# 7. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide ($CO_2$) flux[1] caused by 1) changes in forest carbon stocks, 2) changes in carbon stocks in urban trees, 3) changes in agricultural soil carbon stocks, and 4) changes in carbon stocks in landfilled yard trimmings and food scraps. Seven components of forest carbon stocks are analyzed: trees, understory vegetation, forest floor, down dead wood, soils, wood products in use, and landfilled wood products. The estimated $CO_2$ flux from each of these forest components was derived from U.S. forest inventory data, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in carbon stocks in urban trees were estimated based on field measurements in ten U.S. cities and data on national urban tree cover, using a methodology consistent with the *Revised 1996 IPCC Guidelines*. Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to use and management of cropland and grazing land, and emissions of $CO_2$ due to the application of crushed limestone and dolomite to agricultural soils (i.e., soil liming). The methods used to estimate all three components of changes in agricultural soil carbon stocks are consistent with the *Revised 1996 IPCC Guidelines*. Changes in yard trimming and food scrap carbon stocks in landfills were estimated using analysis of life-cycle greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). Note that the chapter title "Land-Use Change and Forestry" has been used here to maintain consistency with the IPCC reporting structure for national greenhouse gas inventories; however, the chapter covers land-use activities, in addition to land-use change and forestry activities. Therefore, except in table titles, the term "land use, land-use change, and forestry" will be used in the remainder of this chapter.

Unlike the assessments in other chapters, which are generally based on annual activity data, the flux estimates in this chapter, with the exception of those from wood products, urban trees, and liming, are based on periodic activity data in the form of forest, land use, and municipal solid waste surveys, which are tabulated on a less frequent basis. Carbon dioxide fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis over five or ten year periods. The resulting annual averages are applied to years between surveys. Because each state is surveyed separately and at different times, using this data structure, the estimated $CO_2$ fluxes from forest carbon stocks differ at the national level from year to year. The exception is forest soils, which are considered only at the regional scale and therefore have constant fluxes over multi-year intervals, with large discontinuities between intervals. Agricultural soils show a pattern similar to that of forest soils. In addition, because the most recent national forest and land-use surveys were completed for the year 1999, the estimates of $CO_2$ flux from forests and agricultural soils are based in part on modeled projections. Carbon dioxide flux from urban trees is based on neither annual data nor periodic survey data, but instead on data collected through the 1990s. The annual average flux for this period has been extrapolated to the entire time series.

Land use, land-use change, and forestry activities in 2002 resulted in a net sequestration of 690.7 Tg $CO_2$ Eq. (188 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 12 percent of total U.S. $CO_2$ emissions. Total land use, land-use change, and forestry net sequestration declined by approximately 28 percent between 1990 and 2002. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings and food scraps also slowed over this period, as did annual carbon accumulation in agricultural soils. The constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for 1990 through 1999), as described above.

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

The methodology, results, and uncertainty associated with each of the four carbon stock categories are discussed in the chapter sections below. Where relevant, the sections also include a discussion of significant recalculations with respect to previous inventory documents, and plans for improvements in the methodology.

Table 7-1: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg $CO_2$ Eq.)

| Sink Category | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| Forests | (846.6) | | (964.1) | (730.1) | (617.8) | (588.4) | (602.3) | (600.2) | (600.8) |
| Urban Trees | (58.7) | | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) |
| Agricultural Soils | (26.5) | | (19.0) | (19.3) | (16.9) | (17.3) | (19.0) | (20.7) | (21.2) |
| Landfilled Yard Trimmings and Food Scraps | (26.0) | | (13.4) | (12.9) | (12.4) | (11.3) | (10.1) | (10.2) | (10.1) |
| **Total** | **(957.9)** | | **(1,055.2)** | **(821.0)** | **(705.8)** | **(675.8)** | **(690.2)** | **(689.7)** | **(690.7)** |

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Gray shading identifies estimates that rely at least partially on projections.

Table 7-2: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg C)

| Sink Category | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| Forests | (231) | | (263) | (199) | (168) | (161) | (164) | (164) | (164) |
| Urban Trees | (16) | | (16) | (16) | (16) | (16) | (16) | (16) | (16) |
| Agricultural Soils | (7) | | (5) | (5) | (5) | (5) | (5) | (6) | (6) |
| Landfilled Yard Trimmings and Food Scraps | (7) | | (4) | (4) | (3) | (3) | (3) | (3) | (3) |
| **Total** | **(261)** | | **(288)** | **(224)** | **(192)** | **(184)** | **(188)** | **(188)** | **(188)** |

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Gray shading identifies estimates that rely at least partially on projections.

## 7.1. Changes in Forest Carbon Stocks (IPCC Source Category 5A)

For estimating carbon flux, carbon in forest ecosystems can be divided into the following seven storage pools.

- Trees, including the coarse roots, stems, branches, and foliage of living trees and standing dead trees.
- Understory vegetation, including shrubs and bushes, including the roots, stems, branches, and foliage.
- Forest floor, including fine woody debris, tree litter, and humus.
- Down dead wood, including logging residue and other coarse dead wood on the ground, and stumps and roots of stumps.
- Soil, including all organic material in soil except coarse roots.
- Harvested wood products in use.
- Harvested wood products in landfills.

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, growth, mortality, and decomposition) and anthropogenic activities (e.g., harvesting, thinning, clearing, and replanting). As trees photosynthesize and grow, carbon is removed from the atmosphere and stored in living tree biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they store a relatively constant amount of carbon. As trees die and otherwise deposit litter and debris on the forest floor, soil organisms consume much of the biomass. Consequently, carbon is released to the atmosphere due to respiration or is added to the soil.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of carbon to the atmosphere. Instead, harvesting transfers carbon to a "product pool." Once in a product pool, most carbon 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 carbon 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 carbon is released to the atmosphere.  If wood products are disposed of in landfills, the carbon contained in the wood may be released many years or decades later, or may be stored almost permanently in the landfill.

This section of the Land-Use Change and Forestry chapter quantifies the net changes in carbon stocks in five forest carbon 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.

Forest carbon storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 7-1.  In this figure, forest carbon storage pools are represented by boxes, while flows between storage pools, and between storage pools and the atmosphere, are represented by arrows.  Note that the boxes are not identical to the storage pools identified in this chapter.  The storage pools identified in this chapter are defined differently in this graphic to better illustrate the processes that result in transfers of carbon from one pool to another, and that result in emissions to the atmosphere as well as uptake from the atmosphere.

Figure 7-1:  Forest Sector Carbon Pools and Flows

Approximately 33 percent (747 million acres) of the U.S. land area is forested (Smith et al. 2001).  From the early 1970s to the early 1980s, forest land declined by approximately 5.9 million acres.  During the 1980s and 1990s, forest area increased by about 9.2 million acres.  These net changes in forest area represent average annual fluctuations of only about 0.1 percent.  Given the low rate of change in U.S. forest land area, the major influences on the current net carbon flux from forest land are management activities and the ongoing impacts of previous land-use changes.  These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems.  For example, intensified management of forests can increase both the rate of growth and the eventual biomass density[2] of the forest, thereby increasing the uptake of carbon.  Harvesting forests removes much of the aboveground carbon, but trees can grow on this area again and sequester carbon.  The reversion of cropland to forest land increases carbon storage in biomass, forest floor, and soils.  The net effect of both forest management and land-use change involving forests is captured in the estimates of carbon stocks and fluxes presented in this chapter.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, as well as timber harvesting and use have resulted in net uptake (i.e., net sequestration) of carbon each year from 1990 through 2002.  Due to improvements in U.S. agricultural productivity, the rate of forest clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased.  As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests or were actively reforested.  The impacts of these land-use changes still affect carbon fluxes from forests in the East.  In addition, carbon fluxes from Eastern forests have been affected by a trend toward active management on private land.  Collectively, these changes have nearly doubled the biomass density in Eastern forests since the early 1950s.  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 carbon 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 landfills rather than by incineration, significant quantities of carbon in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere.  The size of these long-term carbon storage pools has increased during the last century.

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

Changes in carbon stocks in U.S. forests and harvested wood were estimated to account for an average annual net sequestration of 736 Tg $CO_2$ Eq. (201 Tg C) over the period 1990 through 2002 (Table 7-3, Table 7-4, and Figure 7-2). Net sequestration is a reflection of net forest growth and increasing forest area over this period, particularly before 1997, as well as net accumulation of carbon in harvested wood pools. The variation among years in total forest carbon stocks is due primarily to variation in tree carbon stocks. Surveys are periodic, and estimates in non-survey years are interpolated. The national estimates reflect the combination of these individual patterns of variation among survey years that vary for each state. Total land use, land-use change, and forestry net sequestration declined by approximately 28 percent between 1990 and 2002. This decline was primarily due to a decline in the estimated rate of sequestration in forest soils. Estimates of soil carbon stocks depend solely on forest area and type. Thus, any estimated changes in soil carbon stocks over time were due to changes in total forest area and/or changes in forest type. Because the rate of increase in forest area slowed after 1997, a concomitant decrease in the rate of carbon sequestration by forest soils resulted.

The pattern of change in soil carbon stocks reflects the assumption that changes in soil carbon occur instantaneously as a function of changes in net forest area and changes among forest types and the use of survey data only from three nominal reporting years. An improved methodology is being developed to account for the ongoing effects of changes in land use and forest management, as discussed in the "Planned Improvements" section below.

Table 7-3: Net Changes in Carbon Stocks in Forest and Harvested Wood Pools, and Total Net Forest Carbon Flux (Tg $CO_2$ Eq.)

| Carbon Pool | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| **Forest** | **(636.6)** | | **(756.5)** | **(517.4)** | **(411.7)** | **(373.8)** | **(391.5)** | **(386.4)** | **(386.4)** |
| Trees | (354.2) | | (464.6) | (401.0) | (307.5) | (275.0) | (289.9) | (285.5) | (285.5) |
| Understory | 0.8 | | (3.1) | (1.7) | (0.5) | 2.2 | 2.5 | 2.2 | 2.2 |
| Forest Floor | (38.1) | | (12.7) | 2.7 | 11.0 | 16.2 | 17.2 | 16.5 | 16.5 |
| Down Dead Wood | (32.5) | | (63.5) | (62.4) | (59.7) | (62.2) | (66.3) | (64.6) | (64.6) |
| Forest Soils | (212.7) | | (212.7) | (55.0) | (55.0) | (55.0) | (55.0) | (55.0) | (55.0) |
| **Harvested Wood** | **(210.1)** | | **(207.6)** | **(212.7)** | **(206.1)** | **(214.7)** | **(210.8)** | **(213.8)** | **(214.4)** |
| Wood Products | (47.6) | | (56.1) | (57.7) | (51.9) | (61.5) | (58.7) | (59.0) | (59.2) |
| Landfilled Wood | (162.4) | | (151.5) | (155.0) | (154.2) | (153.1) | (152.1) | (154.8) | (155.3) |
| **Total Net Flux** | **(846.6)** | | **(964.1)** | **(730.1)** | **(617.8)** | **(588.4)** | **(602.3)** | **(600.2)** | **(600.8)** |

+ Does not exceed 0.5 Tg $CO_2$ Eq.
Note: Parentheses indicate net carbon sequestration (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Estimates are based on a combination of historical data and projections as described in the text and in Annex 3.12. Forest estimates are based on interpolations between periodic measurements; harvested wood estimates are based on results from annual surveys and models. The sum of estimates in a column may not equal estimated totals due to independent rounding.

Table 7-4: Net Changes in Carbon Stocks in Forest and Harvested Wood Pools, and Total Net Forest Carbon Flux (Tg C)

| Carbon Pool | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| **Forest** | **(174)** | | **(206)** | **(141)** | **(112)** | **(102)** | **(107)** | **(105)** | **(105)** |
| Trees | (97) | | (127) | (109) | (84) | (75) | (79) | (78) | (78) |
| Understory | (+) | | (1) | (+) | (+) | 1 | 1 | 1 | 1 |
| Forest Floor | (10) | | (3) | 1 | 3 | 4 | 5 | 4 | 4 |
| Down Dead Wood | (9) | | (17) | (17) | (16) | (17) | (18) | (18) | (18) |
| Forest Soils | (58) | | (58) | (15) | (15) | (15) | (15) | (15) | (15) |
| **Harvested Wood** | **(57)** | | **(57)** | **(58)** | **(56)** | **(59)** | **(57)** | **(58)** | **(58)** |
| Wood Products | (13) | | (15) | (16) | (14) | (17) | (16) | (16) | (16) |
| Landfilled Wood | (44) | | (41) | (42) | (42) | (42) | (41) | (42) | (42) |
| **Total Net Flux** | **(231)** | | **(263)** | **(199)** | **(168)** | **(160)** | **(164)** | **(164)** | **(164)** |

+ Does not exceed 0.5 Tg C.
Note: Parentheses indicate net carbon sequestration (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Estimates are based on a combination of historical data and projections as described in the text and in Annex 3.12. Forest estimates are based on interpolations between

periodic measurements; harvested wood estimates are based on results from annual surveys and models. The sum of estimates in a column may not equal estimated totals due to independent rounding.

Table 7-5 presents the carbon stock estimates for non-soil forest and harvested wood storage pools, and Table 7-6 presents the carbon stock estimates for forest soil storage pools. Together, the tree and forest soil pools account for approximately 83 percent of total forest carbon stocks. Carbon stocks in all pools, except the understory and forest floor, increased over time. Therefore, carbon sequestration was greater than carbon emission as discussed above. Figure 7-3 shows the average carbon density in forests by state, estimated for 2003.

Table 7-5: Carbon Stocks in Forest and Harvested Wood Pools (Tg C)

| **Carbon Pool** | **1990** | | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** |
|---|---|---|---|---|---|---|---|---|---|
| **Forest** | **23,943** | | **24,587** | **24,735** | **24,861** | **24,958** | **25,045** | **25,137** | **25,227** |
| Trees | 17,618 | | 18,122 | 18,248 | 18,358 | 18,442 | 18,517 | 18,596 | 18,674 |
| Understory | 645 | | 652 | 653 | 654 | 654 | 653 | 652 | 652 |
| Forest Floor | 4,498 | | 4,574 | 4,577 | 4,576 | 4,573 | 4,569 | 4,564 | 4,560 |
| Down Dead Wood | 1,183 | | 1,239 | 1,256 | 1,273 | 1,290 | 1,307 | 1,325 | 1,342 |
| Forest Soils (see Table 7-6) | | | | | | | | | |
| **Harvested Wood** | **1,915** | | **2,250** | **2,307** | **2,365** | **2,421** | **2,480** | **2,537** | **2,595** |
| Wood Products | 1,134 | | 1,217 | 1,232 | 1,248 | 1,262 | 1,279 | 1,295 | 1,311 |
| Landfilled Wood | 781 | | 1,033 | 1,074 | 1,117 | 1,159 | 1,200 | 1,242 | 1,284 |
| **Total Carbon Stock*** | **25,859** | | **26,837** | **27,042** | **27,226** | **27,379** | **27,525** | **27,674** | **27,823** |

Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, or trees on non-forest land (e.g., urban trees). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Estimates are based on a combination of historical data and projections as discussed in Annex 3.12. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Forest soils are based on estimates of stocks in 1987, 1997, and 2002 only. Values for other years are extrapolated from the most recent measurement year. The sum of estimates in a column may not equal estimated totals due to independent rounding.
* Total Carbon Stock values do not include Forest Soils.

Table 7-6: Carbon Stocks in Forest Soils (Tg C)

| | **1987** | **1997** | **2002** |
|---|---|---|---|
| Forest Soils | 25,681 | 26,262 | 26,337 |

Note: Estimates are based on a combination of periodic historical data and projections as described in the text and in Annex 3.12.

Figure 7-2: Estimates of Forest Carbon Flux in Major Pools

Note: Estimates for harvested wood and forest soils are based on the same methodology and data as the previous U.S. Inventory (USEPA, 2003). Estimates for all pools are based on measured forest inventory data and modeled projections as described in the text.
Total Net includes all forest pools: trees, understory, forest floor, down dead wood, forest soils, wood products, and landfilled wood.

Figure 7-3: Average Carbon Density in the Forest Tree Pool in the Conterminous U.S. During 2003.

## Methodology

The methodology described herein is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). For developing estimates of net carbon flux from Land-Use Change and Forestry, including all pools except for harvested wood, carbon stock estimates were derived from periodic inventories of forest stocks, and net changes in carbon stocks were interpolated between survey years. Carbon emissions from harvested wood were determined by accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion).[3] Different data sources were used to estimate the carbon stocks and stock change in (1) forests (live and dead trees, understory, forest floor, and down dead wood), (2) forest soils, and (3) harvested wood products. Therefore, these pools are described separately below.

### Tree, Understory, Forest Floor and Down Dead Wood Carbon

The overall approach for determining non-soil forest carbon stock change was to estimate non-soil forest carbon stocks, based on data from two forest surveys conducted several years apart, and then to subtract the estimates developed for two consecutive years to calculate the net change in carbon stocks. Forest survey data were obtained from the USDA Forest Service, Forest Inventory and Analysis program (Frayer and Furnival 1999, Smith et al. 2001). Historically, the Forest Inventory and Analysis program did not conduct detailed surveys of all forest land, but instead focused on land capable of supporting timber production (timberland[4]). In addition, some reserved forest land and some other forest land were surveyed. To include all forest lands, estimates were made for timberlands and then were extrapolated for non-timberland forests. Growth, harvests, land-use change, and other estimates of temporal change were derived from repeated surveys conducted every 5 to 14 years, depending on the state. Because each state has been surveyed periodically, the most recent data for most states are generally several years old. Therefore, forest areas, volumes, growth, land-use changes, and other forest characteristics, as of January 1, 2003, were extrapolated with a modeling system that represents the U.S. forest sector (see Annex 3.12 and Haynes 2003).

For each periodic inventory in each state, each carbon pool was estimated using coefficients from the FORCARB2 model (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003), which is part of the forest sector modeling system described in Annex 3.12. Tree biomass and carbon stocks were based on the growing stock volume from survey data or model projections. Calculations were made using volume-to-biomass conversion factors for different types of forests as presented in Smith et al. (2003). Biomass estimates were divided by two to obtain estimates of carbon in living trees (i.e., it was assumed that dry biomass is 50 percent carbon). Understory carbon was estimated from inventory data using equations presented in Birdsey (1996). Forest floor carbon was estimated from inventory data using the equations presented in Smith and Heath (2002). Down dead wood was estimated using a procedure similar to that used for estimating carbon in understory vegetation, as described in Annex 3.12.

Carbon stocks were calculated separately for each state between 1991 and 2002, and for the most recent inventory prior to 1991. For each pool in each state in each year, from 1990 through 2002, carbon stocks were estimated by linear interpolation between survey years. Carbon stock estimates for each pool were summed over all states to form estimates for the conterminous United States. Annual stock changes were estimated by subtracting national carbon stocks as of January 1 of the inventory year from that of the subsequent year (i.e., 2002 fluxes represent the January 1, 2003 stock minus the January 1, 2002 stock). Data sources and methods for estimating individual carbon pools are described more fully in Annex 3.12.

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[3] The product estimates in this study use the “production approach” meaning that they do not account for carbon stored in imported wood products, but do include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

[4] Forest land in the United States includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1997, there were about 503 million acres of timberland, which represented 67 percent of all forest lands (Smith and Sheffield 2000). Forest land classified as timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 33 percent of forest land is classified as reserved forest land, which is forest land withdrawn from timber use by statute or regulation, or other forest land, which includes forests on which timber is growing at a rate less than 20 cubic feet per acre per year.

### Forest Soil Carbon

Soil carbon stock estimates are based solely on forest area and on average carbon density for each broad forest type group. Thus, any changes in soil carbon stocks are due to changes in total forest area or changes in the areas of forest types. Unlike other pools, estimates were not made for individual states, but instead for each of 10 regions in the conterminous United States. Data on the carbon content of soils were obtained from the national STATSGO spatial database (USDA 1991). These data were combined with Forest Inventory and Analysis survey data to estimate soil carbon in all forest lands by broad forest type group (see Annex 3.12 for list of forest type groups). Estimates were made for 1987 and 1997 based on compilations of forest inventory data made for these reporting years (Waddell et al. 1989, Smith et al. 2001). For 2002, estimates were projected using the FORCARB2 model as described in Annex 3.12. The average annual soil stock change for 1990 through 1996 was derived by subtracting the January 1, 1997 stock from the 1987 stock, and dividing by the number of years between estimates (10). The net annual stock changes for 1997 through 2001 were derived in the same way using the 1997 and 2002 stocks. The net annual stock change for 2002 was extrapolated from 2001 (i.e., the same estimate was used for 2002 as for 2001). In principal, estimates of soil carbon stocks could be made by interpolation, as described above for other forest carbon pools. However, this approach has not been used because an improved methodology for estimating soil carbon is currently under development (see "Planned Improvements" below). Further information on soil carbon estimates is presented in Annex 3.12 and by Heath et al. (2003), and Johnson and Kern (2003).

### Harvested Wood Carbon

Estimates of carbon stock changes in wood products and wood discarded in landfills were based on the methods described by Skog and Nicholson (1998). Carbon stocks in wood products in use and wood products stored in landfills were estimated from 1910 onward based on historical data from the USDA Forest Service (USDA 1964, Ulrich 1989, Howard 2001), and historical data as implemented in the framework underlying the North American Pulp and Paper (NAPAP, Ince 1994) and the Timber Assessment Market and the Aggregate Timberland Assessment System Timber Inventory models (TAMM/ATLAS, Haynes 2003, Mills and Kincaid 1992) that are part of the forest sector modeling system described in Annex 3.12. Beginning with data on annual wood and paper production, the fate of carbon in harvested wood was tracked for each year from 1910 through 2002, and included the change in carbon stocks in wood products, the change in carbon in landfills, and the amount of carbon emitted to the atmosphere ($CO_2$ and $CH_4$) both with and without energy recovery. To account for imports and exports, the production approach was used, meaning that carbon in exported wood was counted as if it remained in the United States, and carbon in imported wood was not counted.

## Uncertainty

The forest survey data that underlie the forest carbon estimates are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. However, forest survey data that are currently available generally exclude timber stocks on most forest land in Alaska, Hawaii, and U.S. territories. For this reason, estimates have been developed only for the conterminous United States. Within the conterminous United States, the USDA Forest Service mandates that forest area data are accurate within 3 percent at the 67 percent confidence level (one standard error) per 405,000 ha of forest land (Miles et al. 2001). For larger areas, the uncertainty in area is concomitantly smaller. For volume data, the accuracy is targeted to be 5 percent for each 28,300 $m^3$ at the same confidence level. An analysis of uncertainty in growing stock volume data for timber-producing lands was undertaken for five states: Florida, Georgia, North Carolina, South Carolina, and Virginia (Phillips et al. 2000). Nearly all of the uncertainty was found to be due to sampling rather than the regression equations used to estimate volume from tree height and diameter. Standard errors for growing stock volume ranged from 1 to 2 percent for individual states and less than 1 percent for the 5-state region. However, the total standard error for the change in growing stock volume was estimated to be 12 to 139 percent for individual states, and 20 percent for the 5-state region. The high relative uncertainty for growing stock volume change in some states was due to small net changes in growing stock volume. However, the uncertainty in volume change may be smaller than was found in this study because estimates from samples taken at different times on permanent survey plots are correlated, and such correlation reduces the uncertainty in estimates of changes in volume or carbon over time (Smith and Heath 2000). Based on these accuracy guidelines and these results for the Southeastern United States, forest area and volume data for the conterminous United States are expected to be reasonably accurate, although estimates of small changes in growing stock volume may have substantial uncertainty.

In addition to uncertainty in growing stock volume, there is uncertainty associated with the estimates of carbon stocks in other ecosystem pools. Estimates for these pools are derived from extrapolations of site-specific studies to all forest land since survey data on these pools are not generally available. Such extrapolation introduces uncertainty because available studies may not adequately represent regional or national averages. Uncertainty may also arise due to (1) modeling errors, for example relying on coefficients or relationships that are not well known, and (2) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that there is little consensus from available data sets on the effect of land use change and forest management activities (such as harvest) on soil carbon stocks. For example, while Johnson and Curtis (2001) found little or no net change in soil carbon following harvest, on average, across a number of studies, many of the individual studies did exhibit differences. Heath and Smith (2000b) noted that the experimental design in a number of soil studies limited their usefulness for determining effects of harvesting on soil carbon. Because soil carbon stocks are large, estimates need to be very precise, since even small relative changes in soil carbon sum to large differences when integrated over large areas. The soil carbon stock and stock change estimates presented herein are based on the assumption that soil carbon density for each broad forest type group stays constant over time. As more information becomes available, the effects of land use and of changes in land use and forest management will be better accounted for in estimates of soil carbon (see "Planned Improvements" below).

Another source of uncertainty is the use of projected (modeled) estimates of current forest area, forest type, rate of harvest, effect of forest management, and growing stock volume. These projections are used within the forest sector modeling system described in Annex 3.12 to produce current carbon stock estimates. As discussed above, forest survey data for some individual states are many years old, and current estimates thus depend on the use of the forest sector modeling system. Although this modeling system has been used repeatedly for national assessments, there are uncertainties associated with each of the models in this system.

Recent studies have begun to quantify the uncertainty in national-level forest carbon budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000a) report on an uncertainty analysis they conducted on carbon sequestration in privately owned timberlands throughout the conterminous United States. These studies are not exactly comparable to the estimates in this chapter because they used an older version of the FORCARB model and are based on older data. However, the relative magnitudes of the uncertainties are informative. For the period 1990 through 1999, the true mean carbon flux was estimated to be within 15 percent of the reported mean at the 80 percent confidence level. The corresponding true mean carbon stock estimate for 2000 was within approximately 5 percent of the reported mean value at the 80 percent confidence level. The relatively greater uncertainty in flux estimates compared to stock estimates is roughly similar to that found for estimates of growing stock volume discussed above (Phillips et al. 2000). In both analyses, there are greater uncertainties associated with smaller estimates of flux than larger ones. Uncertainty in the estimates presented in this inventory may be greater than those presented by Heath and Smith (2000a) for several reasons. Most importantly, their analysis did not include uncertainty in growing stock volume data or uncertainties in stocks and fluxes of carbon from harvested wood.

## QA/QC and Verification

As discussed above and in Annex 3.12, the USDA Forest Service Forest Inventory and Analysis program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States since 1952. The main purpose of the Forest Inventory and Analysis program has been to estimate areas, volume of growing stock, and timber products output and utilization factors. The Forest Inventory and Analysis program includes numerous quality assurance and quality control 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 Forest Inventory and Analysis program form a strong foundation for carbon stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (<http://fia.fs.fed.us>).

Many key calculations for estimating current forest carbon stocks based on FIA data are based on the forest sector modeling system that is used to project forest area, harvests, tree volumes, and carbon stocks. This modeling system is described briefly in Annex 3.12 and more fully in the citations presented therein. These models have been used for many years—and in some cases decades—to produce national assessments of forest condition, timber products output, and forest carbon stocks and stock changes. This forest sector modeling system has been reviewed and published in the refereed scientific literature as cited in Annex 3.12.

General quality control procedures were used in performing calculations to estimate carbon stocks based on historical FIA data or model projections. Forest Inventory and Analysis data and some model projections are given in English units, but carbon stock estimates were developed using metric units. To avoid unit conversion errors, a standard conversion table in electronic form was used (Appendix B of Smith et al. 2001). Additionally, calculations of total forest area were checked against published Forest Inventory and Analysis data (for example, Smith et al. 2001) to assure that no areas of forest were being counted twice or not counted at all. Finally, carbon stock estimates were compared with previous inventory report estimates to assure that any differences could be explained by either new data or revised calculation methods (see the "Recalculations" discussion below).

## Recalculations Discussion

The forest inventory data used to estimate soil carbon flux and harvested wood flux are the same as in the previous inventory. However, estimates of non-soil forest carbon stocks and fluxes in other pools are now based on forest inventory data from individual states. This methodological change from regionally-based to state-based assessment has resulted in a significant decrease, relative to previous Inventories, in forest stock estimates for recent years. Average survey years for each state are presented in Annex 3.12. Estimating carbon stocks and fluxes for individual states allows greater precision in assigning the survey year for each state. For example, in the previous Inventory (EPA 2003), 1997 was given as the measurement year (Smith et al. 2001) for the 1997 national Resource Planning Act assessment data, although the average survey date was 1990. Because the actual survey year was several years prior to the nominal Resource Planning Act reporting year for most states, using the average survey date for each state has removed a source of bias in estimates of the survey year. Since there is a trend of increasing carbon stocks in forests over time, removing this bias has tended to reduce estimates of recent forest carbon sequestration because the previously reported increase in carbon stocks now occurs at earlier dates. The same amount of carbon stock change is now spread over a longer time period, removing part of the stock change from the time interval considered by this Inventory. This methodology also results in more variation in the non-soil forest carbon fluxes, because average flux values are calculated between different years in different states. Thus current national estimates of non-soil forest carbon fluxes vary substantially among years, whereas previous estimates varied only among years in which Resource Planning Act assessments were reported, such as 1997. These effects can be seen in Figure 7-4, which shows the difference between current and previous estimates of tree and forest carbon flux. Figure 7-4 also demonstrates the consistency in the methodology for reporting soil carbon fluxes relative to last year's inventory, represented by the single line labeled "Forest Soils."

Figure 7-4: Estimates of Forest Carbon Flux in Major Pools: Comparison of New Estimates with those in Previous Inventory

Note : Estimates for harvested wood and forest soils based on the same methodology and data as the previous inventory (EPA 2003).
Total Net includes all forest pools: trees, understory, forest floor, down dead wood, forest soils, wood products, and landfilled wood.

## Planned Improvements

The Forest Inventory and Analysis program has adopted a new annualized design, such that a portion of each state will be surveyed each year (Gillespie 1999). The annualized survey also includes a plan to measure attributes that are needed to estimate carbon in various pools, such as soil carbon and forest floor carbon. Currently, carbon in pools other than trees must be estimated based on other measured characteristics or other less comprehensive data sets. The annualized survey will also improve coverage of non-timberland forests, which have not been surveyed as thoroughly as timberland forests. However, annual data are not yet available for most states. During the next several years, the use of annual data, including new data on soil and forest floor carbon stocks, and new data on non-timberlands, will improve the precision and accuracy of estimates of forest carbon stocks and fluxes.

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 carbon (Birdsey and Lewis 2003). Currently, soil carbon estimates are based on the assumption that soil C density depends only on broad forest type group, not on land use history. However, many forests in the Eastern United States are re-growing on abandoned agricultural land. During such regrowth, soil and forest floor carbon stocks often increase substantially over many years or even decades, especially on highly eroded agricultural land. In addition, with deforestation, soil carbon stocks often decrease over many years. A new methodology is being developed to account for these changes in soil carbon over time. This methodology includes estimates of area changes among land uses (especially forest and agriculture), estimates of the rate of soil carbon stock gain with afforestation, and estimates of the rate of soil carbon stock loss with deforestation over time. This topic is important because soil carbon stocks are large, and soil carbon flux estimates contribute substantially to total forest carbon flux, as shown in Table 7-6 and Figure 7-4.

The estimates of carbon stored in harvested wood products are currently being revised using more detailed wood products production and use data and improved and more detailed parameters on disposition and decay of products. In addition, more validation steps will be taken as suggested by the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF). Preliminary results suggest that the estimated additions of carbon stored in harvested wood products may be somewhat lower than the estimates shown in this report.

## *7.2. Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5A5)*

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). It is estimated that urban areas (cities, towns, and villages), which cover 3.5 percent of the continental United States, contain about 3.8 billion trees. With an average tree canopy cover of 27.1 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 continental United States were estimated by Nowak and Crane (2002) to account for an average annual net sequestration of 58.7 Tg $CO_2$ Eq. (16 Tg C). These data were collected throughout the 1990s, and have been applied to the entire time series in this report (see Table 7-7). Annual estimates of $CO_2$ flux have not been developed, but are believed to be relatively constant from 1990 through 2002. Net carbon flux from urban trees is proportionately greater on an area basis than that of forests. This 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 carbon 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. Urban trees therefore appear to have a greater carbon density than forested areas (Nowak and Crane 2002).

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

| **Year** | **Tg $CO_2$ Eq.** | **Tg C** |
|---|---|---|
| 1990 | (58.7) | (16) |
| | | |
| 1996 | (58.7) | (16) |
| 1997 | (58.7) | (16) |
| 1998 | (58.7) | (16) |
| 1999 | (58.7) | (16) |
| 2000 | (58.7) | (16) |
| 2001 | (58.7) | (16) |
| 2002 | (58.7) | (16) |

Note: Parentheses indicate net sequestration.

## Methodology

The methodology used by Nowak and Crane (2002) is based on average annual estimates of urban tree growth and decomposition, which were derived from field measurements and data from the scientific literature, urban area estimates from U.S. Census data, and urban tree cover estimates from remote sensing data. This approach is consistent with, but more robust than, the default IPCC methodology in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).[5]

Nowak and Crane (2002) developed estimates of annual gross carbon sequestration from tree growth and annual gross carbon emissions from decomposition for ten U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Jersey City, NJ; New York, NY; Oakland, CA; Philadelphia, PA; Sacramento, CA; and Syracuse, NY. The gross carbon sequestration estimates were derived from field data that were collected in these ten cities during the period from 1989 through 1999, including tree measurements of stem diameter, tree height, crown height, and crown width, and information on location, species, and canopy condition. The field data were converted to annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition (forested, park-like, and open growth) by applying allometric equations, a root-to-shoot ratio, moisture contents, a carbon content of 50 percent (dry weight basis), an adjustment factor to account for smaller aboveground biomass volumes (given a particular diameter) in urban conditions compared to forests, an adjustment factor to account for tree condition (fair to excellent, poor, critical, dying, or dead), and annual diameter and height growth rates. The annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition were then scaled up to city estimates using tree population information. The field data from the 10 cities, some of which are unpublished, are described in Nowak and Crane (2002) and references cited therein. The allometric equations were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), and the adjustments to account for smaller volumes in urban conditions were 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). Adjustment factors to account for tree condition were based on percent crown dieback (Nowak and Crane 2002). Tree growth rates were also 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.

The annual gross carbon emission estimates were derived by applying to carbon stock estimates, which were derived as an intermediate step in the gross sequestration calculations, estimates of annual mortality by tree diameter and condition class, assumptions about whether dead trees would be removed from the site—since removed trees were assumed to decay faster than those left on the site—and assumed decomposition rates for dead trees left standing and dead trees that are removed. The annual gross carbon emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Assumptions about whether dead trees would be removed from the site were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak and Crane 2002).

Annual net carbon sequestration estimates were derived for seven of the ten cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[6]

National annual net carbon sequestration by urban trees was estimated from the city estimates of gross and net sequestration, and urban area and urban tree cover data for the contiguous United States. Note that the urban areas are based on U.S. Census data, which define "urban" as having a population density greater than 1,000 people per square mile or population total greater than 2,500. Therefore, urban encompasses most cities, towns, and villages

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[5] It is more robust in that both growth and decomposition are accounted for, and data from individual trees are scaled up to state and then national estimates based on data on urban area and urban tree canopy cover.

[6] Three cities did not have net estimates.

(i.e., it includes both urban and suburban areas). The gross and net carbon 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 (0.30 kg C/$m^2$-year) was then multiplied by an estimate of national urban tree cover area (76,151 $km^2$) to estimate national annual gross sequestration. 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 for those cities that had both estimates. The average of these ratios is 0.70. The urban tree cover area estimates for each of the 10 cities and the contiguous United States were obtained from Dwyer et al. (2000) and Nowak et al. (2001).

Table 7-8: Carbon Stocks (Metric Tons C), Annual Carbon Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual Carbon Sequestration per Area of Tree Cover (kg C/$m^2$ cover-yr) for Ten 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 |
|---|---|---|---|---|---|---|
| New York, NY | 1,225,200 | 38,400 | 20,800 | 20.9 | 0.23 | 0.12 |
| Atlanta, GA | 1,220,200 | 42,100 | 32,200 | 36.7 | 0.34 | 0.26 |
| Sacramento, CA | 1,107,300 | 20,200 | NA | 13.0 | 0.66 | NA |
| Chicago, IL | 854,800 | 40,100 | NA | 11.0 | 0.61 | NA |
| Baltimore, MD | 528,700 | 14,800 | 10,800 | 25.2 | 0.28 | 0.20 |
| Philadelphia, PA | 481,000 | 14,600 | 10,700 | 15.7 | 0.27 | 0.20 |
| Boston, MA | 289,800 | 9,500 | 6,900 | 22.3 | 0.30 | 0.22 |
| Syracuse, NY | 148,300 | 4,700 | 3,500 | 24.4 | 0.30 | 0.22 |
| Oakland, CA | 145,800 | NA | NA | 21.0 | NA | NA |
| Jersey City, NJ | 19,300 | 800 | 600 | 11.5 | 0.18 | 0.13 |

NA = not analyzed

## Uncertainty

Only the uncertainty associated with sampling was quantifiable, as reported by Nowak and Crane (2002). The average standard deviation for urban tree carbon storage was 27 percent of the mean carbon storage on an area basis. Additionally, a 5 percent uncertainty was associated with national urban tree covered area. These estimates are based on field data collected in ten U.S. cities, and uncertainty in these estimates increases as they are scaled up to the national level.

There is additional uncertainty associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there may be some overlap between the urban tree carbon estimates and the forest tree carbon estimates. However, both the omission of urban soil carbon flux and the potential overlap with forest carbon are believed to be relatively minor (Nowak 2002). Because these are inestimable, they are not quantified as part of this analysis.

These values and considerations were assembled under a Tier 1 level uncertainty analysis to yield an uncertainty estimate for the net flux associated with urban trees in the United States for 2002 of 39 percent. The results are shown in Table 7-9.

Table 7-9: Quantitative Uncertainty Estimates for $CO_2$ Emissions from Changes in Carbon Stocks in Urban Trees (Tg $CO_2$ Eq. and Percent)

| IPCC Source Category | Gas | Year 2002 Emissions (Tg $CO_2$ Eq.) | Uncertainty (%) | Uncertainty Range Relative to 2002 Emission Estimate (Tg $CO_2$ Eq.) | |
|---|---|---|---|---|---|
| | | | | Lower Bound | Upper Bound |
| Changes in C Stocks in Urban Trees | $CO_2$ | (58.7) | 39% | (81.4) | (35.9) |

Note: Parentheses indicate net sequestration.

## QA/QC and Verification

The net carbon flux resulting from urban trees was calculated using estimates of gross and net carbon sequestration estimates for urban trees and urban tree coverage area found in 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 the 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 2002).

## *7.3. Changes in Agricultural Soil Carbon Stocks (IPCC Source Category 5D)*

The amount of organic carbon contained in soils depends on the balance between inputs of organic material (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and loss of carbon through decomposition. 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. 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 carbon to or from soils. In addition, the application of carbonate minerals to soils through liming operations results in emissions of $CO_2$. The IPCC methodology for estimation of net $CO_2$ flux from agricultural soils (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: 1) agricultural land-use and land-management activities on mineral soils; 2) agricultural land-use and land-management activities on organic soils; and 3) liming of soils. Mineral soils and organic soils are treated separately because they respond differently to land-use practices.

Mineral soils contain comparatively low amounts of organic carbon (usually less than 20 percent by weight), much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic carbon (by weight), although some mineral soils can be saturated for 30 or more days during normal years and contain as much as 18 percent organic carbon, depending on the clay content (NRCS 1999). Mineral subsoils contain even lower amounts of organic carbon (NRCS 1999, Brady and Weil 1999). When mineral soils undergo conversion from their native state to agricultural use, as much as half the soil organic carbon can be lost to the atmosphere. The rate and ultimate magnitude of carbon loss will depend on native vegetation, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the carbon loss generally occurs within the first 10 years following conversion; after that, carbon stocks continue to decline but at a much slower rate. In temperate regions, carbon loss can continue for several decades. Eventually, the soil will reach a new equilibrium that reflects a balance between carbon accumulation from plant biomass and carbon loss through oxidation. Any changes in land-use or management practices that result in increased organic inputs or decreased oxidation of organic carbon (e.g., improved crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of soil organic carbon until a new equilibrium is achieved.

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999, Brady and Weil 1999). The organic layer of these soils is also typically extremely deep. Organic soils form under waterlogged conditions, in which decomposition of plant residues is retarded. When organic soils are cultivated, they are first drained which, together with tilling or mixing of the soil, aerates the soil, and thereby accelerates the rate of decomposition and $CO_2$ generation. Because of the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which $CO_2$ emissions are generated, is determined primarily by climate, composition (i.e., decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for annual crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils they degrade, thereby generating $CO_2$. Complete degradation of applied limestone and dolomite could take several years, but it could also take significantly less time, depending on the soil conditions and the type of mineral applied.

Of the three activities, use and management of mineral soils was the most important component of total flux during the 1990 through 2002 period. Carbon sequestration in mineral soils in 2002 was estimated at approximately 64.7 Tg $CO_2$ Eq. (18 Tg C), while emissions from organic soils were estimated at 34.7 Tg $CO_2$ Eq. (10 Tg C) and emissions from liming were estimated at 8.8 Tg $CO_2$ Eq. (2 Tg C). Together, the three activities accounted for net sequestration of approximately 21.2 Tg $CO_2$ Eq. (6 Tg C) in 2002. Total annual net $CO_2$ flux was negative (i.e., net sequestration occurred) each year over the 1990 to 2002 period. Between 1990 and 2002, total net carbon sequestration in agricultural soils decreased by close to 20 percent. Net sequestration across the inventory period is largely due to annual cropland converted to permanent pastures and hay production, a reduction in the frequency of summer-fallow use in semi-arid areas, and some increase in the adoption of conservation tillage (i.e. reduced and no till practices). The relatively large shift in annual net sequestration from 1990 to 1995 is the result of calculating average annual mineral and organic soil fluxes from periodic, rather than annual, activity data.[7]

The spatial variability in annual, per hectare $CO_2$ flux for mineral and organic soils is displayed in Figure 7-5 through Figure 7-8. The highest rates of sequestration occur in the southern Great Plains, the corn-belt states of the Midwest, the lower Mississippi River Valley, and the wheat-dominated cropping region of the Pacific Northwest. Sequestration rates are also relatively high in the southeastern United States. Those regions either have high Conservation Reserve Program enrollment, (particularly the Great Plains region), and/or have adopted conservation tillage at a higher rate. The greatest mineral soil sequestration rates are in the south and east central United States and in a small area of the Pacific Northwest, while the greatest organic soil emission rates are along the southeast coast, in the northeast central United States, and along the central west coast.

Table 7-10: Net $CO_2$ Flux from Agricultural Soils (Tg $CO_2$ Eq.)

| Soil Type | 1990 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|
| Mineral Soils | (70.3) | (62.7) | (62.8) | (61.2) | (61.1) | (62.5) | (64.4) | (64.7) |
| Organic Soils | 34.3 | 34.7 | 34.7 | 34.7 | 34.7 | 34.7 | 34.7 | 34.7 |
| Liming of Soils | 9.5 | 8.9 | 8.7 | 9.6 | 9.1 | 8.8 | 9.0 | 8.8 |
| **Total Net Flux** | **(26.5)** | **(19.0)** | **(19.3)** | **(16.9)** | **(17.3)** | **(19.0)** | **(20.7)** | **(21.2)** |

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.

Table 7-11: Net Carbon Flux from Agricultural Soils (Tg C)

| Soil Type | 1990 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|
| Mineral Soils | (19.2) | (17.1) | (17.1) | (16.7) | (16.7) | (17.1) | (17.6) | (17.6) |
| Organic Soils | 9.4 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |
| Liming of Soils | 2.6 | 2.4 | 2.4 | 2.6 | 2.5 | 2.4 | 2.4 | 2.4 |
| **Total Net Flux** | **(7.2)** | **(5.2)** | **(5.3)** | **(4.6)** | **(4.7)** | **(5.2)** | **(5.7)** | **(5.8)** |

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.

Figure 7-5: Net Annual $CO_2$ Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1990-1992

Figure 7-6: Net Annual $CO_2$ Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1993-2002

Figure 7-7: Net Annual $CO_2$ Flux, per Hectare, From Organic Soils Under Agricultural Management, 1990-1992

[7] Mineral and organic soil results for the entire time series are presented in Annex 3.13.

Figure 7-8: Net Annual $CO_2$ Flux, per Hectare, From Organic Soils Under Agricultural Management, 1993-2002

The flux estimates presented here are restricted to $CO_2$ fluxes associated with the use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly nitrous oxide ($N_2O$) from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane ($CH_4$) from flooded rice cultivation. These emissions are accounted for in the Agriculture chapter.[8] It should be noted that other land-use and land-use change activities result in fluxes of non-$CO_2$ greenhouse gases to and from soils that are not comprehensively accounted for currently. These include emissions of $CH_4$ and $N_2O$ from managed forest soils (above what would occur if the forest soils were undisturbed), as well as $CH_4$ emissions from artificially flooded lands, resulting from activities such as dam construction. Aerobic (i.e., non-flooded) soils are a sink for $CH_4$, so soil drainage can result in soils changing from a $CH_4$ source to a $CH_4$ sink, but if the drained soils are used for agriculture, fertilization, and tillage, disturbance can reduce the ability of soils to oxidize $CH_4$. The non-$CO_2$ emissions and sinks from these other land use and land-use change activities were not assessed due to scientific uncertainties about the greenhouse gas fluxes that result from these activities.

## Methodology

The methodologies used to calculate net $CO_2$ flux from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997, Ogle et al. 2002, Ogle et al. in press), except where noted below. (Additional details on the methodology and data used to estimate flux from mineral and organic soils are described in Annex 3.13). Mineral soil organic carbon stocks were estimated for 1982, 1992, and 1997 for the conterminous United States and Hawaii using U.S. data on climate, soil types, land use and land management activity data, reference carbon stocks (for agricultural soils rather than native soils) and field studies addressing management effects on soil organic carbon storage. National-scale data on land-use and management changes over time were obtained from the *1997 National Resources Inventory* (USDA-NRCS 2000). The *1997 National Resources Inventory* provides land use/management data and soils information for more than 400,000 locations in U.S. agricultural lands. Two other sources were used to supplement the land-use information from the *1997 National Resources Inventory*. The Conservation Technology Information Center (CTIC 1998) provided data on tillage activity, with adjustments for long-term adoption of no-till agriculture (Towery 2001), and Euliss and Gleason (2002) provided activity data on wetland restoration of Conservation Reserve Program Lands.

Major Land Resource Areas (MLRAs) were used as 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).[9] Major Land Resource Areas were classified into climate zones according to the IPCC categories using the Parameter-Evaluation Regressions on Independent Slopes Model (PRISM) climate-mapping program of Daly et al. (1994). Reference carbon stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997) and cultivated cropland as the reference condition, rather than native vegetation as used in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). 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). Management factors were derived from published literature to determine the impact of management practices on soil organic carbon storage, including changes in tillage, cropping rotations and intensification, as well as land-use change between cultivated and uncultivated conditions (Ogle et al. in press). Euliss and Gleason (2002) provided the data for computing the change in soil organic carbon storage resulting from restoration of Conservation Reserve Program Lands (Olness et al. in press, Euliss et al. in prep). Combining information from these data sources, carbon stocks were estimated

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[8] Nitrous oxide emissions from agricultural soils and methane emissions from rice fields are addressed under the Agricultural Soil Management and Rice Cultivation sections, respectively, of the Agriculture chapter.

[9] The polygons displayed in Figure 6-5 through Figure 6-8 are the Major Land Resource Areas.

50,000 times for 1982, 1992, and 1997, using a Monte Carlo simulation approach and the probability density functions for U.S.-specific management factors, reference carbon stocks, and land-use activity data (Ogle et al. in press, Ogle et al. 2002). The annual carbon flux for 1990 through 1992 was estimated by calculating the annual change in stocks between 1982 and 1992; annual carbon flux for 1993 through 2002 was estimated by calculating the annual change in stocks between 1992 and 1997.

Annual carbon emission estimates from organic soils used for agriculture between 1990 and 2002 were derived using *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except that U.S.-specific carbon loss rates were used in the calculations rather than default IPCC rates (Ogle et al. 2002). Similar to mineral soils, the final estimates include a measure of uncertainty as determined from the Monte Carlo simulation. Data from published literature were used to derive probability density functions for carbon loss rates (Ogle et al. in press), which were used in turn to compute emissions based on the 1992 and 1997 land areas in each climate/land-use category defined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The area estimates were derived from the same climate, soil, and land-use/management databases that were used for mineral soil calculations (Daly et al. 1994, 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 2002.

Annual carbon flux estimates for mineral soils between 1990 and 2002 were adjusted to account for additional carbon sequestration from manure and sewage sludge applications, as well as gains or losses in carbon sequestration due to changes in Conservation Reserve Program enrollment after 1997. The amount of land receiving manure and sewage sludge was estimated from nitrogen application data from the Agricultural Soil Management section of the Agriculture chapter of this volume, and an assumed application rate derived from Kellogg et al. (2000). The total land area was subdivided between cropland and grazing land based on supplemental information collected by the USDA (ERS 2000, NASS 2002). Carbon storage rate was estimated at 0.10 metric tons C per hectare per year for cropland and 0.33 metric tons C per hectare per year for grazing land. To estimate the impact of enrollment in the Conservation Reserve Program after 1997, the change in enrollment acreage relative to 1997 were derived based on Barbarika (2002), and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied (see Table 7-12) by $CO_2$ emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[10] These emission factors are based on the assumption that all of the carbon in these materials evolves as $CO_2$ in the same year in which the minerals are applied. 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, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003; USGS 2002, 2003). To develop these data, 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).

To estimate the "unspecified" and "estimated" amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils in a specific year were equal to the fraction of "specified" production that was applied to agricultural soils in that same year. In addition, data were not available for 1990, 1992, and 2002 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

[10] The default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/metric ton of dolomite; the correct value is 0.130 metric ton carbon/metric ton of dolomite.

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 2002 data, the previous year's fractions were applied to a 2002 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2002* (USGS 2002).

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

Table 7-12: Quantities of Applied Minerals (Thousand Metric Tons)

| **Mineral** | **1990** | **1991** | **1992** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Limestone | 19,012 | 20,312 | 17,984 | 15,609 | 16,686 | 17,297 | 17,479 | 16,539 | 14,882 | 16,894 | 15,863 | 16,097 | 15,799 |
| Dolomite | 2,360 | 2,618 | 2,232 | 1,740 | 2,264 | 2,769 | 2,499 | 2,989 | 6,389 | 3,420 | 3,812 | 3,951 | 3,878 |

## Uncertainty

Uncertainties for mineral and organic soils were quantified using a Monte Carlo Approach by constructing probability distribution functions (PDF) for inputs to the IPCC equations, including management factors, carbon emission rates for organic soils, and land use and management activity data, and then simulating a range of values based on 50,000 iterations (Ogle et al. in press, Annex 3.13). Uncertainty estimates do not include manure, sludge, or Conservation Reserve Program contributions to C storage. Uncertainty results based on the Monte Carlo simulation are shown in Table 7-13. PDFs for management factors were derived from a synthesis of 91 published studies, which addressed the impact of management on soil organic carbon storage. Uncertainties in land use and management activity data were also derived from a statistical analysis. The National Resources Inventory (NRI) has a two-stage sampling design that allowed PDFs to be constructed assuming a multivariate normal distribution accounting for dependencies in activity data. PDFs for the tillage activity data, as provided by the Conservation Technology and Information Center, were constructed on a bivariate normal distribution with a log-ratio scale, accounting for the negative dependence among the proportions of land under conventional and conservation tillage practices. Lastly, enrollment in wetland restoration programs was estimated from contract agreements, but due to a lack of information, PDFs were constructed assuming a nominal ±50 percent uncertainty range.

Table 7-13: Quantitative Uncertainty Estimates for $CO_2$ Flux from Agricultural Soil Carbon Stocks (Tg $CO_2$ Eq. and Percent)

| **Source** | **Gas** | **Average Annual Emission Estimate[a] (1993-2002) (Tg $CO_2$ Eq.)** | **Uncertainty Range Relative to Emission Estimate[b]** | | | |
|---|---|---|---|---|---|---|
| | | | **(Tg $CO_2$ Eq.)** | | **(%)** | |
| | | | **Lower Bound** | **Upper Bound** | **Lower Bound** | **Upper Bound** |
| Mineral Soils | $CO_2$ | (40.8) | (59.0) | (23.8) | -42% | +45% |
| Organic Soils | $CO_2$ | 34.7 | 23.5 | 49.1 | -32% | +42% |

[a] Includes mineral and organic soils only; estimates do not include the change in carbon storage resulting from the annual application of manure and sewage sludge, or the change in Conservation Reserve Program enrollment after 1997; the emissions value represents the average of years 1993-2002.
[b] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

The time-series calculations were consistent for each reporting year of the inventory in terms of methodology, with the only difference in reported values stemming from the changes in land use and management activities across U.S. agricultural lands. In addition, the same management factors (i.e., emission factors) were used each year for calculating the impact of land use and management on soil C stocks. There is no evidence that changing management practices has a quantitatively different impact on soil C stocks over the inventory period. For example, changing from conventional to no-till management in 1990 or at a later date such as the year 2000 is assumed to have the same cumulative impact on soil C stocks over a 20 year period.

Although the mineral and organic soil estimates have been improved during the last two years using a Monte Carlo approach with the incorporation of U.S.-specific reference carbon stocks and management factor values, several limitations remain in the analysis. First, minimal data exist on where and how much manure and sewage sludge has been applied to U.S. agricultural lands. Consequently, uncertainties have not been estimated for the change in soil organic carbon storage resulting from these applications. Second, due to the IPCC requirement that inventories include all land areas that are potentially subject to land-use change, the *1997 National Resources Inventory* dataset includes some points designated as non-agricultural land-uses if this designation changed during the period from 1992 to 1997. The non-agricultural land uses are urban, water, and miscellaneous non-cropland (e.g., roads and barren areas). The impact on carbon storage resulting from converting cropland to non-agricultural uses is not well understood, and therefore, those points were not included in the calculations. Third, this inventory may underestimate losses of carbon from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, this methodology does not take into account changes in carbon stocks due to pre-1982 land use and land-use change.

Uncertainties in the estimates of emissions from liming result from both the methodology and the activity data. The IPCC method assumes that all the inorganic carbon in the applied minerals evolves to $CO_2$, and that this degradation occurs in the same year that the minerals are applied. However, recent research has shown that liming can either be a carbon source or a sink, depending upon weathering reactions, which are pH dependent (Hamilton et al. 2002). Moreover, it can take several years for agriculturally applied limestone and dolomite to degrade completely. However, application rates are fairly constant over the entire time series, so this latter assumption may not contribute significantly to overall uncertainty.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands. The *Mineral Industry Surveys* further excludes Alaska and Hawaii from its totals.

## Recalculations Discussion

The estimates of changes in agricultural soil C stocks have been modified in several ways relative to the previous inventory. First, management factors have been rescaled to provide a better approximation of impacts in different climatic regions of the United States, instead of using a single management factor for the entire country (Ogle et al., in prep). These changes only affected mineral soil calculations, and served to provide better regional estimates of land use and management impacts. New factors were derived if there were a sufficient number of studies to evaluate climate trends and if management effects differed significantly across thermal and moisture regimes based on the IPCC climate types. These revisions alter the mineral soil calculations by removing statistical bias that can result from the application of a single management factor value for all agricultural lands. For example, tillage factors were derived for moist and dry climates because field experiments have shown that the impact of tillage differs due to the prevailing moisture regime (i.e., changing tillage management alters the amount of soil organic carbon more in a moist climate than it does in a dry climates). The second change in this year's inventory involved incorporation of the latest soils information, based on a new version of the soil database that accompanies the National Resources Inventory (USDA-NRCS 2000). Those data were incorporated into the analysis and the total areas in various soil categories were adjusted based on the revisions.

Estimates of $CO_2$ emissions from agricultural soil management have been revised due to methodological and historical data changes in the calculations of nitrogen from livestock that is applied to soils. These changes include corrections to: the typical animal mass value for beef cows and calves; the accounting of sheep in New England states; state broiler populations; and updated NASS animal population estimates for the years 1998 through 2001.

Additionally, the factor for converting short tons to metric tons was revised to include another significant digit, and the percent residue applied for rice in the year 2001 was corrected. In combination, these changes resulted in a minor effect on the agricultural soil C estimates with a reduction in the $CO_2$ sink by less than 1 percent.

Emissions from organic soils have changed slightly from those reported in the previous inventory for the years 1993 to 2001, as a result of altering the number of significant digits used for converting the mass of carbon to $CO_2$.

The quantity of applied minerals reported in the previous inventory for 2001 has been revised. Consequently, the reported emissions resulting from liming in 2001 have also changed. In the previous inventory, to estimate 2001 data, the previous year's fractions were applied to a 2001 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2002* (USGS 2002). 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 2001. These values have replaced those used in the previous inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

## Planned Improvements

Three planned improvements are currently underway that will enhance reporting of changes in agricultural soil carbon stocks. First, uncertainty will be estimated for the change in carbon storage due to manure additions to crop and grazing lands. Through this revision, the impact of manure management will be fully integrated into the uncertainty analysis, instead of estimating its impact in a separate set of calculations (see Annex 3.13).

Second, losses from organic soils will be re-calculated in future inventories to include area which has been converted between agricultural uses and urban, miscellaneous non-cropland or open water. This inventory does not estimate the impacts of non-agricultural uses on soil C stocks (nor will this be included in future estimates), but does need to estimate the impacts of the agricultural uses during the time periods when organic soils are managed with drainage for cropping and grazing purposes. Consequently, emissions have been underestimated, leading to lower implied emission factors in the Common Reporting Format (CRF) tables. This problem will be corrected and there will be a slight increase in estimated emissions from those soils.

The third improvement deals with an alternative inventory approach to better represent between-year variability in annual fluxes. This new annual activity-based inventory will use the Century ecosystem simulation model, which relies on actual climate, soil, and land use/management databases to estimate variation in fluxes. This inventory will provide a more robust accounting of carbon stock changes in U.S. agricultural lands than the more simplistic IPCC soil C accounting approach. This approach is likely to be used in the future for reporting of land use and management impacts on agricultural soil C stocks, and therefore a short description of this method compared to the IPCC approach is provided.

The Century ecosystem model has been widely tested and found to be successful in simulating those processes affecting soil organic carbon storage (Metherell et al. 1993, Parton et al. 1994). Simulation modeling differs from the IPCC approach in that annual changes are computed dynamically as a function of inputs of carbon and nitrogen to soil (e.g., crop residues, manure) and carbon emissions from organic matter decomposition, which are governed by climate and soil factors as well as management practices. The model distinguishes between all major field crops (maize, wheat and other small grains, soybean, sorghum, cotton) as well as hay and pasture (grass, alfalfa, clover). Management variables include tillage, fertilization, irrigation, drainage, and manure addition.

Input data are largely derived from the same sources as the IPCC-based method (i.e., climate variables come from the PRISM database; crop rotation, irrigation and soil characteristics from the National Resources Inventory (NRI); and tillage data from the Conservation Technology Information Center (CTIC). In addition, the Century analysis uses detailed information on crop rotation-specific fertilization and tillage implements obtained from USDA's Economic Research Service. The main difference between the methods is that the climate, soil, and management data serve as driving variables in the Century simulation, whereas in the IPCC approach these data are more highly aggregated and are used for classification purposes. In the Century-based analysis, land areas having less than 5 percent of total area in crop production are excluded and several less-dominant crops (e.g., vegetables, sugar beets and sugar cane, potatoes, tobacco, orchards, and vineyards), for which the model has not yet been parameterized, are not included.  Thus, the total area included in the Century analysis (149 million hectares) will be smaller than the corresponding area of cropland (165 million hectares) included in the IPCC estimates.

Preliminary results using the Century model suggest (as with the IPCC model) that U.S. cropland mineral soils (excluding organic soils) are currently acting as a carbon sink.  The Century model estimates are that U.S. cropland soils sequestered an average of approximately 77 Tg $CO_2$ Eq. annually (21 Tg C/year) for 1992 through 1997. Organic soils (which contribute large C losses) have not yet been simulated by Century.

As with the IPCC method, increases in mineral soil C stocks in the Century analysis are associated with reduced tillage, Conservation Reserve Program lands, reduced bare fallow and some increase in hay area.  However, the Century analysis also includes the effect of a long-term trend in increasing residue inputs due to higher productivity on cropland in general, contributing to increasing soil carbon stocks.  Work is underway to refine model input data and to estimate uncertainty for the dynamic model approach.

Potential advantages of a dynamic simulation-based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of soil carbon change.  This would facilitate annual estimates of carbon stock changes and $CO_2$ emissions from soils that would better reflect interannual variability in cropland production and weather influences on carbon cycle processes.

## *7.4.    Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (IPCC Source Category 5E)*

As is the case with carbon in landfilled forest products, carbon contained in landfilled yard trimmings and food scraps can be stored indefinitely.  In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps comprise a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are discarded in landfills.  However, both the amount of yard trimmings and food scraps collected annually and the fraction that is landfilled have declined over the last decade.  In 1990, nearly 51 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection or taken to disposal or composting facilities) (EPA 2003).  Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 20 percent decrease in the amount of yard trimmings collected.  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 34 percent in 2002.  There is considerably less centralized composting of food scraps; generation has grown by 26 percent since 1990, though the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 77 percent in 2002.  Overall, there has been a decrease in the yard trimmings and food scrap landfill disposal rate, which has resulted in a decrease in the rate of landfill carbon storage from 26.0 Tg $CO_2$ Eq. in 1990 to 10.1 Tg $CO_2$ Eq. in 2002 (Table 7-15and Table 7-14).

Table 7-14:  Net Changes in Yard Trimming and Food Scrap Stocks (Tg $CO_2$ Eq.)

| Carbon Pool | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| **Yard Trimmings** | **(23.2)** | | **(11.3)** | **(10.4)** | **(9.6)** | **(8.4)** | **(7.2)** | **(7.4)** | **(7.4)** |
| Grass | (2.5) | | (1.0) | (0.9) | (0.8) | (0.7) | (0.6) | (0.7) | (0.7) |
| Leaves | (11.2) | | (5.9) | (5.4) | (5.1) | (4.5) | (4.0) | (4.0) | (4.0) |
| Branches | (9.6) | | (4.4) | (4.0) | (3.7) | (3.2) | (2.6) | (2.7) | (2.7) |
| **Food Scraps** | **(2.8)** | | **(2.1)** | **(2.5)** | **(2.8)** | **(2.9)** | **(2.9)** | **(2.8)** | **(2.7)** |
| **Total Net Flux** | **(26.0)** | | **(13.4)** | **(12.9)** | **(12.4)** | **(11.3)** | **(10.1)** | **(10.2)** | **(10.1)** |

Note: Totals may not sum due to independent rounding.

Table 7-15:  Net Changes in Yard Trimming and Food Scrap Stocks (Tg C)

| Carbon Pool | 1990 | | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|
| **Yard Trimmings** | **(6.3)** | | **(3.1)** | **(2.8)** | **(2.6)** | **(2.3)** | **(2.0)** | **(2.0)** | **(2.0)** |
| Grass | (0.7) | | (0.3) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) |
| Leaves | (3.0) | | (1.6) | (1.5) | (1.4) | (1.2) | (1.1) | (1.1) | (1.1) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Branches | (2.6) | | (1.2) | (1.1) | (1.0) | (0.9) | (0.7) | (0.7) | (0.7) |
| **Food Scraps** | **(0.8)** | | **(0.6)** | **(0.7)** | **(0.8)** | **(0.8)** | **(0.8)** | **(0.8)** | **(0.7)** |
| **Total Net Flux** | **(7.1)** | | **(3.7)** | **(3.5)** | **(3.4)** | **(3.1)** | **(2.8)** | **(2.8)** | **(2.8)** |

Note: Totals may not sum due to independent rounding.

## Methodology

Estimates of net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years. Carbon stock estimates were calculated by determining the mass of landfilled carbon resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the portion of carbon landfilled in previous years that decomposed.

To determine the total landfilled carbon 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 carbon storage factor of the landfilled yard trimmings and food scraps, and 4) the rate of decomposition of the degradable carbon. 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 carbon 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 in the United States: 2001 Facts and Figures* (EPA 2003). That report provides data for 1960, 1970, 1980, 1990, 1995, and 1999 through 2001. To provide data for some of the missing years in the 1990 through 1999 period, two earlier reports were used (*Characterization of Municipal Solid Waste in the United States: 1998 Update* (EPA 1999), and *Municipal Solid Waste in the United States: 2000 Facts and Figures* (EPA 2002)). Remaining years in the time series for which data were not provided were estimated using linear interpolation, except for 2002, which was assumed to have the same discards as 2001. These reports do not subdivide discards of individual materials into volumes landfilled and combusted, although they provide an estimate of the proportion of overall wastestream discards managed in landfills and combustors (i.e., ranging from 81 percent and 19 percent respectively in 1990, to 79 percent and 21 percent in 2001).

The amount of carbon 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) carbon 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 carbon contents were determined by Barlaz (1998) (Table 7-16).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate. According to Barlaz (1998), a portion of the initial carbon resists decomposition and is essentially persistent in the landfill environment; the modeling approach applied here builds on his findings. Barlaz (1998) 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 carbon 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 carbon content. The mass of carbon remaining, divided by the original dry weight of the material, was reported as the carbon storage factor (Table 7-16).

For purposes of simulating U.S. landfill carbon flows, the carbon storage factors are divided by the initial carbon content to determine the proportion of initial carbon that does not decompose. The remaining portion is assumed to degrade (and results in emissions of $CH_4$ and $CO_2$). For example, for branches Barlaz (1998) reported the carbon storage factor as 38 percent (of dry weight), and the initial carbon content as 49 percent (of dry weight). Thus, the proportion of initial carbon that does not decompose is 77 percent (i.e., 0.38/0.49). The remaining 23 percent degrades.

The degradable portion of the carbon is assumed to decay according to first order kinetics. Grass and food scraps are assumed to have a half-life of 5 years; leaves and branches are assumed to have a half-life of 20 years.

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

$$LFC_{i,t} = \sum_{n} W_{i,n} * (1 - MC_i) * ICC_i * \{[CSF_i / ICC_i] + [(1 - (CSF_i / ICC_i)) * e^{-k*(t-n)}]\}$$

where,

t is the year for which carbon stocks are being estimated,
$LFC_{i,t}$ is the stock of carbon in landfills in year *t*, for waste *i* (grass, leaves, branches, food scraps)
$W_{i,n}$ is the mass of waste *i* disposed in landfills in year *n*, in units of wet weight
n is the year in which the waste was disposed, where $1960 \leq n \leq t$
$MC_i$ is moisture content of waste *i*,
$ICC_i$ is the initial carbon content of waste *i*,
$CSF_i$ is the carbon storage factor of waste *i*,
e is the natural logarithm,
k is the first order rate constant for waste *i*, and is equal to 0.693 divided by the half-life for decomposition.

For a given year *t*, the total stock of carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials. The annual flux of carbon 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 carbon placed in a landfill in year n is tracked for each year t through the end of the inventory period (2002). For example, disposal of food scraps in 1960 resulted in depositing about 1,140,000 metric tons of carbon. Of this amount, 16 percent (180,000 metric tons) is persistent; the remaining 84 percent (960,000 metric tons) is degradable. By 1965, half of the degradable portion (480,000 metric tons) decomposes, leaving a total of 660,000 tonnes (the persistent portion, plus the remaining half of the degradable portion).

Continuing the example, by 2002, the total food scraps carbon originally disposed in 1960 had declined to 182,000 metric tons (i.e., virtually all of the degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed in subsequent years (1961 through 2002), the total landfill carbon from food scraps in 2002 was 28.7 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2002, yielding a value of 239.6 million metric tons (as shown in Table 7-17). In exactly the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 7-15) is the difference in the landfill carbon stock for a given year minus the stock in the preceding year. For example, the net change in 2002 shown in Table 7-15 (2.8 Tg C) is equal to the stock in 2002 (239.6 Tg C) minus the stock in 2001 (236.8 Tg C).

When applying the carbon storage factor data reported by Barlaz (1998), an adjustment was made to the reported value for leaves, because the carbon storage factor was higher than the initial carbon content. This anomalous result, probably due to errors in the laboratory measurements, was addressed by applying a mass balance calculation, and assuming that (a) the initial carbon content was correctly measured, and (b) the carbon storage factor was incorrect. The same experiment measured not only the persistence of carbon (i.e., the carbon storage factor), but also the yield of methane for each of the individual waste materials (Eleazer et al. 1997). The anaerobic decomposition process results in release of equal molar volumes of $CH_4$ and $CO_2$. Thus, to derive a more realistic estimate of the carbon storage factor for leaves, the carbon released in the form of methane during decomposition was multiplied by two (to include the loss of carbon through $CO_2$), and then subtracted from the initial carbon content of the leaves. This estimate of carbon remaining was used to derive the carbon storage factor (0.46).

Table 7-16: Moisture Content (%), Carbon Storage Factor, Initial Carbon Content (%), Proportion of Initial Carbon Sequestered (%), and Half-Life (years) for Landfilled Yard Trimmings and Food Scraps

| Variable | Yard Trimmings: Grass | Yard Trimmings: Leaves | Yard Trimmings: Branches | Food Scraps |
|---|---|---|---|---|
| Moisture Content (% $H_2O$) | 70 | 30 | 10 | 70 |
| CSF (kg C sequestered / dry kg waste) | 0.32 | 0.46[a] | 0.38 | 0.08 |
| Initial Carbon Content (%) | 45 | 49 | 49 | 51 |
| Proportion of initial carbon sequestered (%) | 71 | 94 | 77 | 16 |
| Half-life (years) | 5 | 20 | 20 | 5 |

[a] Adjusted using methane yields in Eleazer et al. (1997).

Table 7-17: Carbon Stocks in Yard Trimmings and Food Scraps (Tg of C)

| Carbon Pool | 1990 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|
| **Yard Trimmings** | **167.8** | **197.1** | **199.9** | **202.5** | **204.8** | **206.8** | **208.8** | **210.8** |
| Grass | 18.8 | 21.8 | 22.0 | 22.2 | 22.4 | 22.6 | 22.8 | 23.0 |
| Leaves | 78.7 | 93.1 | 94.6 | 96.0 | 97.2 | 98.3 | 99.4 | 100.5 |
| Branches | 70.3 | 82.2 | 83.3 | 84.3 | 85.1 | 85.9 | 86.6 | 87.4 |
| **Food Scraps** | **20.3** | **24.2** | **24.9** | **25.7** | **26.4** | **27.2** | **28.0** | **28.7** |
| **Total Carbon Stocks** | **188.1** | **221.3** | **224.8** | **228.2** | **231.3** | **234.0** | **236.8** | **239.6** |

Note: Totals may not sum due to independent rounding.

## Uncertainty

Uncertainty in the landfilled carbon storage estimates results from a small carbon storage factor data set. Very few experiments have measured the amount of carbon persisting in conditions promoting decomposition. Furthermore, since these experiments have only used conditions conducive to decomposition, they may underestimate carbon storage.

Additionally, the method used to calculate carbon storage in landfills does not account for varying landfill moisture contents resulting from different climates and degrees of landfill cover. Landfills still receiving waste receive a thin, loose soil cover at the end of the day, while landfills which have been filled and permanently removed from operation are covered to prevent infiltration and leaching. Accounting for the amount of moisture and infiltration in a landfill could greatly increase or decrease the estimated rate of decomposition in landfills.

## Recalculations Discussion

The methods used in the current inventory to estimate landfilled carbon storage vary from previous years' inventories in the following three ways.

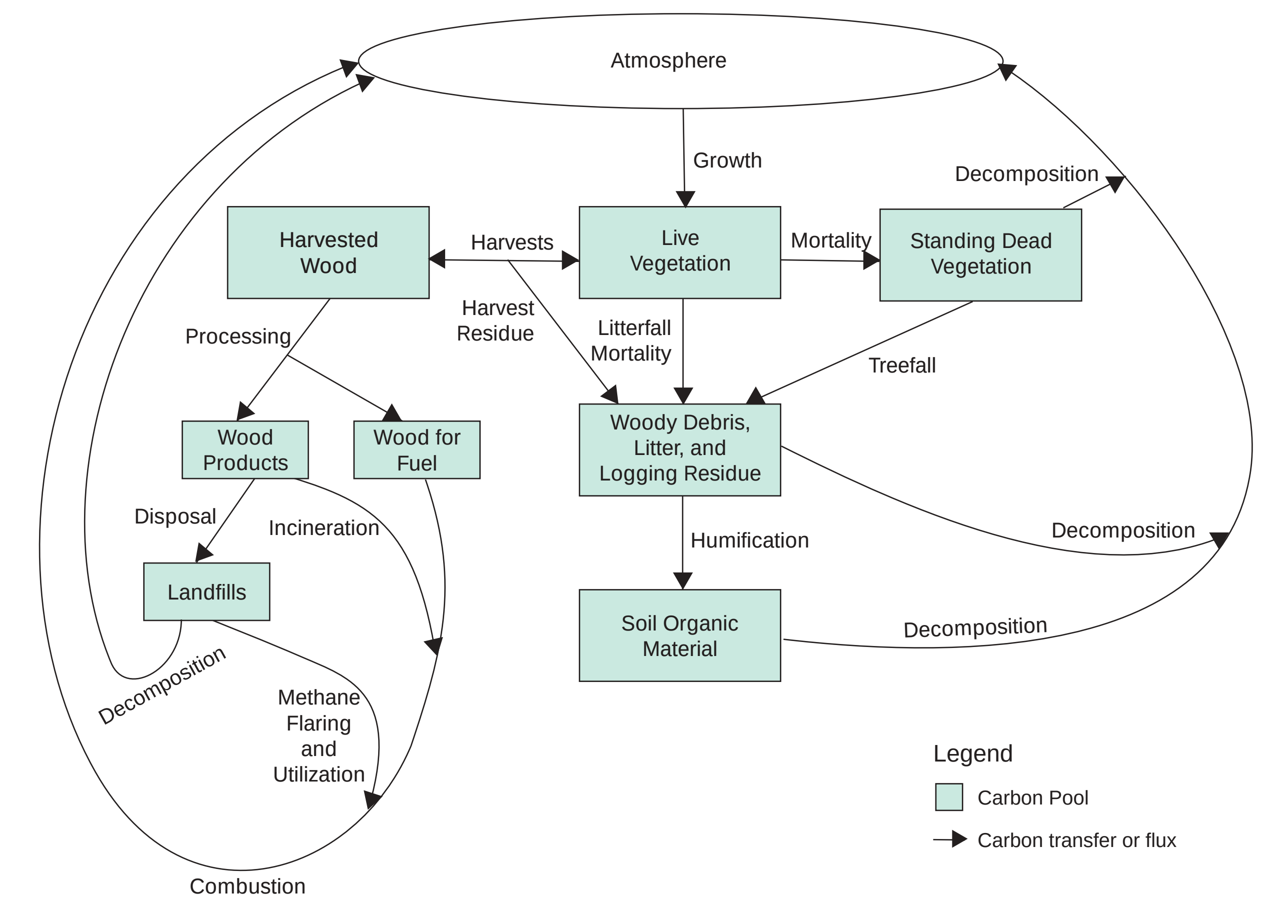
- The current inventory accounts for the landfilling of food scraps for the first time; this increases the landfilled carbon flux by 10 to 29 percent over the period with respect to the flux for yard trimmings.
- The current inventory uses carbon storage factors for grass clippings and branches, which were measured experimentally. The previous inventory used carbon storage factors for grass clippings and branches derived by subtracting the carbon emitted as CH4 and CO2, during decomposition, from the carbon in the original dried yard trimmings, i.e., the same approach as used for leaves in the current inventory.
- The approach used to express the timing of carbon storage in previous inventories differed from the approach used for the current inventory. Unlike the approach used currently, in which the stocks of landfill carbon were computed, and net flux was calculated as the difference in stocks from year to year, a "static" approach was used previously. Specifically, in the static method, the "ultimate" carbon storage—i.e., the amount stored after all degradation is complete—was attributed in the year of disposal. There was no tracking of the degradable portion of carbon, and no simulation of the dynamics of decomposition and their effect of net landfill carbon stocks. As an example of the static approach, in 2000, disposal of branches resulted in deposition of 1,140,000 metric tons of carbon. Of that mass, 77 percent, or 874,000 metric tons is stored indefinitely. The previous inventory would have calculated carbon storage from branches as 874,000 metric tons, i.e., it did not track storage and decomposition from preceding years in the time series, as is done in the current inventory. The stocks approach adopted this year reflects the physical conditions in landfills more accurately, and it is conceptually consistent with the approach used to estimate landfill carbon storage for harvested wood products.

## Planned Improvements

As noted above, the estimates presented in this section are driven by a small carbon storage factor data set, and some of these measurements (especially for leaves) deserve close scrutiny.  There are ongoing efforts to conduct additional measurements of some of the samples from Dr. Mort Barlaz's original experiments, with the objective of improving the mass balance for several materials.  There are also efforts to assure consistency between the estimates of carbon storage described in this chapter and the estimates of landfill $CH_4$ emissions described in the Waste chapter.

**Figure 7-1**

## Forest Sector Carbon Pools and Flows




Source: Adapted from Heath and Birdsey (1997)

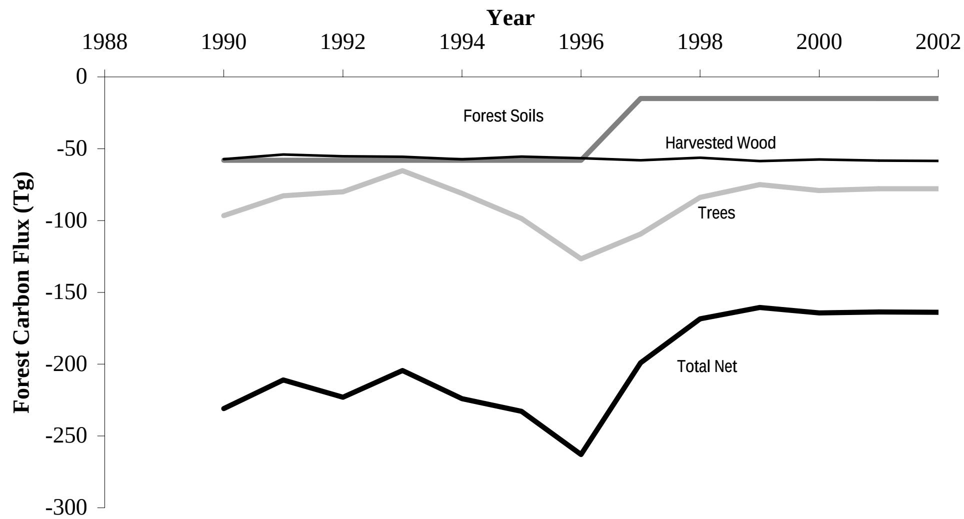
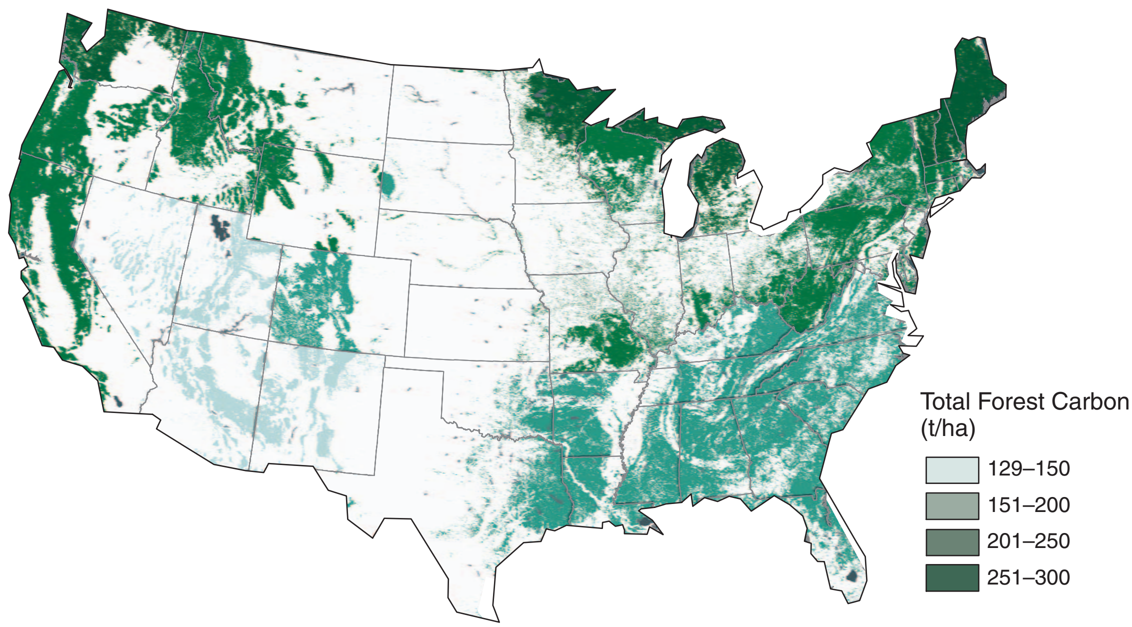



Figure 7-2: Estimates of Forest Carbon Flux in Major Pools

**Figure 7-3**

## Average Carbon Density in Forests in the Conterminuous USA During 2003




Note: Estimates are based on forest inventory data and modeled projections as described in the text.

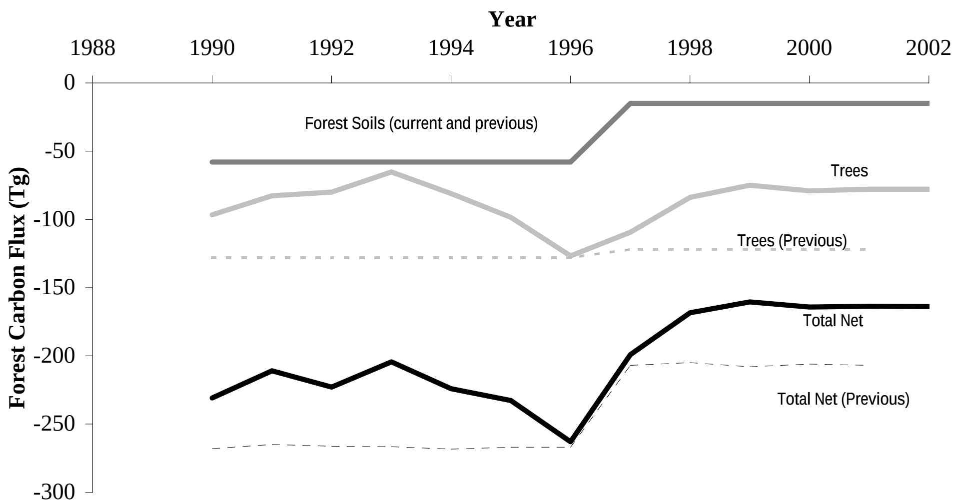
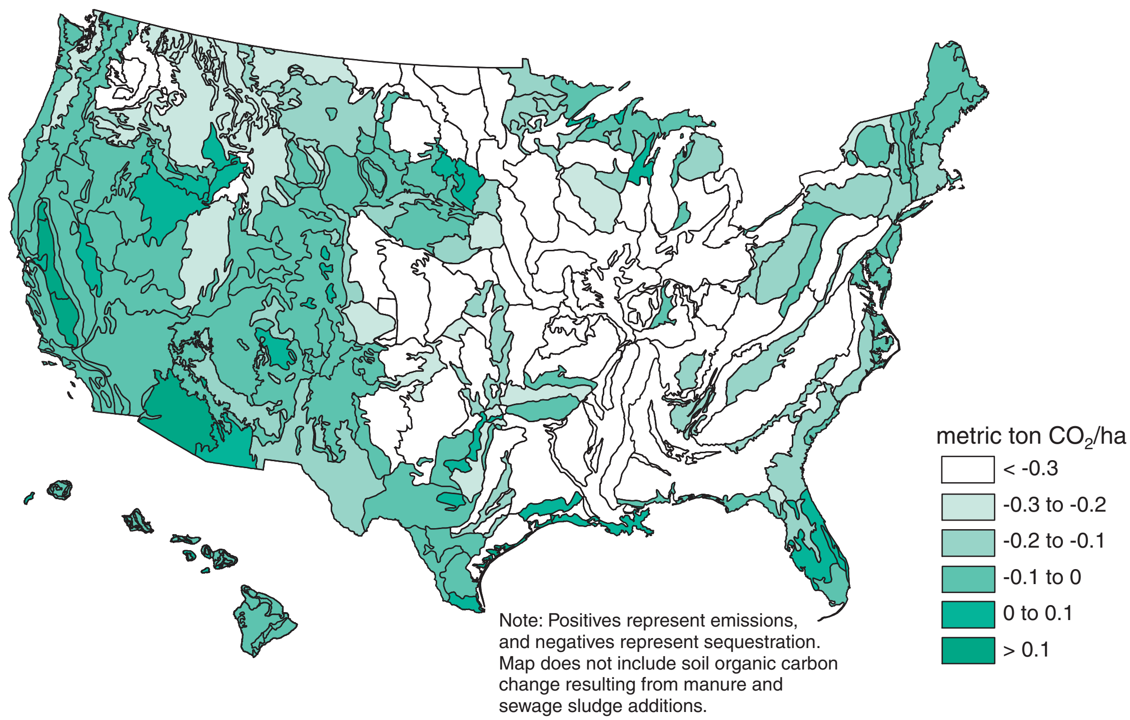



Figure 7-4.Estimates of Forest Carbon Flux in Major Pools: Comparison to Previous Inventories

Figure 7-5

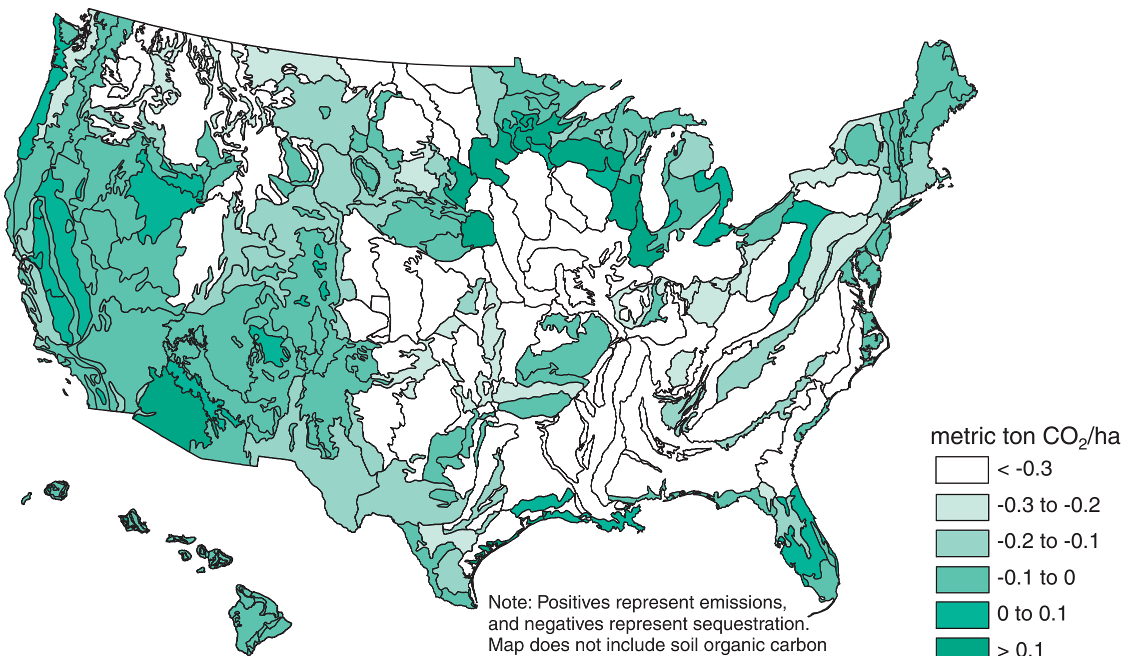
## Net Annual $CO_2$ Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1990-1992




This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1990 through 1992.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 7-6

## Net Annual $CO_2$ Flux, per Hectare, From Mineral Soils Under Agricultural Management, 1993-2002

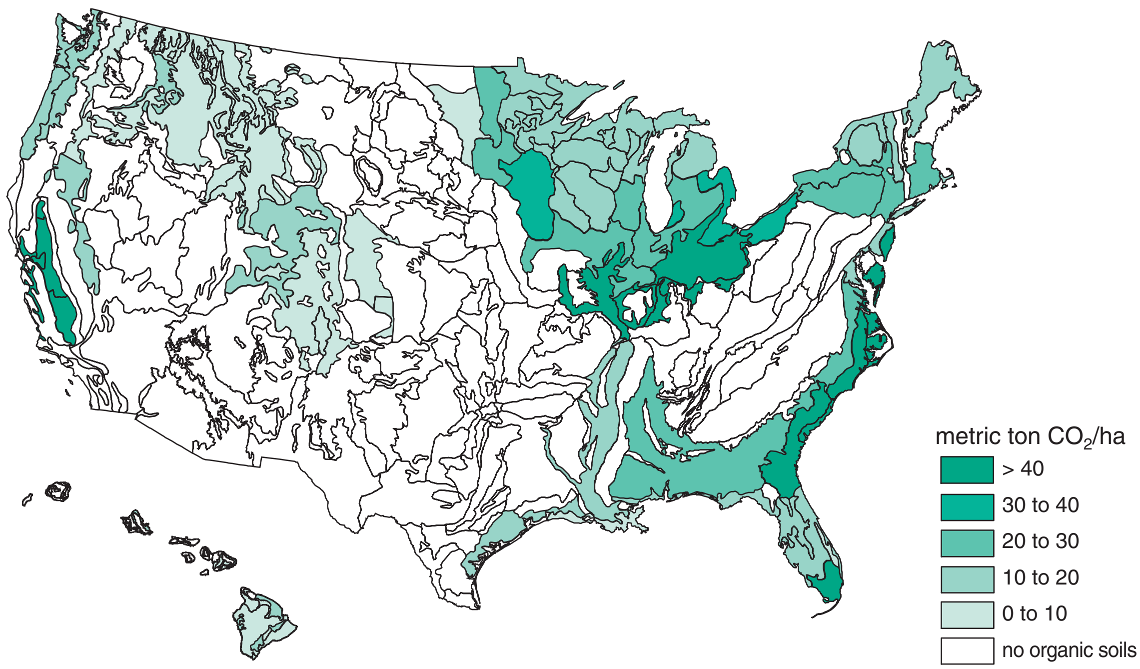



Note: Positives represent emissions, and negatives represent sequestration. Map does not include soil organic carbon change resulting from manure and sewage sludge additions or enrollment in CRP after 1997.

This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1993 through 2002. The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 7-7

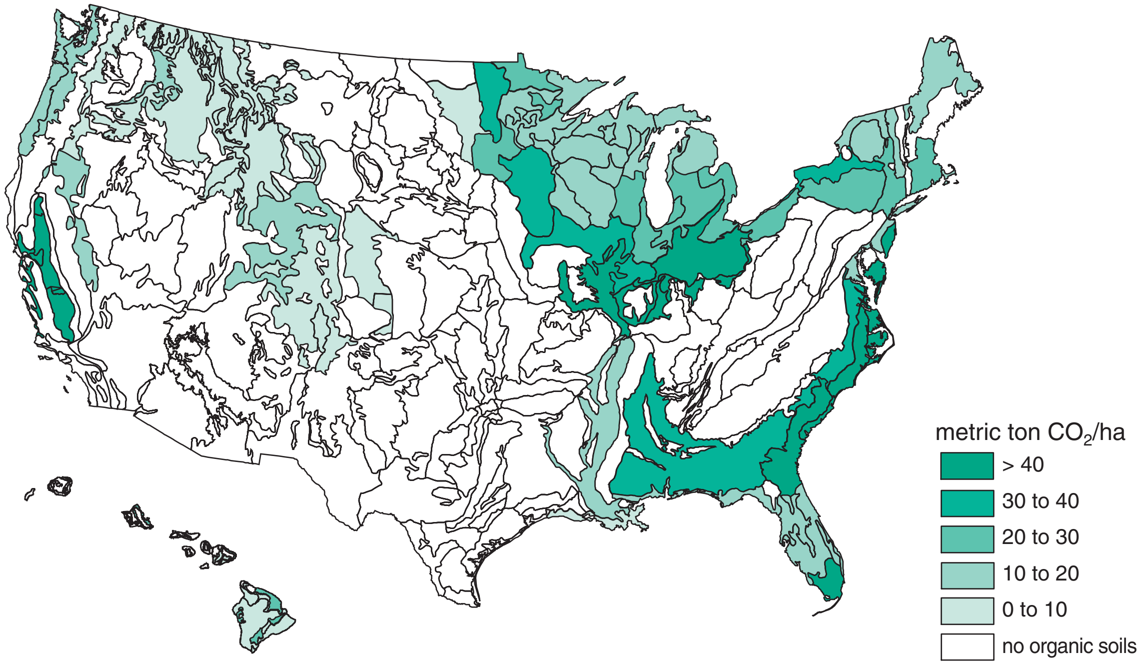
## Net Annual $CO_2$ Flux, per Hectare, From Organic Soils Under Agricultural Management, 1990-1992




This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1990 through 1992.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

Figure 7-8

## Net Annual $CO_2$ Flux, per Hectare, From Organic Soils Under Agricultural Management, 1993-2002




This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1993 through 2002.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

**Descriptions of Figures: Land-Use Change and Forestry**

Figure 7-1 illustrates forest sector carbon pools and flows. Forest carbon storage pools are represented by boxes, while flows between storage pools, and between storage pools and the atmosphere, are represented by arrows.

Figures 7-2 is a line graph indicating forest carbon flux for the years 1990 through 2002. Total net carbon flux is the bottom line that combines forest soils, harvested wood, and trees. Total net carbon flux increased from -260 Tg in 1990 to -130 Tg in 2002, after a significant decrease in 1996.

Figure 7-3 is a map of the Unites States that illustrates the average carbon density in forests, estimated for 2003. The states along both the east and west coasts are shaded darker, indicating a higher carbon density than central states.

Figure 7-4 is a line graph that compares forest carbon stocks in major pools to previous inventories. Forest soils for current and previous inventories are represented by the same line, indicating no change. Carbon stocks from trees, for previous inventories, is represented a horizontal line at -128 Tg. Carbon stocks for trees, in the current Inventory, starts at approximately -100 Tg, decreases in 1996, and increases to -77 Tg in 2002.

Figures 7-5 through 7-8 are maps of the United States illustrating $CO_2$ flux from mineral soils for the years 1990-2002. For a full description of figures 7-5 through 7-8, refer to the Inventory text found in Chapter 7.