

2003. A new NRI dataset is available with land use and management information through 2007, and the inventory will be updated with this additional activity data by the next NIR. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2010 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 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.²²⁴ 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, and the annual flux estimated for 1997 was applied to 1993 through 2010.

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

²²⁴ 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).

the uncertain quantities). The combined uncertainty for soil C stocks in *Land Converted to Grassland* ranged from 15 percent below to 15 percent above the 2010 estimate of -23.6 Tg CO₂ Eq.

Table 7-36: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (Tg CO₂ Eq. and Percent)

Source	2010 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	(19.5)	(22.2)	(16.7)	-14%	+14%
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	(23.6)	(27.0)	(20.0)	-15%	+15%

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 2010. 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*.

Planned Improvements

The main planned improvement for the next Inventory is to integrate the assessments of soil C stock changes and soil N₂O emissions into a single analysis. This improvement will ensure that the N and C cycles are treated consistently in the national inventory, which is important because the cycles of these elements are linked through plant and soil processes in agricultural lands. This improvement will include the development of an empirically-based uncertainty analysis, which will provide a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

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.

CO₂ 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 CH₄ and N₂O. The natural production of CH₄ is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al., 2004 as cited in IPCC 2006); however, CH₄ emissions are assumed to be insignificant under Tier 1 (IPCC, 2006). N₂O emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions, and at present no methodology is provided by IPCC (2006) to estimate greenhouse gas emissions or removals from restored peatlands. This inventory estimates both CO₂ and N₂O emissions from *Peatlands Remaining Peatlands* in accordance with Tier 1 IPCC (2006) guidelines.

CO₂ and N₂O Emissions from *Peatlands Remaining Peatlands*

IPCC (2006) recommends reporting CO₂ and N₂O 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 CO₂ emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N₂O emissions, since off-site N₂O 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 CO₂ is emitted from the oxidation of the peat. Since N₂O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N₂O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain 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 N₂O.

Off-site CO₂ emissions from managed peatlands occur from the horticultural and landscaping use of peat. Nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most of the CO₂ emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for horticultural purposes.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 1.098 Tg CO₂ Eq. in 2010 (see Table 7-37) comprising 0.983 Tg CO₂ Eq. (983 Gg) of CO₂ and 0.005 Tg CO₂ Eq. (0.016 Gg) of N₂O. Total emissions in 2010 were about 11 percent smaller than total emissions in 2009, with the decrease due to the decrease in peat production reported in Alaska in 2010.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO₂ Eq. across the time series with a decreasing trend from 1990 until 1994 followed by an increasing trend through 2000. After 2000, emissions generally increased until 2006 and then decreased until 2009, when the trend reversed. Emissions in 2010 represent a slight decline from emissions in 2009. CO₂ emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO₂ across the time series, and these emissions drive the trends in total emissions. N₂O emissions remained close to zero across the time series, with a decreasing trend from 1990 until 1995 followed by an increasing trend through 2002. N₂O emissions decreased between 2000 and 2008, followed by a leveling off since 2008.

Table 7-37: Emissions from *Peatlands Remaining Peatlands* (Tg CO₂ Eq.)

Gas	1990	2005	2006	2007	2008	2009	2010
CO ₂	1.0	1.1	0.9	1.0	1.0	1.1	1.0
N ₂ O	+	+	+	+	+	+	+
Total	1.0	1.1	0.9	1.0	1.0	1.1	1.0

+ Less than 0.01 Tg CO₂ 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 *Peatlands Remaining Peatlands* (Gg)

Gas	1990	2005	2006	2007	2008	2009	2010
CO ₂	1,033	1,079	879	1,012	992	1,089	983
N ₂ O	+	+	+	+	+	+	+

+ Less than 0.05 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).

Methodology

Off-Site CO₂ Emissions

CO₂ emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO₂ 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 C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, 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 1991–2011). 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. On average, about 75 percent of the peat operations respond to the survey. USGS estimated data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from Alaska’s annual Mineral Industry Reports (Szumigala et al. 2010). Similar to the U.S. Geological Survey, Alaska’s Mineral Industry Report methodology solicits voluntary reporting of peat production from producers. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production (USGS 1991-2011). The methodology estimates Alaska emissions separately from lower 48 emissions 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 CO₂ emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).²²⁵

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 CO₂ emissions from the use of all horticultural 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; from 2006 to 2009, imports of sphagnum moss (nutrient-poor) peat from Canada represented 97 percent of total U.S. peat imports (USGS 2011a). 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 CO₂ 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.

²²⁵ 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	2005	2006	2007	2008	2009	2010
Nutrient-Rich	595.1	657.6	529.0	581.0	559.7	560.3	563.0
Nutrient-Poor	55.4	27.4	22.0	54.0	55.4	48.7	49.0
Total Production	692.0	685.0	551.0	635.0	615.0	609.0	612.0

Source: United States Geological Survey (USGS) (1991–2011)..

Table 7-40: Peat Production of Alaska (in thousands of Cubic Meters)

	1990	2005	2006	2007	2008	2009	2010
Total Production	49.7	47.8	50.8	52.3	64.1	183.9	78.2

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2011) Alaska's Mineral Industry Report (1997–2010).

On-site CO₂ 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 method²²⁶ 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 CO₂ 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 bulk peat 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 C 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 C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006).

On-site N₂O Emissions

IPCC (2006) suggests basing the calculation of on-site N₂O 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 CO₂ emissions methodology above details the calculation of area data from production data. In order to estimate N₂O emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2006).

Uncertainty

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. The peat

²²⁶ 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).

type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution). 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 Alaska Department of Natural Resources estimates 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 CO₂ and N₂O emissions from *Peatlands Remaining Peatlands*. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-41. CO₂ emissions from *Peatlands Remaining Peatlands* in 2010 were estimated to be between 0.7 and 1.4 Tg CO₂ Eq. at the 95 percent confidence level. This indicates a range of 33 percent below to 38 percent above the 2010 emission estimate of 1.0 Tg CO₂ Eq. N₂O emissions from *Peatlands Remaining Peatlands* in 2010 were estimated to be between 0.001 and 0.007 Tg CO₂ Eq. at the 95 percent confidence level. This indicates a range of 74 percent below to 42 percent above the 2010 emission estimate of 0.005 Tg CO₂ Eq.

Table 7-41: Tier-2 Quantitative Uncertainty Estimates for CO₂ Emissions from *Peatlands Remaining Peatlands*

Source	Gas	2010 Emissions Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emissions Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
<i>Peatlands Remaining Peatlands</i>	CO ₂	1.0	0.7	1.4	-33%	38%
	N ₂ O	+	+	+	-74%	42%

+ Does not exceed 0.01 Tg CO₂ Eq. or 0.5 Gg.

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

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

The current inventory represents the fourth inventory report in which emissions from *Peatlands Remaining Peatlands* are included. The inventory estimates for 2009 have been updated to incorporate new information on the proportion of rich and poor peat soil, and the bulk density of peat types in 2009. These data are from the advance release of the *2009 Mineral Yearbook: Peat* (USGS 2011b), which was released too late to be fully incorporated into last year's inventory estimates. Updating these 2009 input values resulted in less than a 1 percent decrease compared to the previous 2009 emission estimate.

Planned Improvements

In order to further improve estimates of CO₂ and N₂O 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 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 77.5 Tg CO₂ Eq. (21.1 Tg C) over the period from 1990 through 2010. Net C flux from urban trees in 2010 was estimated to be -98.0 Tg CO₂ Eq. (-26.7 Tg C). Annual estimates of CO₂ flux (Table 7-43) were developed based on periodic (1990 and 2000) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report, by an average of 19 percent over the 1990 through 2010 time series—i.e., the Census urban area is a subset of the *Settlements* area.

In 2010, urban area was about 7 percent smaller than the total area defined as *Settlements*. Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 72 percent between 1990 and 2010 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. As a result, the estimates presented in this chapter are not truly representative of changes in carbon stocks in urban trees for *Settlements* areas, but are representative of changes in carbon stocks in urban trees for census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in carbon stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

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). However, 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 basis of C sequestered per unit area of tree cover, rather than C sequestered per total land area. Expressed per unit of tree cover, areas covered by urban trees have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: urban areas have a smaller C density than forest areas.

Table 7-42: Net C Flux from Urban Trees (Tg CO₂ Eq. and Tg C)

Year	Tg CO ₂ Eq.	Tg C
1990	(57.1)	(15.6)
2005	(87.8)	(23.9)
2006	(89.8)	(24.5)
2007	(91.9)	(25.1)
2008	(93.9)	(25.6)
2009	(95.9)	(26.2)
2010	(98.0)	(26.7)

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. Finally, sequestration estimates for these cities, in units of carbon sequestered per unit area of tree cover, were 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 separately 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.

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 7-44, 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 C storage estimates between year 1 and year $(x + 1)$ represents 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. The area of assessment for each city was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates (Nowak 2011a).

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).

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).

Estimates of gross and net sequestration rates for each of the 14 cities (Table 7-44) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of national urban area and urban tree cover data to calculate national annual net C sequestration by urban trees for the United States. This method was described in Nowak and Crane (2002) and has been modified to incorporate U.S. Census data.

Specifically, 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).

Settlements area, as assessed in the Representation of the U.S. Land Base developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates. However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). Specifically, tree canopy cover of U.S. urban areas was estimated by Nowak et al. (2001) to be 27 percent, assessed across Census-delineated urbanized areas, urban places, and places containing urbanized area. This canopy cover percentage is multiplied by the urban area estimated for each year to produce an estimate of national urban tree cover area.

Net annual C sequestration estimates were derived for the 14 cities by subtracting the gross annual emission estimates from the gross annual sequestration estimates. 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/m²-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	0.20	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), Nowak (2007a,c), and 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 in the Planned Improvements section 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 2010 was estimated to be between -120.1 and -78.0 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 23 percent below and 20 percent above the 2010 flux estimate of -98.0 Tg CO₂ Eq.

Table 7-44: Tier 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (Tg CO₂ Eq. and Percent)

Source	Gas	2010 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	(98.0)	(120.1)	(78.0)	23%	-20%

Note: Parentheses indicate negative values or net sequestration.

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, 2011a).

Planned Improvements

A consistent representation of the managed land base in the United States is discussed at the beginning of the *Land Use, Land-Use Change, and Forestry* chapter, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. 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 this report. For example, Nowak (2012, in preparation) estimates that 13.7 percent of urban land is measured by the forest inventory plots, and could be responsible for up to 87 Tg C of overlap.

Urban forest data for 28 cities are expected in the near future, including updated data for cities currently included in the estimates (Nowak 2012, in preparation). The use of these data will refine the estimated median Gross Annual Sequestration per Area of Tree Cover value.

The U.S. Census Bureau expects to publish data on urban areas from the 2010 Census in early 2013 (Allen 2011). These data would allow for refinement of the urban area time series. Revisions to urban area time series will result in revisions to all years’ C flux estimates.

A revised average tree canopy cover percentage of 33.5 percent for U.S. urban areas has also been established, and is in preparation for publication (Nowak 2012, in preparation). Revisions to tree cover percentage will result in revisions to all years’ C flux estimates. Furthermore, urban tree cover data specific to six states has also been developed (Nowak 2012, in preparation). It may be possible to develop and use a set of state-specific sequestration rates for estimating regional C flux estimates.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all *Settlements* land. To provide estimates for all *Settlements*, research would need to establish the extent of overlap between *Settlements* and Census-defined urban areas, and would have to characterize sequestration on non-urban *Settlements* land.

Direct N₂O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 2.4 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 N₂O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas. In 2010, N₂O emissions from settlement soils were 1.4 Tg CO₂ Eq. (4.5 Gg). There was an overall increase of 43 percent over the period from 1990 through 2010 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: Direct N₂O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO₂ Eq. and Gg N₂O)

Year	Tg CO ₂ Eq.	Gg
1990	1.0	3.2
2005	1.5	4.7
2006	1.5	4.8
2007	1.6	5.1
2008	1.5	4.7
2009	1.4	4.4
2010	1.4	4.5

Note: These estimates include direct N₂O emissions from N fertilizer additions only. Indirect N₂O 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 N₂O

emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N₂O emissions from soils in settlements were based on the amount of N in synthetic commercial fertilizers applied to settlement soils, and 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 is 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 forest lands; values for 2002 through 2008 were based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. 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 N₂O emissions (IPCC 2006). The volatilized and leached/runoff N fractions for settlements, 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 indirect emissions, as reported in the N₂O Emissions from Agricultural Soil Management source category of the Agriculture chapter (consistent with reporting guidance that all indirect emissions are included in the Agricultural Soil Management source category).

Uncertainty and Time-Series Consistency

The amount of N₂O emitted from settlements depends not only on N inputs and fertilized area, 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 N₂O flux is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except 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 of ± 50 percent²²⁷. 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 2010 emission estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-46. N₂O emissions from soils in Settlements Remaining Settlements in 2010 were estimated to be between 0.7 and 3.7 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2010 emission estimate of 1.4 Tg CO₂ Eq.

²²⁷ No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative $\pm 50\%$ was used in the analysis.

Table 7-46: Quantitative Uncertainty Estimates of N₂O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO₂ Eq. and Percent)

Source	Gas	2010 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 ₂ O Fluxes from Soils	N ₂ O	1.4	0.7	3.7	-49%	163%

Note: This estimate includes direct N₂O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Planned Improvements

A minor improvement is planned 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 CO₂ or N₂O 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, yard trimmings (i.e., grass clippings, leaves, and branches) 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 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 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 53 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 2011; 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 5 percent decrease in the tonnage generated (i.e., collected for composting or disposal). At the same time, an 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 35 percent in 2010. The net effect of the reduction in generation and the increase in composting is a 54 percent decrease in the quantity of yard trimmings disposed in landfills since 1990.

Food scrap generation has grown by 46 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 80 percent in 2010, the tonnage disposed in landfills has increased considerably (by 42 percent). Overall, the decrease in the landfill disposal rate of yard trimmings 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 24.2 Tg CO₂ Eq. in 1990 to 13.3 Tg CO₂ Eq. in 2010 (Table 7-47 and Table 7-48).

Table 7-47: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO₂ Eq.)

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Yard Trimmings	(21.0)	(7.3)	(7.4)	(7.0)	(7.0)	(8.5)	(9.3)
Grass	(1.8)	(0.6)	(0.6)	(0.6)	(0.6)	(0.8)	(0.9)
Leaves	(9.0)	(3.3)	(3.4)	(3.2)	(3.2)	(3.9)	(4.2)
Branches	(10.2)	(3.4)	(3.4)	(3.2)	(3.1)	(3.8)	(4.1)
Food Scraps	(3.2)	(4.3)	(3.5)	(3.9)	(3.9)	(4.2)	(4.1)
Total Net Flux	(24.2)	(11.6)	(11.0)	(10.9)	(10.9)	(12.7)	(13.3)

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

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

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Yard Trimmings	(5.7)	(2.0)	(2.0)	(1.9)	(1.9)	(2.3)	(2.5)
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)
Leaves	(2.5)	(0.9)	(0.9)	(0.9)	(0.9)	(1.1)	(1.1)
Branches	(2.8)	(0.9)	(0.9)	(0.9)	(0.9)	(1.0)	(1.1)
Food Scraps	(0.9)	(1.2)	(1.0)	(1.1)	(1.1)	(1.1)	(1.1)
Total Net Flux	(6.6)	(3.2)	(3.0)	(3.0)	(3.0)	(3.5)	(3.6)

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values

Methodology

When wastes of 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; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. 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 mass 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: Tables and Figures for 2010* (EPA 2011), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, and 2007 through 2010. 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 (2011) 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 landfills²²⁸ and combustors with energy

²²⁸ EPA (2011) reports discards in two categories: “combustion with energy recovery” and “landfill, other disposal,” which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of

recovery (i.e., ranging from 100 percent and 0 percent, respectively, in 1960 to 81 percent and 19 percent in 2000); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

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 CH₄ and CO₂ (the CH₄ 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.

The first-order decay rates, *k*, for each component were derived from De la Cruz and Barlaz (2010). De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is found so that the weighted average decay rate for all components is equal to the AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually. Because AP-42 values were developed using landfill data from approximately 1990, 1990 waste composition for the United States from EPA’s *Characterization of Municipal Solid Waste in the United States: 1990 Update* was used to calculate *f*. This correction factor is then multiplied by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are found, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12). The *Landfills* section of the Inventory (which estimates CH₄ emissions) estimates the overall MSW decay rate by partitioning the U.S. landfill population into three categories, based on annual precipitation ranges of (1) less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 yr⁻¹, respectively.

De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 yr⁻¹), but not for the other two overall MSW decay rates. To maintain consistency between landfill methodologies across the Inventory, the correction factors (*f*) were developed for decay rates of 0.038 and 0.057 yr⁻¹ through linear interpolation. A weighted national average component-specific decay rate was calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The component-specific decay rates are shown in Table 7-49.

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:

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

MSW that occurs includes energy recovery, so all discards to “landfill, other disposal” are assumed to go to landfills.

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),
$LF C_{i,t}$	=	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, and
k	=	First-order decay rate for waste i , (year^{-1}).

For a given year t , the total stock of C in landfills ($TLFC_t$) 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 (2010). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2010, the total food scraps C originally disposed in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed in subsequent years (1961 through 2010), the total landfill C from food scraps in 2010 was 37.0 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 2010, yielding a value of 250.7 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 2010 shown in Table 7-48 (3.6 Tg C) is equal to the stock in 2010 (250.7 Tg C) minus the stock in 2009 (247.0 Tg C).

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

Table 7-49: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Decay Rate (year^{-1}) for Landfilled Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H ₂ O)	70	30	10	70
CS, proportion of initial C stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year^{-1})	0.323	0.185	0.016	0.156

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

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Yard Trimmings	155.8	202.9	205.0	206.9	208.8	211.1	213.6
Branches	74.6	97.5	98.5	99.3	100.2	101.2	102.3
Leaves	66.7	87.3	88.3	89.2	90.0	91.1	92.2
Grass	14.5	18.1	18.2	18.4	18.6	18.8	19.0
Food Scraps	21.3	31.7	32.7	33.7	34.8	35.9	37.0
Total Carbon Stocks	177.2	234.7	237.7	240.6	243.6	247.0	250.7

Note: Totals may not sum due to independent rounding.

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, decay rate, 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 CO₂ flux in 2010 was estimated to be between -20.85 and -6.25 Tg CO₂ Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 57 percent below to 53 percent above the 2010 flux estimate of -13.32 Tg CO₂ Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 7-51: Tier 2 Quantitative Uncertainty Estimates for CO₂ Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO₂ Eq. and Percent)

Source	Gas	2010 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	(13.3)	(20.9)	(6.3)	-57%	+53%

^a Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

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

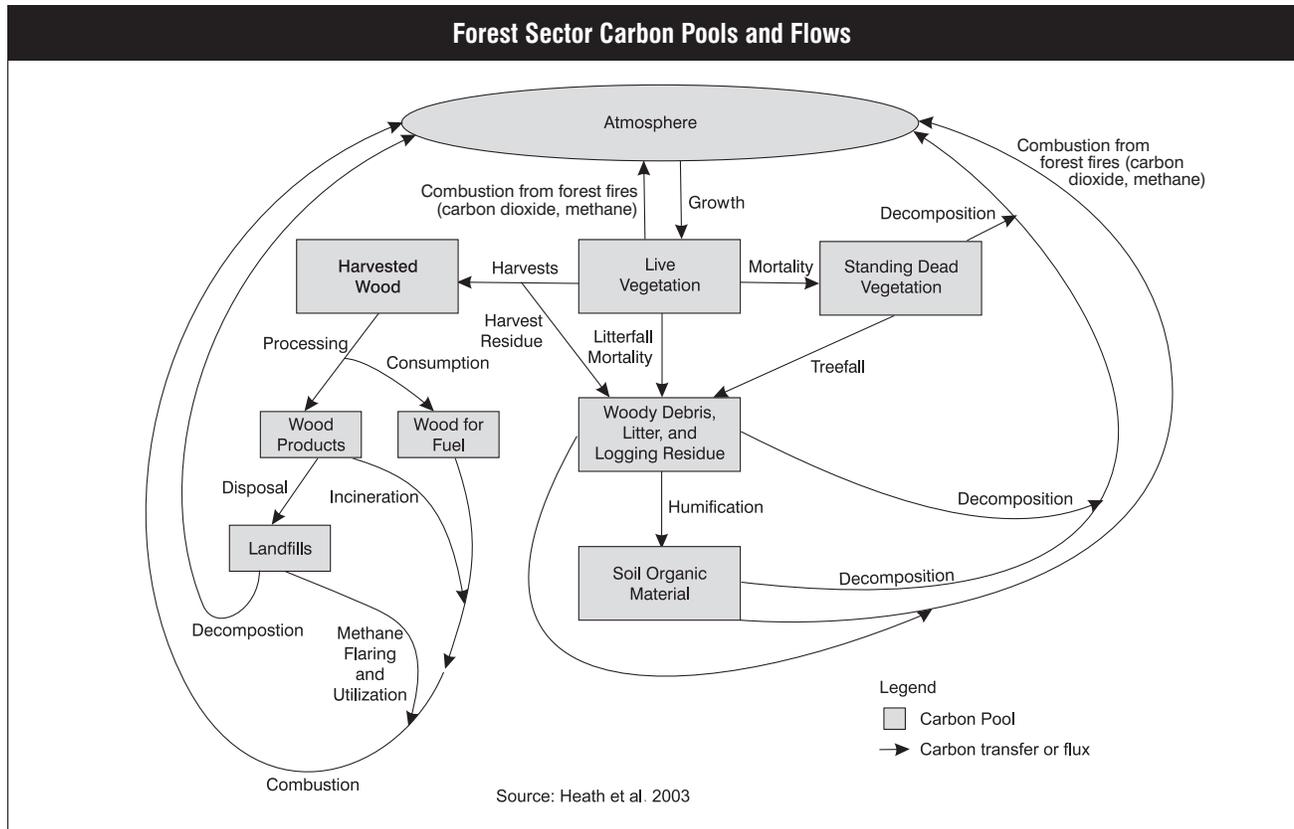
Recalculations Discussion

The current Inventory has been revised relative to the previous report. Input data were updated for the years: 1990, 2000, 2005, and 2007 through 2010 based on the updated values reported in *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010* (EPA 2011). As a result, C storage estimates for those years were revised relative to the previous Inventory. While data inputs for intervening years in the time series 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. These revisions resulted in an annual average decrease in C stored in landfills of 0.1 percent across the time series.

Planned Improvements

Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH₄ emissions described in the Waste chapter. For example, the Waste chapter does not distinguish landfill CH₄ emissions from yard trimmings and food scraps separately from landfill CH₄ emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

Figure 7-2



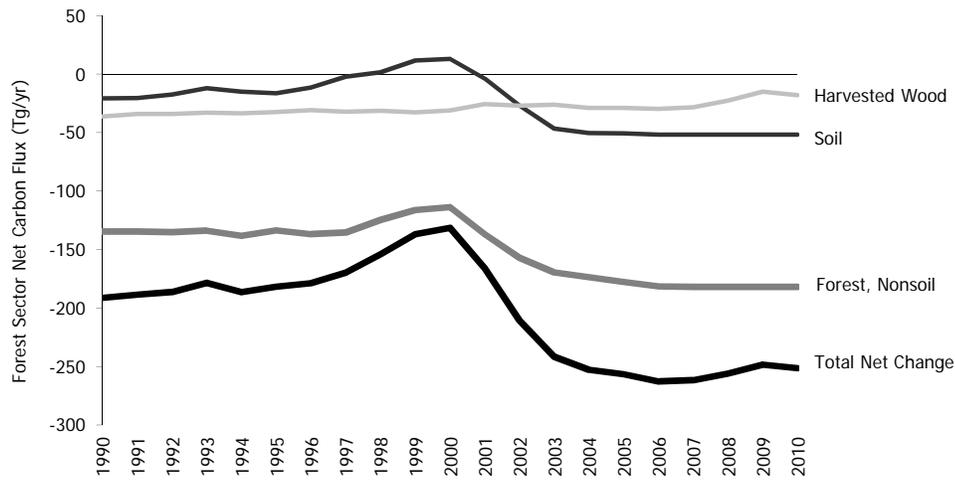


Figure 7-3: Estimates of Net Annual Changes in C Stocks for Major C Pools