions are assumed to be insignificant under Tier 1 (IPCC, 2006). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release GHG emissions, and at present no methodology is provided by IPCC (2006) to estimate GHG emissions or removals from restored peatlands. This Inventory estimates both CO_2 and N_2O emissions from *Peatlands Remaining Peatlands* in accordance with Tier 1 IPCC (2006) guidelines.

CO_2 and N_2O Emissions from Peatlands Remaining Peatlands

IPCC (2006) recommends reporting CO_2 and N_2O emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur in wetland areas where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: sphagnum bogs in northern states and wetlands in states further south. The peat from sphagnum bogs in northern states, which is nutrient poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient rich.

IPCC (2006) recommends considering both on-site and off-site emissions when estimating CO_2 emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N_2O emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat. On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. On-site N_2O is emitted during draining depending on site fertility and if the deposit contains significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O.

Off-site CO_2 emissions from managed peatlands occur from the horticultural and landscaping use of peat. Carbon dioxide emissions occur as the nutrient-poor (but now fertilizer-enriched) peat is used in bedding plants, other greenhouse and plant nursery production, and by consumers, and as nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominately for horticultural purposes. The magnitude of the CO_2 emitted from peat depends on whether the peat has been extracted from nutrient-rich or nutrient-poor peat deposits.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.9 Tg CO_2 Eq. in 2008 (see Table 7-37) comprising 0.9 Tg CO_2 Eq. (941 Gg) of CO_2 and 0.005 Tg CO_2 Eq. (0.016 Gg) of N_2O.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO_2 Eq. across the time series with a decreasing trend from 1990 until 1994 followed by an increasing trend through 2000. Since 2000,

Table 7-37: Emissions from Lands Undergoing Peat Extraction (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007	2008
CO_2	1.0	1.0	1.2	1.1	0.9	1.0	0.9
N_2O	+	+	+	+	+	+	+
Total	**1.0**	**1.0**	**1.2**	**1.1**	**0.9**	**1.0**	**0.9**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports and stockpiles (i.e., apparent consumption).

Table 7-38: Emissions from Lands Undergoing Peat Extraction (Gg)

Gas	1990	1995	2000	2005	2006	2007	2008
CO_2	1,033	1,018	1,227	1,079	879	1,012	941
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.
Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports and stockpiles (i.e., apparent consumption).

total emissions show a decreasing trend until 2006 followed by a leveling off in recent years. Carbon dioxide emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO_2 across the time series and drive the trends in total emissions. Nitrous oxide emissions remained close to zero across the time series with a decreasing trend from 1990 until 1995 followed by an increasing trend through 2002. Nitrous oxide emissions show a decreasing trend between 2002 and 2006 followed by a leveling off in recent years. (See Table 7-37 and Table 7-38).

Methodology

Off-site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from *Peatlands Remaining Peatlands* were calculated by apportioning the annual weight of peat produced in the United States (Table 7-39) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage by weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default carbon fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. Both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1991–2009). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. The USGS often receives a response to the survey from most of the smaller peat producers, but fewer of the larger ones. For example, of the four active operations producing 23,000 or more metric tons per year, two did not respond to the survey in 2007. As a result, the USGS estimates production from the non-respondent peat producers based on responses to previous surveys (responses from 2004 and 2005, in the case above) or other sources. Estimates were made separately for Alaska, because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 7-40). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific carbon fraction conversion factors from IPCC (2006).[41]

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over two-and-a-half times the amount of domestic peat production. Therefore, off-site CO_2 emissions from the use of all horticultural

[41] Peat produced from Alaska was assumed to be nutrient-poor; as is the case in Canada, "where deposits of high-quality [but nutrient-poor] sphagnum moss are extensive" (USGS 2008).

Table 7-39: Peat Production of Lower 48 States (in thousands of metric tons)

Type of Deposit	1990	1995	2000	2005	2006	2007	2008
Nutrient-Rich	595.1	531.4	728.6	657.6	529.0	581.0	562.7
Nutrient-Poor	55.4	116.6	63.4	27.4	22.0	54.0	52.3
Total Production	**692.0**	**648.0**	**792.0**	**685.0**	**551.0**	**635.0**	**615.0**

Sources: *Minerals Yearbook: Peat* (1990–2007 Reports), *Mineral Commodity Summaries: Peat* (1996–2008 Reports), and *Mineral commodity summaries 2010* (2010 Report). United States Geological Survey.

Table 7-40: Peat Production of Alaska (in thousands of cubic meters)

	1990	1995	2000	2005	2006	2007	2008
Total Production	49.7	26.8	27.2	47.8	50.8	52.3	7.2

Sources: *Alaska's Mineral Industry* (1992–2007) *Reports and Alaska's mineral industry 2008: A summary.* Division of Geological & Geophysical Surveys, Alaska Department of Natural Resources.

peat within the United States are not accounted for using the Tier 1 approach. The United States has increasingly imported peat from Canada for horticultural purposes; in 2008, imports of sphagnum moss (nutrient-poor) peat from Canada represented 98 percent of total U.S. peat imports (USGS 2009). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emissions estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but in accordance with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method[42] can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006). The area of land managed for peat extraction in the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year. The annual land area estimates were then multiplied by the appropriate nutrient-rich or nutrient-poor IPCC (2006) default emission factor in order to calculate on-site CO_2 emission estimates. Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from *Peatlands Remaining Peatlands* in Alaska, the production data by volume were converted to weight using annual average peat bulk density values, and then converted to land area estimates using the same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which accounts for emissions resulting from the change in carbon stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006).

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emissions estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site

[42] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2006).

Uncertainty and Time-Series Consistency

The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed. The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. This same uncertainty and distribution was assumed for the peat type production percentages. The uncertainty associated with the Alaskan reported production data was assumed to be the same as the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the Alaskan Department of Natural Resources estimate that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008). The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008). IPCC (2006) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emissions factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed. The uncertainty values surrounding the carbon fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed. Based on these values and distributions, a Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 and N_2O emissions from *Peatlands Remaining Peatlands*. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-41. CO_2 emissions from *Peatlands Remaining Peatlands* in 2008 were estimated to be between 0.66 and 1.26 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 30 percent below to 34 percent above the 2008 emission estimate of 0.94 Tg CO_2 Eq. N_2O emissions from *Peatlands Remaining Peatlands* in 2008 were estimated to be between 0.001 and 0.007 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 74 percent below to 36 percent above the 2008 emission estimate of 0.005 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

This is only the second year that emissions from *Peatlands Remaining Peatlands* are included in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A revised 2007 estimate of peat production by volume for Alaska was reported in late 2008 (DGGS 2008). Updating the 2007 data with this revised estimate led to an incremental but not significant change in the 2007 emission estimates. In 2008, the preliminary peat production estimate for Alaska was approximately 7,220 cubic meters (9,444 cubic yards) for the year compared with 52,270 cubic meters (68,367 cubic

Table 7-41: Tier-2 Quantitative Uncertainty Estimates for CO_2 and N_2O Emissions from *Peatlands Remaining Peatlands*

Source	Gas	2008 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.9	0.7	1.3	-30%	+34%
Peatlands Remaining Peatlands	N_2O	+	+	+	-74%	+36%

+ Does not exceed 0.05 Tg CO_2 Eq.
[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

yards) produced in 2007. The peat sector in Alaska suffered what appears to be a loss of production during the year, but this is likely primarily due to "an obvious reporting shortfall" in the sector (Szumigala et al. 2009).

Planned Improvements

In order to further improve estimates of CO_2 and N_2O emissions from *Peatlands Remaining Peatlands*, future efforts will consider options for obtaining better data on the quantity of peat harvested per hectare and the total area undergoing peat extraction.

7.9. Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 4.4 percent of the United States (Nowak et al. 2005). With an average tree canopy cover of 27 percent, urban areas account for approximately 3 percent of total tree cover in the continental United States (Nowak et al. 2001). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 75.5 Tg CO_2 Eq. (20.6 Tg C) over the period from 1990 through 2008. Total sequestration increased by 65 percent between 1990 and 2008 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. Annual estimates of CO_2 flux (Table 7-42) were developed based on periodic (1990 and 2000) U.S. Census data on urban area. Net C flux from urban trees in 2008 was estimated to be −93.9 Tg CO_2 Eq. (−25.6 Tg C).

Net C flux from urban trees is proportionately greater on an area basis than that of forests. This trend is primarily the result of different net growth rates in urban areas versus forests—urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). Also, areas in each case are accounted for differently. Because urban areas contain less tree coverage than forest areas, the C storage per hectare of land is in fact smaller for urban areas. However, urban tree reporting occurs on a per unit tree cover basis (tree canopy area), rather than total land area. Areas covered by urban trees, therefore, appear to have a greater C density than do forested areas (Nowak and Crane 2002).

Table 7-42: Net C Flux from Urban Trees ($Tg\ CO_2$ Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(57.1)	(15.6)
1995	(67.3)	(18.4)
2000	(77.5)	(21.1)
2005	(87.8)	(23.9)
2006	(89.8)	(24.5)
2007	(91.9)	(25.1)
2008	(93.9)	(25.6)

Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak and Crane (2002) and Nowak (1994). In general, the methodology used by Nowak and Crane (2002) to estimate net C sequestration in urban trees followed three steps. First, field data from 14 cities were used to generate allometric estimates of biomass from measured tree dimensions. Second, estimates of tree growth and biomass increment were generated from published literature and adjusted for tree condition and land-use class to generate estimates of gross C sequestration in urban trees. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration values to derive estimates of net C sequestration. Estimates for these cities were then used to estimate urban forest C sequestration in the U.S. by using urban area estimates from U.S. Census data and urban tree cover estimates from remote sensing data, an approach consistent with Nowak and Crane (2002).

This approach is also consistent with the default IPCC methodology in IPCC (2006), although sufficient data are not yet available to determine interannual gains and losses in C stocks in the living biomass of urban trees. Annual changes in net C flux from urban trees are based solely on changes in total urban area in the United States. Most of the field data used to develop the methodology of Nowak et al. were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model. UFORE is a computer model that uses standardized field data from random plots in each city and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. UFORE was used with field data from a stratified random sample of plots in each city to quantify the characteristics of the urban forest. (Nowak et al. 2007a).

In order to generate the allometric relationships between tree dimensions and tree biomass, Nowak and Crane (2002) and Nowak (1994, 2007c, 2009) collected field measurements in a number of U.S. cities between 1989 and 2002. For a sample of trees in each of the cities in Table 7-43, data including tree measurements of stem diameter, tree height, crown height and crown width, and information on location, species, and canopy condition were collected. The data for each tree were converted into C storage by applying allometric equations to estimate aboveground biomass, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, moisture content, a C content of 50 percent (dry weight basis), and an adjustment factor of 0.8 to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). C storage estimates for deciduous trees include only carbon stored in wood. These calculations were then used to develop an allometric equation relating tree dimensions to C storage for each species of tree, encompassing a range of diameters.

Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. Growth calculations were adjusted by a factor to account for tree condition (fair to excellent, poor, critical, dying, or dead). For each tree, the difference in carbon storage estimates between year 1 and year (x + 1) gave the gross amount of C sequestered. These annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (e.g., parks, transportation, vacant, golf courses) were then scaled up to city estimates using tree population information.

Gross C emissions result from tree death and removals. Estimates of gross C emissions from urban trees were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site to the total C stock estimate for each city. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass. The estimated annual gross C emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

The field data for 13 of the 14 cities are described in Nowak and Crane (2002), Nowak et al. (2007a), and references cited therein. Data for the remaining city, Chicago, were taken from unpublished results (Nowak 2009). The allometric equations applied to the field data for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus was used. The adjustment (0.8) to account for less live tree biomass in urban trees was based on information in Nowak (1994). A root-to-shoot ratio of 0.26 was taken from Cairns et al. (1997), and species- or genus-specific moisture contents were taken from various literature sources (see Nowak 1994). Tree growth rates were taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. As described above, growth rates were adjusted to account for tree condition. Growth factors for Atlanta, Boston, Freehold, Jersey City, Moorestown, New York, Philadelphia, and Woodbridge were adjusted based on the typical growth conditions of different land-use categories (e.g., forest stands, park-like stands). Growth factors for the more recent studies in Baltimore, Chicago, Minneapolis, San Francisco, Syracuse, and Washington were adjusted using an updated methodology based on the condition of each individual tree, which is determined using tree competition factors (depending on whether it is open grown or suppressed) (Nowak 2007b).

Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak and Crane 2002).

National annual net C sequestration by urban trees was calculated based on estimates of gross and net sequestration for each of the 14 cities (Table 7-43), as well as urban area and urban tree cover data for the United States. This method was described in Nowak and Crane (2002) and has been updated to incorporate U.S. Census data. Net annual C sequestration estimates were derived for these 14 cities by subtracting the net annual emission estimates from the gross annual sequestration estimates. The urban area estimates were based on 1990 and 2000 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent "urban places," which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the "urban places" category with a new category of urban land called an "urban cluster," which included areas with more than 500 people per square mile. Urban land area increased by approximately 36 percent from 1990 to 2000; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under both 1990 and 2000 definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). The gross and net annual C sequestration values for each city were divided by each city's area of tree cover to determine the average annual sequestration rates per unit of tree area for each city. The median value for gross sequestration per unit area of tree cover (0.29 kg C/m2-yr) was then multiplied by the estimate of national urban tree cover area to estimate national annual gross sequestration, per the methods of Nowak and Crane (2002). To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration (0.72) for those cities that had both estimates. The urban tree cover estimates for each of the 14 cities and the United States were obtained from Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban area estimates were taken from Nowak et al. (2005).

Table 7-43: C Stocks (Metric Tons C), Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2-yr) for 14 U.S. Cities

City	Carbon Stocks	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net:Gross Annual Sequestration Ratio
Atlanta, GA	1,219,256	42,093	32,169	36.7%	0.34	0.26	0.76
Baltimore, MD	541,589	14,696	9,261	21.0%	0.35	0.22	0.63
Boston, MA	289,392	9,525	6,966	22.3%	0.30	0.22	0.73
Chicago, IL	649,000	22,800	16,100	17.2%	0.22	0.16	0.71
Freehold, NJ	18,144	494	318	34.4%	0.28	0.18	0.64
Jersey City, NJ	19,051	807	577	11.5%	0.18	0.13	0.71
Minneapolis, MN	226,796	8,074	4,265	26.4%	0.20	0.11	0.53
Moorestown, NJ	106,141	3,411	2,577	28.0%	0.32	0.24	0.76
New York, NY	1,224,699	38,374	20,786	20.9%	0.23	0.12	0.54
Philadelphia, PA	480,808	14,606	10,530	15.7%	0.27	0.02	0.72
San Francisco, CA	175,994	4,627	4,152	11.9%	0.33	0.29	0.90
Syracuse, NY	156,943	4,917	4,270	23.1%	0.33	0.29	0.87
Washington, DC	477,179	14,696	11,661	28.6%	0.32	0.26	0.79
Woodbridge, NJ	145,150	5,044	3,663	29.5%	0.28	0.21	0.73
					Median: 0.29		**Mean: 0.72**

NA = not analyzed.
Sources: Nowak and Crane (2002) and Nowak (2007a,c), Nowak (2009).

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 14 U.S. cities. A 10 percent uncertainty was associated with urban area estimates while a 5 percent uncertainty was associated with percent urban tree coverage. Both of these uncertainty estimates were based on expert judgment. Uncertainty associated with estimates of gross and net C sequestration for each of the 14 U.S. cities was based on standard error estimates for each of the city-level sequestration estimates reported by Nowak (2007c) and Nowak (2009). These estimates are based on field data collected in each of the 14 U.S. cities, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban tree and forest tree estimates will be addressed through the land-representation effort described at the beginning of this chapter.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-44. The net C flux from changes in C stocks in urban trees in 2008 was estimated to be between -114.5 and -75.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below and 19 percent above the 2008 flux estimate of -93.9 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The net C flux resulting from urban trees was predominately calculated using estimates of gross and net C sequestration estimates for urban trees and urban tree coverage area published in the literature. The validity of these data for their use in this section of the inventory was evaluated through correspondence established with an author of the papers. Through this correspondence, the methods used to collect the urban tree sequestration and area data were further clarified and the use of these data in the inventory was reviewed and validated (Nowak 2002a, 2007b).

Recalculations Discussion

Revised data for Chicago's urban forest, consisting of complete data on carbon storage, sequestration rates, and tree cover, was provided in Nowak (2009). Previous versions of the Inventory incorporated only a gross sequestration rate for Chicago, as reported in Nowak and Crane (2002). The incorporation of the new Chicago data resulted in a lower median gross sequestration value and a lower net sequestration to gross sequestration ratio for the set of 14 cities. These changes resulted in changes in the estimates of net annual C flux for urban trees for the time period 1990 through 2007. On average, estimates of net annual C flux for urban trees increased by 4.7 Tg CO_2 Eq. over the period from 1990 to 2007 compared to the previous report, representing on average a 5.9 percent decrease in annual sequestration over the same period.

Table 7-44: Tier 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(93.9)	(114.5)	(75.9)	-22%	+19%

Note: Parentheses indicate net sequestration.

Planned Improvements

A consistent representation of the managed land base in the United States is being developed. A component of this effort, which is discussed at the beginning of the Land Use, Land-Use Change, and Forestry chapter, will involve reconciling the overlap between urban forest and non-urban forest greenhouse gas inventories. It is highly likely that urban forest inventories are including areas also defined as forest land under the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, resulting in "double-counting" of these land areas in estimates of C stocks and fluxes for the Inventory. Planned improvements to the FIA program include the development of a long-term dataset that will define urban area boundaries and make it possible to identify what area is forested. Once those data become available, they will be incorporated into estimates of net C flux resulting from urban trees.

Urban forest data for additional cities are expected in the near future, and the use of these data will further refine the estimated median sequestration value. It may also be possible to report C losses and gains separately in the future. It is currently not possible, since existing studies estimate rather than measure natality or mortality; net sequestration estimates are based on assumptions about whether dead trees are being removed, burned, or chipped. There is an effort underway to develop long-term data on permanent plots in at least two cities, which would allow for direct calculation of C losses and gains from observed rather than estimated natality and mortality of trees.

Direct N_2O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 2.5 percent are currently applied to lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N_2O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas. In 2008, N_2O emissions from this source were 1.6 Tg CO_2 Eq. (5.1 Gg). There was an overall increase of 61 percent over the period from 1990 through 2008 due to a general increase in the application of synthetic N fertilizers to an expanding settlement area. Interannual variability in these emissions is directly attributable to interannual variability in total synthetic fertilizer consumption and sewage sludge applications in the United States. Emissions from this source are summarized in Table 7-45.

Table 7-45: N_2O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	1.0	3.2
1995	1.2	3.8
2000	1.1	3.7
2005	1.5	4.7
2006	1.5	4.8
2007	1.6	5.1
2008	1.6	5.1

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach was used to estimate soil N_2O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N_2O emissions from soils in settlements were based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in sewage sludge applied to non-agricultural land and surface disposal of sewage sludge (see Annex 3.11 for a detailed discussion of the methodology for estimating sewage sludge application).

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer was assumed to be applied to settlements and forests and values for 2002 through 2008 were based on 2001 values adjusted for annual total N fertilizer sales in the United States. Settlement application was calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.11 for further detail). The total amount of N resulting from these sources was multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N_2O emissions (IPCC 2006). The volatilized and leached/runoff proportions, calculated with the IPCC default volatilization factors (10 or 20 percent, respectively, for synthetic or organic N fertilizers) and leaching/runoff factor for wet areas (30 percent), were included with the total N contributions to indirect emissions, as reported in the N_2O Emissions from Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from settlements depends not only on N inputs, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. The IPCC default methodology does not incorporate any of these variables and only accounts for variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application was assigned a default level[43] of ±50 percent. Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. Uncertainty in the emission factors was provided by the IPCC (2006).

Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2008 emission estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-46. Nitrous oxide emissions from soils in *Settlements Remaining Settlements* in 2008 were estimated to be between 0.8 and 4.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2008 emission estimate of 1.6 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

The total amount of fertilizer applied in non-agricultural lands (settlements and forest land) has been estimated by the USGS for 1990 through 2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). In the previous Inventory, N fertilizer applications and subsequent N_2O emissions was only estimated for southeastern forest plantations, but the analysis was extended in this Inventory to include N applications to commercial Douglas fir timberlands in Oregon and Washington. Consequently, there was less estimated N fertilizer for application to settlements. This change resulted

Table 7-46: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emissions (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	1.6	0.8	4.2	-49%	+163%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

[43] No uncertainty is provided with the USGS application data (Ruddy et al. 2006) so a conservative ±50% was used in the analysis.

in an average change in N_2O emission of less than 4 percent relative to the previous Inventory.

Planned Improvements

A minor improvement is to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

7.10. Land Converted to Settlements (Source Category 5E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. However, data on the amount of land converted to settlements is currently lacking. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

7.11. Other (IPCC Source Category 5G)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

In the United States, a significant change in C stocks results from the removal of yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps from settlements to be disposed in landfills. Yard trimmings and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are discarded in landfills. C contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are a component of the forest ecosystem. The wood products serve as reservoirs to which

Table 7-47: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	1990	1995	2000	2005	2006	2007	2008
Yard Trimmings	**(21.2)**	**(12.5)**	**(8.2)**	**(6.6)**	**(6.8)**	**(6.3)**	**(6.3)**
Grass	(1.9)	(0.8)	(0.4)	(0.4)	(0.5)	(0.4)	(0.4)
Leaves	(9.7)	(6.0)	(4.0)	(3.3)	(3.3)	(3.1)	(3.1)
Branches	(9.7)	(5.8)	(3.7)	(2.9)	(3.0)	(2.8)	(2.7)
Food Scraps	**(2.2)**	**(1.4)**	**(3.1)**	**(3.5)**	**(3.6)**	**(3.5)**	**(3.3)**
Total Net Flux	**(23.5)**	**(13.9)**	**(11.3)**	**(10.1)**	**(10.3)**	**(9.8)**	**(9.5)**

Note: Totals may not sum due to independent rounding.

Table 7-48: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2005	2006	2007	2008
Yard Trimmings	**(5.8)**	**(3.4)**	**(2.2)**	**(1.8)**	**(1.8)**	**(1.7)**	**(1.7)**
Grass	(0.5)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Leaves	(2.7)	(1.6)	(1.1)	(0.9)	(0.9)	(0.8)	(0.8)
Branches	(2.6)	(1.6)	(1.0)	(0.8)	(0.8)	(0.8)	(0.7)
Food Scraps	**(0.6)**	**(0.4)**	**(0.9)**	**(1.0)**	**(1.0)**	**(0.9)**	**(0.9)**
Total Net Flux	**(6.4)**	**(3.8)**	**(3.1)**	**(2.8)**	**(2.8)**	**(2.7)**	**(2.6)**

Note: Totals may not sum due to independent rounding.

C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. C stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is therefore reported under the "Other" source category.

Both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 50 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2009; Schneider 2007, 2008). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 6 percent decrease in the tonnage generated (i.e., collected for composting or disposal). At the same time, a dramatic increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 29 percent in 2008. The net effect of the reduction in generation and the increase in composting is a 62 percent decrease in the quantity of yard trimmings disposed in landfills since 1990.

Food scraps generation has grown by 53 percent since 1990, but the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 79 percent in 2008. Overall, the decrease in the yard trimmings landfill disposal rate has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual landfill carbon storage from 23.5 Tg CO_2 Eq. in 1990 to 9.5 Tg CO_2 Eq. in 2008 (Table 7-47 and Table 7-48).

Methodology

When wastes of sustainable, biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the global C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008), and thus the stock of carbon in landfills can increase, with the net effect being a net atmospheric removal of carbon. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years, based on methodologies presented for the Land Use, Land-Use Change and Forestry sector in IPCC (2003). C stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the portion of C landfilled in previous years that decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (1) the composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2008 Facts and Figures* (EPA 2009), which provides data for 1960, 1970, 1980, 1990, 2000, 2003, and 2005 through 2008. To provide data for some of the missing years, detailed backup data were obtained from Schneider (2007, 2008). Remaining years in the time series for which data were not provided were estimated using linear interpolation. The EPA (2009) report does not subdivide discards of individual materials into volumes landfilled and combusted, although it provides an estimate of the proportion of overall waste stream discards managed in landfills and combustors (i.e., ranging from 92 percent and 8 percent respectively in 1984–1986 to 67 percent and 33 percent in 1960).

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 7-49).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with a "seed" containing methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of initial C (shown in the row labeled "CS" in Table 7-49).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade, resulting in emissions of CH_4 and CO_2 (the CH_4 emissions resulting from decomposition of yard trimmings and food scraps are accounted for in the "Waste" chapter). The degradable portion of the C is assumed to decay according to first order kinetics. Default IPCC 2006 Guidelines values for first order rate constants are used to derive half-lives for branches and food scraps, while expert judgment was used to estimate the half-lives of grass and leaves. Food scraps are assumed to have a half-life of 3.7 years; grass is assumed to have a half-life of 5 years; leaves are assumed to have a half-life of 20 years; and branches are assumed to have a half-life of 23.1 years. The half-life of food scraps is consistent with analysis for landfill CH_4 in the "Waste" chapter.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to the following formula:

$$LFC_{i,t} = \sum_n W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

- t = Year for which C stocks are being estimated (year)
- i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps)
- $LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (metric tons)
- $W_{i,n}$ = Mass of waste *i* disposed in landfills in year *n* (metric tons, wet weight)
- n = Year in which the waste was disposed (year, where 1960 < n < t)
- MC_i = Moisture content of waste *i* (percent of water)
- CS_i = Proportion of initial C that is stored for waste *i* (percent)
- ICC_i = Initial C content of waste *i* (percent),
- e = Natural logarithm
- k = First order rate constant for waste *i*, which is equal to 0.693 divided by the half-life for decomposition ($year^{-1}$)

For a given year *t*, the total stock of C in landfills (*TLFCt*) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year *t* is calculated as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{t-1}$$

Thus, the C placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period (2008). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. Of this amount,

Table 7-49: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Half-Life (years) for Landfilled Yard Trimmings and Food Scraps in Landfills

	Yard Trimmings			Food Scraps
Variable	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
CS, proportion of initial C stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Half-life (years)	5	20	23	4

16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1964, more than half of the degradable portion (500,000 metric tons) decomposes, leaving a total of 635,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2008, the total food scraps C originally disposed in 1960 had declined to 179,000 metric tons (i.e., virtually all of the degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed in subsequent years (1961 through 2008), the total landfill C from food scraps in 2008 was 31.5 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2008, yielding a value of 243.0 million metric tons (as shown in Table 7-50). In exactly the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 7-48) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2008 shown in Table 7-48 (2.6 Tg C) is equal to the stock in 2008 (243.0 Tg C) minus the stock in 2007 (240.4 Tg C).

The C stocks calculated through this procedure are shown in Table 7-50.

Uncertainty and Time-Series Consistency

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decomposition rate (half-life), and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-51. Total yard trimmings and food scraps CO_2 flux in 2008 was estimated to be between −18.3 and −4.6 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 93 percent below to 51 percent above the 2008 flux estimate of −9.5 Tg CO_2 Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990

Table 7-50: C Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2005	2006	2007	2008
Yard Trimmings	**160.3**	**183.5**	**196.0**	**206.2**	**208.0**	**209.7**	**211.4**
Grass	16.2	18.0	18.6	19.2	19.4	19.5	19.6
Leaves	71.7	82.5	88.6	93.6	94.5	95.3	96.2
Branches	72.5	83.1	88.8	93.4	94.2	94.9	95.7
Food Scraps	**18.4**	**20.9**	**24.3**	**28.7**	**29.7**	**30.6**	**31.5**
Total Carbon Stocks	**178.7**	**204.4**	**220.3**	**234.9**	**237.7**	**240.4**	**243.0**

Note: Totals may not sum due to independent rounding.

Table 7-51: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(9.5)	(18.3)	(4.6)	-93%	+51%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net C sequestration.

through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation.

Recalculations Discussion

Input data were updated for the years: 2003, 2005, and 2006 based on the update values reported in *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2008 Facts and Figures* (EPA 2009). As a result, C storage estimates for the years 2003, 2005, and 2006 were revised relative to the previous Inventory, resulting in an annual average decrease in C stored of 0.2 percent. While data inputs for the years 2004 and 2007 were not revised, overall C storage in any given year is dependent on the previous year's storage (as shown in the second equation above), and so C storage estimates for those years were also revised. This residual change decreased the overall C stored in 2004 and 2007 by 0.1 percent on average compared to previous Inventory.

Planned Improvements

Future work is planned to develop improved estimates of the decay rates for the individual materials. Additional analysis may also be performed to evaluate the potential contribution of inorganic C, primarily in the form of carbonates, to landfill sequestration, as well as the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the "Waste" chapter.

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 22 percent of total U.S. anthropogenic methane (CH_4) emissions in 2008, the second largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 4 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. Nitrous oxide emissions from composting were also estimated. Together, these waste activities account for less than 2 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Carbon dioxide, N_2O, and CH_4 emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2008 resulted in 13.1 Tg CO_2 Eq. emissions, nearly half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3-7.

Figure 8-1

2008 Waste Chapter Greenhouse Gas Emission Sources

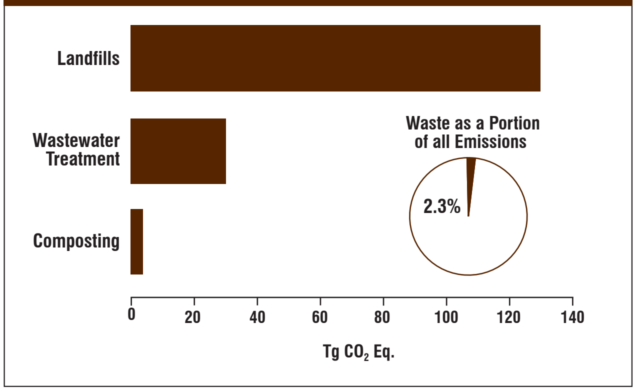


Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007	2008
CH_4	**173.2**	**169.6**	**147.1**	**151.5**	**153.1**	**152.5**	**152.3**
Landfills	149.3	144.1	120.7	125.6	127.1	126.5	126.3
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4	24.3
Composting	0.3	0.7	1.3	1.6	1.6	1.7	1.7
N_2O	**4.0**	**4.8**	**5.8**	**6.5**	**6.6**	**6.7**	**6.8**
Domestic Wastewater Treatment	3.7	4.0	4.5	4.7	4.8	4.9	4.9
Composting	0.4	0.8	1.4	1.7	1.8	1.8	1.8
Total	**177.2**	**174.5**	**153.0**	**158.0**	**159.7**	**159.3**	**159.1**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007	2008
CH_4	**8,246**	**8,078**	**7,006**	**7,213**	**7,292**	**7,264**	**7,254**
Landfills	7,111	6,860	5,747	5,980	6,050	6,023	6,016
Wastewater Treatment	1,120	1,183	1,199	1,158	1,166	1,162	1,158
Composting	15	35	60	75	75	79	80
N_2O	**13**	**16**	**19**	**21**	**21**	**22**	**22**
Domestic Wastewater Treatment	12	13	14	15	15	16	16
Composting	1	3	4	6	6	6	6

Note: Totals may not sum due to independent rounding.

Overall, in 2008, waste activities generated emissions of 159.1 Tg CO_2 Eq., or just over 2 percent of total U.S. greenhouse gas emissions.

8.1 Landfills (IPCC Source Category 6A1)

In 2008, landfill CH_4 emissions were approximately 126.3 Tg CO_2 Eq. (6,016 Gg of CH_4), representing the second largest source of CH_4 emissions in the United States, behind enteric fermentation. Emissions from municipal solid waste (MSW) landfills, which received about 64.5 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 (*BioCycle* 2006, adjusted to include missing data from five states).

After being placed in a landfill, waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume. Significant CH_4 production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years or longer.

From 1990 to 2008, net CH_4 emissions from landfills decreased by approximately 15 percent (see Table 8-3 and Table 8-4). This net CH_4 emissions decrease is the result of increases in the amount of landfill gas collected and combusted, which has more than offset the additional CH_4 generation resulting from an increase in the amount of municipal solid waste landfilled over the past 19 years. Over the past 7 years, however, the net CH_4 emissions have slowly increased from 2001 to 2006, but have shown a decreasing trend in the past two years. While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase no longer exceeds that rate of additional CH_4 generation resulting from an increase in the amount of municipal solid waste landfilled as the U.S. population grows.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of waste in MSW landfills, which is related to total waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in MSW landfills increased from about 209 Tg in 1990 to 294 Tg in 2008, an increase of 41 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from MSW landfills increased as well. In 1990, for example, approximately 871 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills, while in 2008, 6,451 Gg CH_4 was combusted, resulting in a 5 percent increase in the quantity of CH_4 recovered and combusted from 2007 levels. In 2008, an estimated 64 new landfill gas-to-energy (LFGTE) projects and 41 new flares began operation.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007	2008
MSW Landfills	172.6	191.8	206.9	241.2	248.1	254.2	260.3
Industrial Landfills	11.6	12.9	14.4	15.3	15.3	15.4	15.6
Recovered							
Gas-to-Energy	(13.2)	(22.5)	(49.4)	(56.6)	(59.1)	(63.8)	(68.3)
Flared	(5.1)	(22.5)	(37.91)	(60.3)	(63.2)	(65.3)	(67.2)
Oxidized[a]	(16.6)	(16.0)	(13.4)	(14.0)	(14.1)	(14.1)	(14.0)
Total	**149.3**	**144.1**	**120.7**	**125.6**	**127.1**	**126.5**	**126.3**

[a] Includes oxidation at both municipal and industrial landfills.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	1995	2000	2005	2006	2007	2008
MSW Landfills	8,219	9,132	9,854	11,486	11,813	12,107	12,395
Industrial Landfills	554	615	687	728	730	735	741
Recovered							
Gas-to-Energy	(629)	(1,055)	(2,352)	(2,696)	(2,812)	(3,038)	(3,252)
Flared	(242)	(1,069)	(1,804)	(2,874)	(3,008)	(3,111)	(3,200)
Oxidized[a]	(790)	(762)	(639)	(664)	(672)	(669)	(668)
Total	**7,111**	**6,860**	**5,747**	**5,980**	**6,050**	**6,023**	**6,016**

[a] Includes oxidation at both municipal and industrial landfills.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Over the next several years, the total amount of municipal solid waste generated is expected to increase as the U.S. population continues to grow. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to continue to increase as a result of 1996 federal regulations that require large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005), voluntary programs encouraging CH_4 recovery and use such as EPA's Landfill Methane Outreach Program (LMOP), and federal and state incentives that promote renewable energy (e.g. tax credits, low interest loans, and Renewable Portfolio Standards).

Methodology

A detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

Methane emissions from landfills were estimated to equal the CH_4 produced from municipal solid waste landfills, plus the CH_4 produced by industrial landfills, minus the CH_4 recovered and combusted, minus the CH_4 oxidized before being released into the atmosphere:

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

where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from municipal solid waste landfills
$CH_{4,\text{ind}}$ = CH_4 generation from industrial landfills
R = CH_4 recovered and combusted
Ox = CH_4 oxidized from MSW and industrial landfills before release to the atmosphere

The methodology for estimating CH_4 emissions from municipal solid waste landfills is based on the first order decay model described by the Intergovernmental Panel on Climate Change (IPCC 2006). Values for the CH_4 generation potential (L_0) and rate constant (k) were obtained from an analysis of CH_4 recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges, and historical census data were used to account for the shift in population to more arid areas over time. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 2007 and 2008 were extrapolated based on *BioCycle* data and the U.S. Census population from 2008. Data for 1989 through 2006 were obtained from *BioCycle* (2006). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2009) and national per capita solid waste generation from *BioCycle* (2006). Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in this Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed of in landfills (Methane Conversion Factor, MCF, of 1) and those disposed of in dumps (MCF of 0.6). Please see Annex 3.14 for more details.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2008), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). As the EIA database only included data through 2006, 2007 and 2008 recovery for projects included in the EIA database were assumed to be the same as in 2006. The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2008 was estimated. This quantity likely underestimates flaring because these databases do not have information on all flares in operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for landfills with LFGTE projects. If a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors*, Chapter 2.4 (EPA 1998) efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Emissions from industrial landfills were estimated from activity data for industrial production (ERG 2009), waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper industries, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every landfill for each year of its operation. The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4, as determined from several studies of CH_4 recovery at landfills, are representative of U.S. landfills.

Additionally, the approach used to estimate the contribution of industrial wastes to total CH_4 generation introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation by cover soils. There is also uncertainty in the estimates of methane that is recovered by flaring and energy projects. The IPCC default value of 10 percent for uncertainty in recovery estimates was used in the uncertainty analysis when metering was in place (for about 64 percent of the CH_4 estimated to be recovered). For flaring without metered recovery data (approximately 34 percent of the CH_4 estimated to be recovered), a much higher uncertainty of approximately 50 percent was used (e.g., when recovery was estimated as 50 percent of the flare's design capacity).

Nitrous oxide emissions from the application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the 2006 IPCC Guidelines (IPCC 2006) did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, any uncertainty or bias caused by not including N_2O emissions from landfills is expected to be minimal.

The results of the IPCC Good Practice Guidance Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2008 were estimated to be between 71.5 and 172.6 Tg CO_2 Eq., which indicates a range of 43 percent below to 37 percent above the 2008 emission estimate of 126.3 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. A primary focus of the QA/QC checks was to ensure that CH_4 recovery estimates were not double-counted. Both manual and electronic checks were made to ensure that emission avoidance from each landfill was calculated in only one of the three databases. The primary calculation spreadsheet is tailored from the IPCC waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values were verified by secondary QA/QC review.

Recalculations Discussion

In developing the current Inventory, additional steps were taken in order to further describe the uncertainty surrounding CH_4 emissions from landfills relative to the previous Inventory. A separate Monte Carlo analysis for MSW and industrial landfills was conducted to emphasize

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2008 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	**CH_4**	**126.3**	**71.5**	**172.6**	**-43%**	**+37%**
MSW	CH_4	112.3	70.8	172.7	-37%	+54%
Industrial	CH_4	14.0	10.2	16.9	-27%	+21%

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

Box 8-1: Biogenic Emissions and Sinks of Carbon

Carbon dioxide emissions from the combustion or decomposition of biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. In contrast, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this inventory.

Depositing wastes of biogenic origin in landfills causes the removal of carbon from its natural cycle between the atmosphere and biogenic materials. As empirical evidence shows, some of these wastes degrade very slowly in landfills, and the carbon they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2005). Estimates of carbon removals from landfilling of forest products, yard trimmings, and food scraps are further described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in IPCC (2003) and IPCC (2006).

the greater amount of uncertainty surrounding industrial waste data.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of the amount of waste placed in MSW landfills. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares.

8.2 Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic[1] and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. In the United States, approximately 20 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2007).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the N present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but is more often associated with denitrification.

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater.

In 2008, CH_4 emissions from domestic wastewater treatment were 15.7 Tg CO_2 Eq. (749 Gg). Emissions gradually increased from 1990 through 1997, but have

[1] Throughout the Inventory, emissions from domestic wastewater also includes any commercial and industrial wastewater collected and co-treated with domestic wastewater.

Table 8-6: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Gas/Activity	1990	1995	2000	2005	2006	2007	2008
CH_4	**23.5**	**24.8**	**25.2**	**24.3**	**24.5**	**24.4**	**24.3**
Domestic	16.4	16.9	16.8	16.2	16.0	15.9	15.7
Industrial[a]	7.1	8.0	8.4	8.2	8.5	8.5	8.6
N_2O	**3.7**	**4.0**	**4.5**	**4.7**	**4.8**	**4.9**	**4.9**
Domestic	3.7	4.0	4.5	4.7	4.8	4.9	4.9
Total	**27.2**	**28.9**	**29.6**	**29.0**	**29.3**	**29.3**	**29.2**

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.
Note: Totals may not sum due to independent rounding.

Table 8-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Gas/Activity	1990	1995	2000	2005	2006	2007	2008
CH_4	**1,120**	**1,183**	**1,199**	**1,158**	**1,166**	**1,162**	**1,158**
Domestic	782	804	801	770	763	757	749
Industrial[a]	338	380	398	389	403	406	409
N_2O	**11.9**	**13.0**	**14.4**	**15.3**	**15.5**	**15.7**	**15.9**
Domestic	11.9	13.0	14.4	15.3	15.5	15.7	15.9

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.
Note: Totals may not sum due to independent rounding.

decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. In 2008, CH_4 emissions from industrial wastewater treatment were estimated to be 8.6 Tg CO_2 Eq. (409 Gg). Industrial emission sources have increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 8-6 and Table 8-7 provide CH_4 and N_2O emission estimates from domestic and industrial wastewater treatment. With respect to N_2O, the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2008 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 4.6 Tg CO_2 Eq. (15 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 4.9 Tg CO_2 Eq. (16 Gg). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. Methane emissions from septic systems were estimated by multiplying the total 5-day BOD (BOD_5) produced in the United States by the percent of wastewater treated in septic systems (20 percent), the maximum CH_4 producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD), and the CH_4 correction factor (MCF) for septic systems (0.5). Methane emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (80 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing capacity of domestic wastewater (0.6), and the relative MCFs for aerobic (zero or 0.3) and anaerobic (0.8) systems. Methane emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4) , and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). The methodological equations are:

Emissions from Septic Systems = A

= (% onsite) × (total BOD_5 produced) × (B_o) × (MCF-septic) × $1/10^6$

Emissions from Centrally Treated Aerobic Systems = B

= [(% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/primary) × (1-% BOD removed in prim. treat.)] × (% operations not well managed) × (B_o) × (MCF-aerobic_not_well_man.) × $1/10^6$

Emissions from Centrally Treated Anaerobic Systems = C

= [(% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/primary) × (1-%BOD removed in prim. treat.)] × (B_o) × (MCF-anaerobic) × $1/10^6$

Emissions from Anaerobic Digesters = D

= [(POTW_flow_AD) × (digester gas)/(per capita flow)] × conversion to m^3 × (FRAC_CH_4) × (365.25) × (density of CH_4) × (1-DE) × $1/10^9$

Total CH_4 Emissions (Gg) = A + B + C + D

where,

% onsite	=	Flow to septic systems/total flow
% collected	=	Flow to POTWs/total flow
% aerobic	=	Flow to aerobic systems/total flow to POTWs
% anaerobic	=	Flow to anaerobic systems/total flow to POTWs
% aerobic w/out primary	=	Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary	=	Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat.	=	32.5 %
% operations not well managed	=	Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary	=	Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary	=	Percent of anaerobic systems that employ primary treatment
Total BOD_5 produced	=	kg BOD/capita/day × U.S. population × 365.25 days/yr
B_o	=	Maximum CH_4-producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD)
MCF-septic	=	CH_4 correction factor for septic systems (0.5)
$1/10^6$	=	Conversion factor, kg to Gg
MCF-aerobic_ not_ well_man.	=	CH_4 correction factor for aerobic systems that are not well managed (0.3)
MCF-anaerobic	=	CH_4 correction factor for anaerobic systems (0.8)
DE	=	CH_4 destruction efficiency from flaring or burning in engine (0.99 for enclosed flares)
POTW_ flow_AD	=	Wastewater influent flow to POTWs that have anaerobic digesters (gal)
digester gas	=	Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) (Metcalf and Eddy 1991)

per capita flow = Wastewater flow to POTW per person per day (100 gal/person/day)

conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)

FRAC_CH_4 = Proportion CH_4 in biogas (0.65)

density of CH_4 = 662 (g CH_4/m^3 CH_4)

$1/10^9$ = Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2009a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 8-8 presents U.S. population and total BOD_5 produced for 1990 through 2008. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, and 2007 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2007), with data for intervening years obtained by linear interpolation. The wastewater flow to aerobic and anaerobic systems, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 *Clean Watershed Needs Survey* (EPA 1992, 1996, 2000, and 2004a). Data for intervening years were obtained by linear interpolation. The BOD_5 production rate (0.09 kg/capita/day) for domestic wastewater was obtained from Metcalf and Eddy (1991 and 2003).

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	8,350
1995	271	8,895
2000	286	9,414
2001	289	9,509
2002	292	9,598
2003	295	9,681
2004	297	9,770
2005	300	9,858
2006	303	9,950
2007	306	10,047
2008	308	10,139

Source: U.S. Census Bureau (2009a); Metcalf & Eddy 1991 and 2003.

The CH_4 emission factor (0.6 kg CH_4/kg BOD_5) and the MCFs were taken from IPCC (2006). The CH_4 destruction efficiency, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in *AP-42 Compilation of Air Pollutant Emission Factors*, Chapter 2.4 (EPA 1998), efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used by the Landfill Methane Outreach Program (LMOP). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf and Eddy (1991). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "Recommended Standards for Wastewater Facilities (Ten-State Standards)" (2004).

Industrial Wastewater CH_4 Emission Estimates

Methane emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified. High volumes of wastewater generated and a high organic wastewater load were the main criteria. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2008 are displayed in Table 8-9 below. Table 8-10 contains production data for these industries.

Methane emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the percentage of organic loading assumed to degrade

Table 8-9: Industrial Wastewater CH_4 Emissions by Sector for 2008

	CH_4 Emissions ($Tg\ CO_2$ Eq.)	% of Industrial Wastewater CH_4
Pulp & Paper	4.0	47%
Meat & Poultry	3.7	43%
Petroleum Refineries	0.6	7%
Fruit & Vegetables	0.1	1%
Ethanol Refineries	0.1	1%
Total	**8.6**	**100%**

Note: Totals may not sum due to independent rounding.

Table 8-10: U.S. Pulp and Paper; Meat and Poultry; Vegetables, Fruits and Juices Production; and Fuels Production (Tg)

Year	Pulp and Paper	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.7	702.4
1995	140.9	30.8	18.9	46.9	4.2	735.6
2000	142.8	32.1	22.2	50.9	4.9	795.2
2001	134.3	31.6	22.8	45.0	5.3	794.9
2002	132.7	32.7	23.5	47.7	6.4	794.4
2003	131.9	32.3	23.7	44.8	8.4	804.2
2004	136.4	31.2	24.4	47.8	10.2	821.5
2005	131.4	31.4	25.1	42.9	11.7	818.6
2006	137.4	32.5	25.5	42.9	14.5	826.7
2006	135.9	33.4	26.0	44.8	19.4	827.6
2007	134.5	34.4	26.5	45.8	26.9	829.0
2008	134.5	34.4	26.5	45.8	26.9	829.0

anaerobically, and the emission factor. Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment and secondary treatment. For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated.

The methodological equations are:

$$CH_4 \text{ (industrial wastewater)} = P \times W \times COD \times TA \times B_o \times MCF$$

$$\%TA_p = [\%Plants_o \times \%WW_{a,p} \times \%COD_p]$$

$$\%TA_s = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plants_t \times \%WW_{a,t} \times \%COD_s]$$

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)

P = Industry output (metric tons/year)

W = Wastewater generated (m^3/metric ton of product)

COD = Organics loading in wastewater (kg /m^3)

S = Removal of COD as sludge prior to anaerobic treatment (kg COD/year)

$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment

$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment

$\%Plants_o$ treatment = Percent of plants with onsite

$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment

$\%COD_p$ = Percent of COD entering primary treatment

$\%Plants_a$ = Percent of plants with anaerobic secondary treatment

$\%Plants_t$ = Percent of plants with other secondary treatment

$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment

$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment

Table 8-11: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (%)

	Industry						
Variable	Pulp and Paper	Meat Processing	Poultry Processing	Fruit/Vegetable Processing	Ethanol Production —Wet Mill	Ethanol Production —Dry Mill	Petroleum Refining
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	10.5	33	25	4.2	33.3	75	100
$\%Plants_o$	60	100	100	11	100	100	100
$\%Plants_a$	25	33	25	5.5	33.3	75	100
$\%Plants_t$	35	67	75	5.5	66.7	25	0
$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

$\%COD_s$ = Percent of COD entering secondary treatment

B_o = Maximum CH_4 producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)

MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

As described below, the values presented in Table 8-11 were used in the inventory calculations.

Pulp and Paper. Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. No anaerobic activity is assumed to occur in activated sludge systems or aerated stabilization basins (note: although IPCC recognizes that some CH_4 can be emitted from anaerobic pockets, they recommend an MCF of zero). However, about 25 percent of the wastewater treatment systems used in the United States are non-aerated stabilization basins. These basins are typically 10 to 25 feet deep. These systems are classified as anaerobic deep lagoons (MCF = 0.8).

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the *Lockwood-Post Directory* (Lockwood-Post 2002). Published data from the American Forest and Paper Association, data published by Paper Loop, and other published statistics were used to estimate production for 2002 through 2008 (Pulp and Paper 2005, 2006 and monthly reports from 2003 through 2008; Paper 360 2007). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps and dissolved air flotation when treating wastewater on site. About 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default Bo of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the *USDA Agricultural Statistics Database and the Agricultural Statistics Annual Reports* (USDA 2009a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m3/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default Bo of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2009a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-12, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors.

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. According to the Renewable Fuels Association, 82 percent of ethanol production facilities use corn as the sole feedstock and 7 percent of facilities use a combination of corn and another starch-based feedstock. The fermentation of corn is the principal ethanol production process in the United States and is expected to increase through 2012, and potentially more; therefore, emissions associated with wastewater treatment at starch-based ethanol production facilities were estimated (ERG 2006).

Table 8-12: Wastewater Flow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.77	0.805
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.783	1.831

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallon per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling)

(Ruocco 2006a,b; Merrick 1998; Donovan 1996; and NRBP 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the CH_4 is recovered through the use of biomethanators (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = \{\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times [(\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p) + (\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s) + (\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s)] \times B_o \times \text{MCF} \times \%\text{ Not Recovered}\} + \{\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times [(\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p) + (\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s) + (\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s)] \times B_o \times \text{MCF} \times \%\text{ Recovered} \times (1\text{-DE})\} \times 1/10^9$$

where,

Production	=	Gallons ethanol produced (wet milling or dry milling)
Flow	=	Gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD	=	COD concentration in influent (3 g/l)
3.785	=	Conversion, gallons to liters
$\%Plants_o$	=	Percent of plants with onsite treatment (100%)
$\%WW_{a,p}$	=	Percent of wastewater treated anaerobically in primary treatment (0%)
$\%COD_p$	=	Percent of COD entering primary treatment (100%)
$\%Plants_a$	=	Percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
$\%Plants_t$	=	Percent of plants with other secondary treatment (66.7% wet, 25% dry)
$\%WW_{a,s}$	=	Percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
$\%WW_{a,t}$	=	Percent of wastewater treated anaerobically in other secondary treatment (0%)
$\%COD_s$	=	Percent of COD entering secondary treatment (100%)
B_o	=	Maximum methane producing capacity (0.25 g CH_4/g COD)
MCF	=	Methane conversion factor (0.8 for anaerobic systems)
% Recovered	=	Percent of wastewater treated in system with emission recovery
% Not Recovered	=	1 - percent of wastewater treated in system with emission recovery
DE	=	Destruction efficiency of recovery system (99%)
$1/10^9$	=	Conversion factor, g to Gg

A time series of CH_4 emissions for 1990 through 2008 was developed based on production data from the Renewable Fuels Association (RFA 2009).

Petroleum Refining. Petroleum refining wastewater treatment operations produce CH_4 emissions from anaerobic wastewater treatment. The wastewater inventory section includes CH_4 emissions from petroleum refining wastewater treated on site under intended or unintended anaerobic conditions. Most facilities use aerated biological systems, such as trickling filters or rotating biological contactors; these systems can also exhibit anaerobic conditions that can result in the production of CH_4. Oil/water separators are used as a primary treatment method; however, it is unlikely that any COD is removed in this step.

Available information from the industry was compiled. The wastewater generation rate, from CARB 2007 and Timm 1985, was determined to be 35 gallons per barrel of finished product. An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al.).

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times B_o \times \text{MCF}$$

Where:

Flow	=	Annual flow treated through anaerobic treatment system (m^3/year)
COD	=	COD loading in wastewater entering anaerobic treatment system (kg/m^3)

B_o = Maximum methane producing potential of industrial wastewater (default value of 0.25 kg CH_4 / kg COD)

MCF = Methane conversion factor (0.3)

A time series of CH_4 emissions for 1990 through 2008 was developed based on production data from the Energy Information Association (EIA 2009).

Domestic Wastewater N_2O Emission Estimates

N_2O emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial wastewater N, and emissions from advanced centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with sewage sludge, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The N disposal into aquatic environments is reduced to account for the sewage sludge application.
- The IPCC methodology uses annual, per capita protein consumption (kg protein/[person-year]). For this Inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then adjusts that data using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 grams N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2000 CWNS shows that plants with denitrification as one of their unit operations serve a population of 2.4 million people. Based on an emission factor of 7 grams per capita per year, approximately 17.5 metric tons of additional N_2O may have been emitted via denitrification in 2000. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are assumed to generate 3.2 grams N_2O per capita per year.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [US_{POPND} \times EF_2 \times F_{IND\text{-}COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND} \times F_{IND\text{-}COM}] \times EF_1\} \times 1/10^9$$

$$N_2O_{EFFLUENT} = \{[((US_{POP} - (0.9 \times US_{POPND})) \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10^6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kg)

N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kg)

$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kg)

$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kg)

$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kg)

US_{POP} = U.S. population

US_{POPND} = U.S. population that is served by biological denitrification (from CWNS)

WWTP = Fraction of population using WWTP (as opposed to septic systems)

EF_1 = Emission factor (3.2 g N2O/person-year) – plant with no intentional denitrification

EF_2 = Emission factor (7 g N2O/person-year) – plant with intentional denitrification

Protein = Annual per capita protein consumption (kg/person/year)

F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)

Table 8-13: U.S. Population (Millions), Available Protein [kg/(person-year)], and Protein Consumed [kg/(person-year)]

Year	Population	Available Protein	Protein Consumed
1990	254	38.7	29.6
1995	271	39.8	30.4
2000	286	41.3	31.6
2001	289	42.0	32.1
2002	292	40.9	31.3
2003	294	40.9	31.3
2004	297	41.3	31.6
2005	300	41.7	32.1
2006	303	41.9	32.1
2007	306	42.1	32.2
2008	308	42.2	32.4

Source: U.S. Census Bureau (2009a), USDA (2009b).

$F_{NON-CON}$ = Factor for non-consumed protein added to wastewater (1.4)

$F_{IND-COM}$ = Factor for industrial and commercial co-discharged protein into the sewer system (1.25)

N_{SLUDGE} = N removed with sludge, kg N/yr

EF_3 = Emission factor (0.005 kg N_2O -N/ kg sewage-N produced) – from effluent

0.9 = Amount of nitrogen removed by denitrification systems

44/28 = Molecular weight ratio of N_2O to N_2

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2009a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, and 2007 American Housing Survey (U.S. Census 2007). Data for intervening years were obtained by linear interpolation. The emission factor (EF_1) used to estimate emissions from wastewater treatment was taken from IPCC (2006). Data on annual per capita protein intake were provided by U.S. Department of Agriculture Economic Research Service (USDA 2009b). Protein consumption data for 2005 through 2008 were extrapolated from data for 1990 through 2004. Table 8-13 presents the data for U.S. population and average protein intake. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-N/ kg sewage-N produced) was applied. The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2008 were forecasted from the rest of the time series. An estimate for the nitrogen removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping. In 2008, 269 Tg N was removed with sludge.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2008 CH_4 and N_2O emissions estimates from wastewater treatment and discharge was calculated using the IPCC Good Practice Guidance Tier 2 methodology (2000). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-14. Methane emissions from wastewater treatment were estimated to be between 15.3 and 35.8 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 37 percent below to 47 percent above the 2008 emissions estimate of 24.3 Tg CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 1.2 and 9.6 Tg CO_2 Eq., which indicates a range of approximately 77 percent below to 94 percent above the actual 2008 emissions estimate of 4.9 Tg CO_2 Eq.

Table 8-14: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Wastewater Treatment ($Tg CO_2$ Eq. and Percent)

Source	Gas	2008 Emission Estimate ($Tg CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**24.3**	**15.3**	**35.8**	**-37%**	**+47%**
Domestic	CH_4	15.7	7.7	26.5	-51%	+69%
Industrial	CH_4	8.6	5.2	13.2	-40%	+54%
Domestic Wastewater Treatment	**N_2O**	**4.9**	**1.2**	**9.6**	**-77%**	**+94%**

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

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed on activity data, documentation, and emission calculations. This effort included a Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected emissions estimates trends; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Planned Improvements Discussion

The methodology to estimate CH_4 emissions from domestic wastewater treatment currently utilizes estimates for the percentage of centrally treated wastewater that is treated by aerobic systems and anaerobic systems. These data come from the 1992, 1996, 2000, and 2004 CWNS. The question of whether activity data for wastewater treatment systems are sufficient across the timeline to further differentiate aerobic systems with the potential to generate small amounts of CH_4 (aerobic lagoons) versus other types of aerobic systems, and to differentiate between anaerobic systems to allow for the use of different MCFs for different types of anaerobic treatment systems, continues to be explored. Currently, it is assumed that all aerobic systems are well managed and produce no CH_4 and that all anaerobic systems have an MCF of 0.8. Efforts to obtain better data reflecting emissions from various types of municipal treatment systems are currently being pursued.

Available data on wastewater treatment emissions at organic chemical manufacturers was reviewed and determined to be a potentially significant source for the Inventory. Existing data for wastewater generation and COD was used along with an estimate of the number of plants treated wastewater anaerobically to estimate 631 Gg of CH_4 emitted. However, this estimate was performed with data collected for EPA's Office of Water in the 1980s. A more recent source of industry-level data that could be used to fully construct a time series has not been identified. However, data sources will continue to be investigated in order to include emissions from wastewater treatment at organic chemical manufacturers in future inventories.

A review of other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD and COD has begun. Food processing industries have the highest potential for CH_4 generation due to the waste characteristics generated, and the greater likelihood to treat the wastes anaerobically. However, in all cases there is dated information available on U.S. treatment operations for these industries. The canned and seafood processing and miscellaneous foods and beverages industries (including wineries and distilleries) will be specifically reviewed to estimate their potential to generate CH_4. Industry-level emissions will be estimated assuming anaerobic treatment systems are in place, and consider potential inclusion of these categories in future years of the Inventory.

With respect to estimating N_2O emissions, the default emission factor for indirect N_2O from wastewater effluent and direct N_2O from centralized wastewater treatment facilities has a high uncertainty. Current research is being conducted by the Water Environment Research Foundation to measure N_2O emissions from municipal treatment systems. Such data will be reviewed as they are available to determine if a country-specific N_2O emission factor can or should be developed.

In addition, the estimate of N entering municipal treatment systems is under review. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent N concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow. The dataset previously provided by NACWA was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the inventory. However, this limited dataset did not represent the number of systems by state and the service populations served in the United States.

8.3 Composting (IPCC Source Category 6D)

Composting of organic waste, such as food waste, garden (yard) and park waste and sludge, is common in the United States. Advantages of composting include reduced volume in the waste material, stabilization of the waste, and destruction of pathogens in the waste material. The end products of composting, depending on its quality, can be recycled as fertilizer and soil amendment, or be disposed in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into CO_2. Methane is formed in anaerobic sections of the compost, but it is oxidized to a large extent in the aerobic sections of the compost. Anaerobic sections are created in composting piles when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few per cent of the initial C content in the material (IPCC 2006). Composting can also produce N_2O emissions. The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006).

From 1990 to 2008, the amount of material composted in the United States has increased from 3,810 Gg to 19,886 Gg, an increase of approximately 422 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage (see Table 8-15 and Table 8-16). In 2008, CH_4 emissions from composting were 1.7 Tg CO_2 Eq. (80 Gg), and N_2O emissions from composting were 1.8 Tg CO_2 Eq. (6 Gg). The wastes that are composted include primarily yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from residences and commercial establishments (such as grocery stores, restaurants, and school and factory cafeterias). The composting waste quantities reported here do not include backyard composting. The growth in composting is attributable primarily to two factors: (1) steady growth in population and residential housing, and (2) state and local governments started enacting legislation that discouraged the disposal of yard trimmings in landfills. In 1992, 11 states and the District of Columbia had legislation in effect that banned or discouraged disposal of yard trimmings in landfills. In 2005, 21 states and the District of Columbia, representing about 50 percent of the nation's population, had enacted such legislation (EPA 2006).

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and

Table 8-15: CH_4 and N_2O Emissions from Composting (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007	2008
CH_4	0.3	0.7	1.3	1.6	1.6	1.7	1.7
N_2O	0.4	0.8	1.4	1.7	1.8	1.8	1.8
Total	**0.7**	**1.5**	**2.6**	**3.3**	**3.3**	**3.5**	**3.5**

Table 8-16: CH_4 and N_2O Emissions from Composting (Gg)

Gas	1990	1995	2000	2005	2006	2007	2008
CH_4	15	35	60	75	75	79	80
N_2O	1	3	4	6	6	6	6

peat) used, temperature, moisture content and aeration during the process.

The emissions shown in Table 8-15 and Table 8-16 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, Gg CH_4 or N_2O

M = mass of organic waste composted in Gg

EF_i = emission factor for composting, 4 g CH_4/kg of waste treated (wet basis) and 0.3 g N_2O/kg of waste treated (wet basis)

i = designates either CH_4 or N_2O

Estimates of the quantity of waste composted (M) are presented in Table 8-17. Estimates of the quantity composted for 1990 and 1995 were taken from the *Characterization of Municipal Solid Waste in the United States: 1996 Update* (Franklin Associates 1997); estimates of the quantity composted for 2000, 2005, 2006, and 2007 were taken from EPA's *Municipal Solid Waste In The United States: 2007 Facts and Figures* (EPA 2008); estimates of the quantity composted for 2008 were calculated using the 2007 quantity composted.

Uncertainty and Time-Series Consistency

The estimated uncertainty from the 2006 IPCC Guidelines is ±50 percent for the Tier 1 methodology. Emissions from composting in 2008 were estimated to be between 1.8 and 5.3 Tg CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2008 emission estimate of 3.5 Tg CO_2 Eq. (see Table 8-18).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 8-17: U.S. Waste Composted (Gg)

Activity	1990	1995	2000	2005	2006	2007	2008
Waste Composted	3,810	8,682	14,923	18,643	18,852	19,695	19,886

Source: Franklin Associates (1997) and EPA (2008).

Table 8-18: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	3.5	1.8	5.3	-50%	+50%

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search may be conducted to determine if emission factors specific to various composting systems and composted materials are available.

8.4 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2008 are provided in Table 8-19.

Methodology

These emission estimates were obtained from preliminary data (EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided by sector, using a "top down" estimating procedure–emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 *National Acid Precipitation and Assessment Program Emissions Inventory*, and other EPA databases.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

Table 8-19: Emissions of NO_x, CO, and NMVOCs from Waste (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007	2008
NO_x	**+**	**1**	**2**	**2**	**2**	**2**	**2**
Landfills	+	1	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+
CO	**1**	**2**	**8**	**7**	**7**	**7**	**7**
Landfills	1	2	7	6	6	6	6
Wastewater Treatment	+	+	1	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+
NMVOCs	**673**	**731**	**119**	**114**	**113**	**111**	**109**
Wastewater Treatment	58	68	22	22	21	21	21
Miscellaneous[a]	57	61	51	49	49	48	47
Landfills	557	602	46	43	43	42	41

+ Does not exceed 0.5 Gg.
[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.

9. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

10. Recalculations and Improvements

Each year, emission and sink estimates are recalculated and revised for all years in the Inventory of U.S. Greenhouse Gas Emissions and Sinks, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. In this effort, the United States follows the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance*, which states, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected" (IPCC 2000).

The results of all methodological changes and historical data updates are presented in this section; detailed descriptions of each recalculation are contained within each source's description found in this report, if applicable. Table 10-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table 10-2 summarizes the quantitative effect on net CO_2 flux to the atmosphere, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2007 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide equivalent (Tg CO_2 Eq.).

The Recalculations Discussion section of each source presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2007) has been recalculated to reflect the change, per IPCC (2000). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

The following emission sources, which are listed in descending order of absolute average annual change in emissions between 1990 and 2007, underwent some of the most important methodological and historical data changes. A brief summary of the recalculation and/or improvement undertaken is provided for each emission source.

- *Land Use, Land-use Change, and Forestry.* The time series for Forest Land area was updated with a new release of data from the Forest Inventory and Analysis Program. Most eastern states have completed the first full cycle of annualized inventories and are providing annual updates to the state's forest inventory, resulting in increased accuracy of the model used to estimate Forest Land area. In addition, an average estimate of logging residue was incorporated into the down dead wood carbon calculations to explicitly account for down dead wood following harvest on lands that were reforested. These updates resulted in an average annual decrease in carbon storage of 8 percent. Also, changes in carbon stock in urban trees from the incorporation of new data on the city of Chicago resulted in a lower median gross sequestration value and a lower net sequestration to gross sequestration ratio for the set of 14 cities used to estimate total carbon sequestration in urban trees. On average, the change in carbon stocks from urban trees led to a 5.9 percent decrease in annual sequestration from 1990 through 2007. Overall, these changes resulted in an average annual increase in estimated net flux of CO_2 to the atmosphere of 77.6 Tg CO_2 Eq. (7 percent) for the period 1990 through 2007 compared to the previous Inventory's estimate of Forest Land net CO_2 flux.

- *Fossil Fuel Combustion.* Changes in CO_2 emissions from Fossil Fuel Combustion resulted from updated energy consumption statistics provided by the Energy Information Administration. These revisions impacted the emission estimates for the entire time series. Carbon content coefficients were also updated based on an EPA analysis. Overall, these changes resulted in an average annual increase of 23.7 Tg CO_2 Eq. (0.4 percent) in CO_2 emissions from Fossil Fuel Combustion for the period 1990 through 2007.
- *Iron and Steel Production & Metallurgical Coke Production.* In the previous Inventory, pig iron consumption for basic oxygen furnaces was being counted twice as a process input. This was the result of an incorrect interpretation of two tables in the American Iron and Steel Institute (AISI) *Annual Statistical Yearbook*. This issue has been corrected and decreased the 1990 through 2007 emissions from iron and steel production by an average of 8 percent per year. Overall, these changes resulted in an average annual decrease of 6.5 Tg CO_2 Eq. (7.1 percent) in CO_2 emissions from Iron and Steel Production and Metallurgical Coke Production for the period of 1990 through 2007.
- *Forest Land Remaining Forest Land (N_2O).* Nitrogen fertilizer applications to commercial Douglas-fir forests in western Oregon and Washington were added to the N_2O Fluxes from Soils category, which resulted in an average annual increase in emissions of approximately 24 percent compared to the previous Inventory. Additionally, non-CO_2 emissions were recalculated using the 2006 IPCC default emission factors for CH_4 and N_2O. The update caused the estimated values for N_2O emissions to increase by a factor of approximately four. Overall, these changes resulted in an average annual increase of 5.7 Tg CO_2 Eq. (282 percent) in N_2O emissions from Forest Land Remaining Forest Land for the period 1990 through 2007.
- *Incineration of Waste.* Changes in CO_2 emissions from Incineration of Waste stem from two changes in methodology. First, rather than basing the estimate of the percentage discards combusted on data from *MSW Facts and Figures*, as had been done in previous years, EPA updated the percent of discards combusted with *Biocycle*'s time series estimate. The change in the source for percentage combusted was made because using *Biocycle* data for discards is in line with other estimates in the Inventory; *Biocycle* data are used to estimate CH_4 emissions from landfills and N_2O emissions from waste incineration. This change decreases CO_2 emissions annually on average by 32 percent for materials other than tires (the estimate for tires is not affected by this change). Additionally, the Rubber Manufacturers Association changed their reporting for the scrap tire market for 2007 and as a result, EPA had to adjust the calculations for CO_2 from scrap tire incineration with updated data on scrap tire weight, tire composition, and scrap tire market composition. This updated methodology resulted in an average annual increase in CO_2 emissions from scrap tire incineration of 52 percent. Overall, these changes resulted in an average annual decrease of 5.4 Tg CO_2 Eq. (30 percent) in CO_2 emissions from Incineration of Waste.
- *Agricultural Soil Management.* Several revisions were made for the current Inventory that resulted in changes in N_2O emissions from Agricultural Soil Management. In the previous Inventory, it was assumed that nitrate leaching was not significant in soils with precipitation input that did not exceed potential evapotranspiration, except in soils that were irrigated. Quality control measures revealed that nitrate leaching was under-estimated using this criterion, so the threshold was revised to better reflect U.S. conditions. Second, in the previous Inventory, the leaching criterion was not applied for lands estimated using Tier 1 methodology. For this year's Inventory, nitrate leaching was assumed to occur in states where the area weighted mean precipitation plus irrigation input was equal to or greater than 80 percent of the potential evapotranspiration. Third, the emission factor for pasture/range/paddock manure associated with horses, sheep and goats was revised to 0.01 in accordance with guidance from IPCC (2006). Fourth, the methodology to calculate livestock manure N was changed such that total manure N added to soils increased by approximately 5 percent. Overall, these changes resulted in an average annual increase of 4.4 Tg CO_2 Eq. (2 percent) in N_2O emissions from Agricultural Soil Management.

- *Forest Land Remaining Forest Land (CH_4).* Non-CO_2 emissions were recalculated using the 2006 IPCC default emission factors for CH_4 and N_2O. Updating to the 2006 IPCC emission factors results in estimates for CH_4 emissions decreasing by a factor of approximately one third between methods. Overall, these changes resulted in an average annual decrease of 3.8 Tg CO_2 Eq. (24 percent) in CH_4 emissions from Forest Land Remaining Forest Land for the period 1990 through 2007.

- *Natural Gas Systems (CO_2).* Changes in CO_2 emissions from Natural Gas Systems are mostly the result of updating the previous Inventory activity data with revised values from the Federal Energy Regulatory Commission. In addition, the data source for the number of liquefied natural gas (LNG) import terminals was changed to Federal Energy Regulatory Commission-reported data to provide a more accurate and current emissions estimate from LNG import terminals. Overall, these changes resulted in an average annual increase of 3.0 Tg CO_2 Eq. (9 percent) in CO_2 emissions from Natural Gas Systems for the period 1990 through 2007.

- *Manure Management (N_2O).* For the current Inventory, cattle population data and total Kjeldahl nitrogen excretion rate (N_{ex}) data were incorporated from the Cattle Enteric Fermentation Model. Population and N_{ex} changes resulted in increases in N_2O emissions across the timeseries. Overall, these changes resulted in an average annual increase of 2.4 Tg CO_2 Eq. (18 percent) in N_2O emissions from Manure Management for the period 1990 through 2007.

- *Non-Energy Use of Fuels.* Changes in CO_2 emissions from Non-Energy Use of Fuels are the result of changes to the scrap tire, carbon black, and synthetic rubber carbon emissions and updates to the energy recovery emission estimates. The Rubber Manufacturers Association's *Scrap Tire Markets in the United States: 9th Biennial Edition* began reporting the amount of scrap tires in each end use market in thousands of tons (as opposed to millions of tires as they had done previously). RMA also updated their assumed weight for passenger and commercial scrap tires to 22.5 pounds and 110 pounds, respectively. As a result, the percentage of rubber abraded during tire use for these two categories was reduced from 20 percent for all tires to 10 and 8 percent for passenger and commercial tires, respectively. These updates resulted in an average 73 percent reduction in carbon black emissions and an average 68 percent reduction in synthetic rubber carbon emissions per year across the time series. Additionally, energy recovery emissions were updated with new Manufacturer's Energy Consumption Survey (MECS) data for 2006, released this past year by the Energy Information Administration. This update resulted in an average annual increase of 4 percent in emissions from feedstocks for 2003 and 2007. Overall, these changes resulted in an average annual increase of 1.8 Tg CO_2 Eq. (1.4 percent) CO_2 emissions from Non-Energy Use of Fuels for the period of 1990 through 2007.

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**24.1**	**19.4**	**22.0**	**17.6**	**2.3**	**16.8**
Fossil Fuel Combustion	26.8	15.6	31.9	29.9	17.4	21.2
Electricity Generation	11.1	9.1	13.7	21.1	19.1	15.6
Transportation	1.3	9.3	9.2	13.9	(4.2)	6.3
Industrial	11.2	+	7.7	(2.4)	6.2	(3.2)
Residential	1.4	(1.1)	0.9	0.4	0.2	1.1
Commercial	2.1	(1.2)	0.7	(0.5)	+	3.0
US Territories	(0.4)	(0.5)	(0.3)	(2.6)	(3.9)	(1.7)
Non-Energy Use of Fuels	2.6	5.5	1.7	(1.5)	(3.8)	1.4
Iron and Steel Production & Metallurgical Coke Production	(7.2)	(7.4)	(7.0)	(5.5)	(5.6)	(4.6)
Cement Production	NC	NC	NC	NC	NC	0.7
Natural Gas Systems	3.6	8.4	+	+	+	2.1
Lime Production	NC	NC	NC	NC	NC	NC

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Gas/Source	1990	1995	2000	2005	2006	2007
Incineration of Waste	(2.9)	(4.3)	(6.2)	(6.9)	(7.1)	(7.5)
Ammonia Production and Urea Consumption	NC	NC	NC	NC	NC	0.2
Cropland Remaining Cropland	NC	NC	NC	NC	+	0.3
Limestone and Dolomite Use	NC	+	NC	NC	NC	1.5
Aluminum Production	NC	NC	NC	NC	NC	NC
Soda Ash Production and Consumption	NC	NC	NC	NC	NC	NC
Petrochemical Production	1.1	1.4	1.5	1.4	1.3	1.3
Titanium Dioxide Production	NC	NC	NC	NC	+	0.1
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC
Wetlands Remaining Wetlands[a]	NC	NC	NC	NC	NC	+
Petroleum Systems	0.2	0.2	0.2	0.2	0.2	0.2
Zinc Production	+	+	+	+	+	(0.1)
Lead Production	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC
Land Use, Land-Use Change, and Forestry (Sink)[b]	*(68.0)*	*8.1*	*53.3*	*172.3*	*91.4*	*107.2*
Wood Biomass and Ethanol Consumption[a]	*NC*	*NC*	*NC*	*(2.1)*	*(2.1)*	*(2.1)*
International Bunker Fuels[a]	*(2.5)*	*(1.8)*	*(0.5)*	*(1.0)*	*18.6*	*18.3*
CH_4	**(3.2)**	**(2.6)**	**(5.1)**	**(8.5)**	**(13.7)**	**(16.1)**
Enteric Fermentation	(0.8)	0.1	2.4	0.7	0.8	2.2
Landfills	0.1	(0.2)	(1.6)	(2.3)	(3.4)	(6.4)
Natural Gas Systems	+	+	(0.2)	(2.7)	(1.8)	(5.2)
Coal Mining	NC	NC	(0.1)	(0.2)	(0.1)	0.4
Manure Management	(1.1)	(0.6)	0.7	0.4	0.5	1.9
Petroleum Systems	+	+	+	+	(0.1)	+
Wastewater Treatment	+	+	+	+	+	0.1
Forest Land Remaining Forest Land	(1.4)	(1.9)	(6.3)	(4.4)	(9.7)	(9.0)
Rice Cultivation	NC	NC	NC	NC	NC	+
Stationary Combustion	+	+	+	(0.1)	(0.1)	(0.1)
Abandoned Underground Coal Mines	NC	NC	NC	+	+	(0.1)
Mobile Combustion	+	(0.1)	(0.1)	+	(0.1)	(0.1)
Composting	NC	NC	NC	NC	NC	NC
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1
Petrochemical Production	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC
Incineration of Waste[b]	+	+	+	+	+	+
International Bunker Fuels[a]	+	+	+	+	+	+
N_2O	**7.3**	**8.4**	**16.4**	**12.4**	**17.4**	**15.8**
Agricultural Soil Management	3.1	3.6	5.6	5.2	2.8	3.1
Mobile Combustion	0.2	0.3	0.4	0.2	0.1	0.2
Nitric Acid Production	(1.1)	(1.2)	(1.2)	(1.0)	(1.0)	(1.2)
Manure Management	2.4	2.5	2.7	2.4	2.7	2.6
Stationary Combustion	+	+	+	+	+	(0.1)
Forest Land Remaining Forest Land	2.2	2.9	9.7	6.6	14.5	13.4
Wastewater Treatment	NC	NC	+	+	+	+

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Gas/Source	1990	1995	2000	2005	2006	2007
N_2O from Product Uses	NC	NC	NC	NC	NC	NC
Adipic Acid Production	0.5	0.3	(0.7)	(1.0)	(1.6)	(2.2)
Composting	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	+	(0.1)	(0.1)	+	+	+
Field Burning of Agricultural Residues	+	+	+	+	+	+
Incineration of Waste	NC	NC	NC	+	NC	NC
Wetlands Remaining Wetlands	NC	NC	NC	NC	NC	NC
International Bunker Fuels[a]	+	+	+	+	*0.2*	*0.2*
HFCs	**NC**	**0.4**	**3.1**	**3.2**	**2.8**	**1.9**
Substitution of Ozone Depleting Substances	NC	0.4	3.1	3.2	2.8	1.9
HCFC-22 Production	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC
PFCs	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Aluminum Production	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC
SF_6	**(0.2)**	**(0.2)**	**(0.1)**	**(0.1)**	**+**	**(0.4)**
Electrical Transmission and Distribution	(0.2)	(0.2)	(0.1)	(0.1)	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	(0.4)
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC
Net Change in Total Emissions[c]	**28.1**	**25.5**	**36.3**	**24.6**	**8.8**	**18.0**
Percent Change	**0.5%**	**0.4%**	**0.5%**	**0.3%**	**0.1%**	**0.3%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)
[a] Not included in emissions total.
[b] New source category relative to previous Inventory.
[c] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption.
Note: Totals may not sum due to independent rounding.

Table 10-2: Revisions to Net Flux of CO_2 to the Atmosphere from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Component: Net CO_2 Flux From Land Use, Land-Use Change, and Forestry	1990	1995	2000	2005	2006	2007
Forest Land Remaining Forest Land	(68.8)	(6.0)	44.9	169.1	87.8	103.2
Cropland Remaining Cropland	NC	NC	NC	NC	NC	NC
Land Converted to Cropland	NC	NC	NC	NC	NC	NC
Grassland Remaining Grassland	(5.3)	9.7	(1.2)	(4.4)	(4.3)	(4.1)
Land Converted to Grassland	2.5	0.2	4.7	2.1	2.2	2.4
Settlements Remaining Settlements	3.6	4.2	4.9	5.5	5.7	5.8
Other	NC	NC	NC	+	+	+
Net Change in Total Flux	**(68.0)**	**8.1**	**53.3**	**172.3**	**91.4**	**107.2**
Percent Change	**-8.1%**	**1.0%**	**7.4%**	**15.4%**	**8.7%**	**10.1%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)
Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere or an increase in net sequestration.
Note: Totals may not sum due to independent rounding.

11. References

Executive Summary

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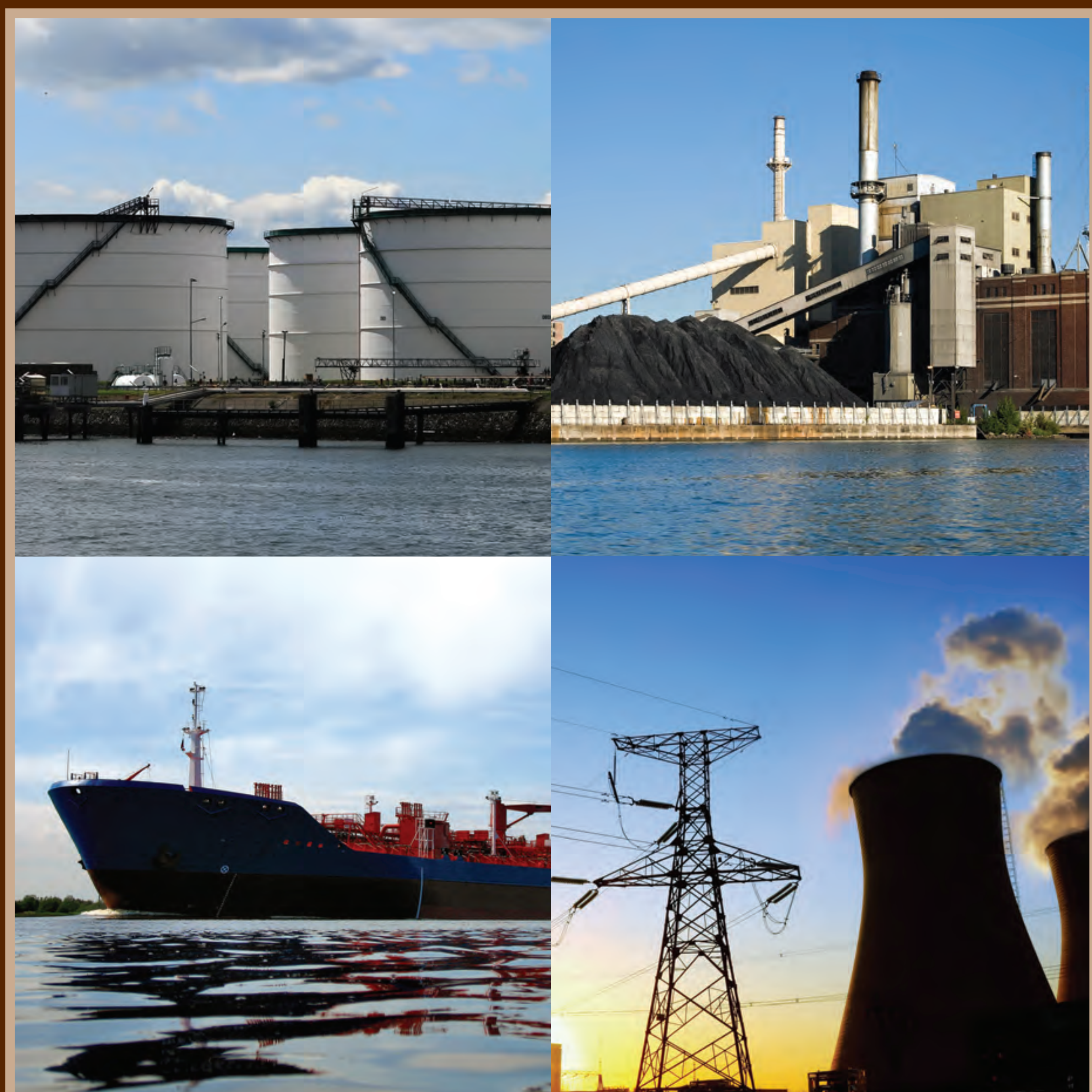

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