Reference: Heath, Linda S., and James E. Smith. 2001. Land use change and forestry and related sections. (Excerpted.) In: US EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 1999. EPA 236-R-01-001. Available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2001.html (05 May 2004). Note that EPA contractors or employees may have written or edited some text, or perhaps formatted tables or redrew some figures for final EPA format.

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INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS:

1990 – 1999

APRIL, 2001

U.S. Environmental Protection Agency

1200 Pennsylvania Ave., N.W.

Washington, DC 20460

U.S.A.

6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by 1) changes in forest carbon stocks; 2) changes in agricultural soil carbon stocks; and 3) changes in yard trimming carbon stocks in landfills. Seven components of forest carbon stocks are analyzed: trees, understory, forest floor, forest soils, logging residues, wood products, and landfilled wood. The estimated CO_2 flux from each of these forest components is based on carbon stock estimates developed by the USDA Forest Service, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to agricultural land use and land management (i.e., 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. The methods in the *Revised 1996 IPCC Guidelines* were used to estimate all three components of changes in agricultural soil carbon stocks. Changes in yard trimming carbon stocks in landfills were estimated using EPA's method of analyzing 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 to retain consistency with IPCC reporting structure; however, the chapter covers land-use activities, as well as 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 based on annual activity data, the flux estimates in this chapter, with the exception of emissions from liming and carbon storage associated with yard trimmings disposed in landfills, are based on periodic activity data in the form of forest and land use surveys. Carbon dioxide fluxes from forest carbon stocks and from agricultural soils are calculated on an average annual basis over five or ten year periods. The resulting annual averages are applied to years between surveys. As a result of this data structure, estimated CO_2 fluxes are constant over multi-year intervals. In addition, because the most recent national forest and land use surveys were completed for the year 1997, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for years since 1997.

Estimated total annual net CO_2 flux from land use, land-use change, and forestry in 1999 is 990.4 Tg CO_2 Eq. (270 Tg C) net sequestration (Table 6-1 and Table 6-2). This represents an offset of approximately 15 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net sequestration declined by about 7 percent between 1990 and 1999. This decline is primarily due to increasing forest harvests and land-use changes, which resulted in decreasing net sequestration rates for forests.

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (Tg CO_2 Eq.)

Component	1990	1995	1996	1997	1998	1999
Forests	(1,001.7)	(938.3)	(942.7)	(903.5)	(897.2)	(905.7)
Agricultural Soils	(40.4)	(68.8)	(68.9)	(69.0)	(77.3)	(77.0)
Landfilled Yard Trimmings	(17.8)	(12.0)	(10.0)	(9.4)	(8.8)	(7.7)
Total Net Flux	**(1,059.9)**	**(1,019.1)**	**(1,021.6)**	**(981.9)**	**(983.3)**	**(990.4)**

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

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Tg C)

Component	1990	1995	1996	1997	1998	1999
Forests	(273)	(256)	(257)	(246)	(245)	(247)
Agricultural Soils	(11)	(19)	(19)	(19)	(21)	(21)
Landfilled Yard Trimmings	(5)	(3)	(3)	(3)	(2)	(2)
Total Net Flux	**(289)**	**(278)**	**(279)**	**(268)**	**(268)**	**(270)**

Note: 1 Tg C = 1 Tg Carbon = 1 million metric tons carbon. This table has been included to facilitate comparison with previous U.S. Inventories. Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Changes in Forest Carbon Stocks

The United States covers roughly 2,263 million acres, of which 33 percent (747 million acres) is forest land (Smith and Sheffield 2000). Forest land acreage has remained fairly constant during the last several decades. Between 1977 and 1987, forest land declined by approximately 5.9 million acres, and then between 1987 and 1997, the area increased by about 9.2 million acres. Although these changes in forest area are in opposite directions, they 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 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 of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils.

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- Trees (i.e., living trees, standing dead trees, roots, stems, branches, and foliage)
- Understory vegetation (i.e., shrubs and bushes)
- Forest floor (i.e., fine woody debris, tree litter, and humus)
- Down dead wood (i.e., logging residue and other dead wood on the ground)
- Soil

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage of carbon in living biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere. For this reason, the term "apparent flux" is used in this chapter. Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net uptake (i.e., net sequestration) of carbon during the 1990s. 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 are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, in recent decades carbon fluxes from Eastern forests have been affected by a trend toward managed growth on private land, resulting in a near doubling of 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 that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling, rather than incineration, significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased over the last century.

U.S. forest components and harvested wood components were estimated to account for an average annual net sequestration of 940.1 Tg CO_2 Eq. (256.4 Tg C) over the period 1990 through 1999 (Table 6-3 and Table 6-4).[1] This net sequestration is a reflection of net forest growth and increasing forestland area. The rate of annual sequestration, however, declined by about 10 percent between 1990 and 1999. This is due to increasing harvests and land-use changes over this period (Haynes 2000, Smith and Sheffield 2000). The relatively large shift in annual net sequestration from 1996 to 1997 is the result of calculating average annual forest fluxes from periodic, rather than annual, activity data.

Table 6-5 presents the carbon stock estimates for forests (i.e., trees, understory, forest floor, and forest soil), wood products, and landfilled wood. The increase in all of these stocks over time indicates that, during the examined periods, forests, forest product pools, and landfilled wood all accumulated carbon (i.e., carbon sequestration by forests was greater than carbon removed in wood harvests and released through decay; and carbon accumulation in product pools and landfills was greater than carbon emissions from these pools by decay and burning). Logging residue stocks were not available because these fluxes were not calculated as a difference between stocks, but as a difference between wood cut and wood removed from the site for processing.

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[1] This average annual net sequestration is based on the entire time series (1990 through 1999), rather than the abbreviated time series presented in Table 6-3 and Table 6-4.

Table 6-3: Net CO_2 Flux from U.S. Forests (Tg CO_2 Eq.)

Description	1990	1995	1996	1997	1998	1999
Apparent Forest Flux	**(791.6)**	**(735.2)**	**(735.2)**	**(690.8)**	**(690.8)**	**(690.8)**
Trees	(414.0)	(384.6)	(384.6)	(387.6)	(387.6)	(387.6)
Understory	(5.1)	(5.1)	(5.1)	(4.0)	(4.0)	(4.0)
Forest Floor	(57.6)	(55.4)	(55.4)	(51.0)	(51.0)	(51.0)
Forest Soils	(251.5)	(226.6)	(226.6)	(184.8)	(184.8)	(184.8)
Logging Residues	(63.4)	(63.4)	(63.4)	(63.4)	(63.4)	(63.4)
Apparent Harvested Wood Flux	**(210.1)**	**(203.1)**	**(207.5)**	**(212.7)**	**(206.4)**	**(214.9)**
Wood Products	(47.7)	(53.9)	(56.1)	(58.6)	(52.1)	(61.6)
Landfilled Wood	(162.4)	(149.2)	(151.4)	(155.1)	(154.4)	(153.3)
Total Flux	**(1,001.7)**	**(938.3)**	**(942.7)**	**(903.5)**	**(897.2)**	**(905.7)**

Note: Parentheses indicate net carbon “sequestration” (i.e., accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word “apparent” is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

Table 6-4: Net CO_2 Flux from U.S. Forests (Tg C)

Description	1990	1995	1996	1997	1998	1999
Apparent Forest Flux	**(216)**	**(201)**	**(201)**	**(188)**	**(188)**	**(188)**
Trees	(113)	(105)	(105)	(106)	(106)	(106)
Understory	(1)	(1)	(1)	(1)	(1)	(1)
Forest Floor	(16)	(15)	(15)	(14)	(14)	(14)
Forest Soils	(69)	(62)	(62)	(50)	(50)	(50)
Logging Residues	(17)	(17)	(17)	(17)	(17)	(17)
Apparent Harvested Wood Flux	**(57)**	**(55)**	**(57)**	**(58)**	**(56)**	**(59)**
Wood Products	(13)	(15)	(15)	(16)	(14)	(17)
Landfilled Wood	(44)	(41)	(41)	(42)	(42)	(42)
Total Flux	**(273)**	**(256)**	**(257)**	**(246)**	**(245)**	**(247)**

Note: Note: 1 Tg C = 1 Tg Carbon = 1 million metric tons carbon. This table has been included to facilitate comparison with previous U.S. Inventories. Parentheses indicate net carbon “sequestration” (i.e., accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word “apparent” is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

Table 6-5: U.S. Forest Carbon Stock Estimates (Tg C)

Description	1987	1992	1997	2000
Forests (excluding logging residue)	**36,251**	**37,243**	**38,160**	**38,672**
Trees	12,709	13,273	13,798	14,115
Understory	557	564	571	574
Forest Floor	3,350	3,428	3,504	3,545
Forest Soils	19,635	19,978	20,287	20,438
Logging Residues	NA	NA	NA	NA
Harvested Wood	**1,920**	**2,198**	**2,479**	**2,651**
Wood Products	1,185	1,245	1,319	1,366
Landfilled Wood	735	953	1,159	1,285

NA (Not Available)

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. Lightly shaded areas indicate values based on a combination of historical data and projections. All other estimates are based on historical data only. Logging residue is not available because logging residue flux is predicted from differences between wood harvested and wood removed from the site. Totals may not sum due to independent rounding.

Methodology

The methodology for estimating annual net forest carbon flux in the United States is based on periodic surveys rather than annual activity data. In addition, because the most recent survey was compiled for 1997, projected data, rather than complete historical data, were used to derive some of the annual flux estimates. A description of the assumptions underlying this projection is given in Haynes (2000). The projection reflects assumptions about variables that affect wood demand and supply, such as population and technological changes; policies regulating forests and their management are assumed fixed.

The carbon budget of forest ecosystems in the United States was estimated using a core model, FORCARB, and several subroutines that calculate additional information, including carbon in wood products (Plantinga and Birdsey 1993, Birdsey et al. 1993, Birdsey and Heath 1995, and Heath et al. 1996). FORCARB is part of an integrated system of models consisting of an area change model (Alig 1985), a timber market model (TAMM; Adams and Haynes 1980), a pulp and paper model (NAPAP; Ince 1994) and an inventory projection model (ATLAS; Mills and Kincaid 1992). Through linkage with these models, FORCARB estimates carbon stocks on private timberlands as a function of management intensity and land-use change. ATLAS does not yet include public timberlands, and harvesting on public lands is not particularly responsive to price, so forest inventory and harvest data for public timberlands are developed exogenously and then used as inputs to the modeling system to estimate carbon stocks on public timberlands (Heath 1997b). Average annual net carbon flux on timberlands is estimated by taking the difference between carbon stocks, and dividing by the length of the period between stock estimates.

The current version of FORCARB partitions carbon storage in the forest into five separate components: trees, understory vegetation, forest floor, forest soils, and logging residues. The tree component includes all above-ground and below-ground portions of all live and dead trees, including the merchantable stem, limbs, tops, cull sections, stump, foliage, bark and rootbark, and coarse tree roots (greater than 2 mm). Understory vegetation includes all live vegetation other than live trees. The forest floor includes litter and fine woody debris. The soil component includes all organic carbon in mineral horizons to a depth of one meter, excluding coarse tree roots. Logging residue is the portion of the harvested wood that is left on the site, i.e., not removed for processing.

The FORCARB model essentially converts merchantable volumes from the model linkages into carbon and predicts carbon in other ecosystem components—such as soil and forest floor—based on other data from forest inventories and additional information from intensive-site ecosystem studies. Estimates of average carbon storage by age or volume class of forest stands—analogous to a forest yield table—are made for each ecosystem component for forest classes defined by region, forest type, productivity class, and land-use history. Equations that estimate carbon stocks in the forest floor, soil, and understory vegetation for each forest class are incorporated in the model. Logging residue is calculated as the difference between the carbon in wood harvested (cut) and wood removed from the site for processing at the mill. Additional details about estimating carbon storage for different regions, forest types, site productivity class, and past land use are provided in Birdsey (1996).

The methodology for reserved forest lands and other forest lands differs from that described above for timberlands.[2] Forest carbon stocks on non-timberland forests were estimated based on average per area carbon estimates derived from timberlands. Reserved forests were assumed to contain the same average per area carbon stocks as timberlands of the same forest type, region, and owner group. These averages were multiplied by the areas in the forest statistics, and then aggregated for a national total. Average carbon stocks per area were

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[2] 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 timberlands, 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.

derived for other forest land by estimating carbon stocks per area for timberlands in the lowest productivity class that is surveyed. These estimates were multiplied by 80 percent to simulate the effects of lower productivity. The results indicated these non-timberland forests are in equilibrium, and therefore contribute little to the flux estimates.

Estimates of carbon in wood products and wood discarded in landfills are based on the methods described in Skog and Nicholson (1998), and aggregation as described in Heath et al. (1996). The disposition of harvested wood carbon removed from the forest can be described in four general pools: products in use, discarded wood in landfills, emissions from wood burned for energy, and emissions from decaying wood or wood burned in which energy was not captured. The apparent fluxes presented here represent the net amounts of carbon that are stored in wood product and landfilled wood pools (i.e., inputs to the pools minus emissions from, or transfers out of, the pools). Annual historical estimates and projections of detailed product production were used to divide consumed roundwood into product, wood mill residue, and pulp mill residue. The carbon decay rates for products and landfills were estimated, and applied to the respective pools. The results were aggregated for national estimates.

The apparent fluxes from wood product and landfilled wood pools include exports and exclude imports. Carbon in exported wood is tracked using the same disposal rates as in the United States. Over the period 1990 through 1999, carbon in exported wood accounts for an average of 21.3 Tg CO_2 Eq. net storage per year, with little variation from year to year. For comparison, imports—which are not included in the harvested wood apparent flux estimates—increase from 26.4 to 44.7 Tg CO_2 Eq. net storage per year from 1990 to 1999.

The methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing estimates of net carbon flux from Land-Use Change and Forestry: 1) using average annual statistics on land use, land-use change, and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux values; or 2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: 1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or 2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this inventory using estimates of carbon stored in wood products and landfilled wood.[3] Although there are uncertainties associated with the data used to develop the flux estimates presented here, the use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely to result in more accurate flux estimates than the alternative IPCC methodology.

Data Sources

The estimates of forest carbon stocks used in this Inventory to calculate forest carbon fluxes are based on areas, volumes, growth, harvests, and utilization factors derived from the forest inventory data collected by the USDA Forest Service. Compilations of these data for 1987, 1992, and 1997 are given in Waddell et al. (1989), Powell et al. (1993), and Smith and Sheffield (2000), respectively. The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land in the contiguous United States, but do not include stocks on forest land in Alaska, Hawaii, or the U.S. territories, or stocks on non-forest land (e.g., urban trees).[4] The timber volume data include estimates by tree species, size class, and other categories. The forest inventory data are augmented or converted to

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[3] Again, the product estimates in this study do not account for carbon stored in imported wood products. However, they do include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

Box 6-1: Comparison to forest carbon stock and flux estimates in the United States Submission on Land Use, Land-Use Change, and Forestry

On August 1, 2000, the U.S. government submitted a document to the UNFCCC on methodological issues related to the treatment of carbon sinks under Articles 3.3 and 3.4 of the Kyoto Protocol (U.S. Department of State 2000). This document, entitled *United States Submission on Land Use, Land-Use Change and Forestry* (i.e., the U.S. Submission on LULUCF), was submitted in response to a request of the Subsidiary Body for Scientific and Technological Advice (SBSTA). The U.S. Submission on LULUCF contains estimates of carbon stocks and flux from forest lands, croplands, and grazing lands. The estimates of forest carbon stocks and flux presented in this Inventory are slightly different from those presented in the U.S. Submission on LULUCF for two reasons: 1) the SBSTA requested stock and flux estimates for a different set of forest areas and activities than are accounted for in national greenhouse gas inventories required under the UNFCCC; and 2) both the estimates presented here, and those presented in the U.S. Submission on LULUCF, reflect interim results of forest carbon modeling refinements that are underway at the USDA Forest Service. These differences are discussed more fully below.

First, the U.S. Submission on LULUCF is concerned with only timberlands, and with carbon fluxes due to activities since 1990. The *U.S. Inventory on Greenhouse Gas Emissions and Sinks* covers timberlands, reserved forests, and other forests; and *U.S. Inventory on Greenhouse Gas Emissions and Sinks* flux estimates for any particular year include fluxes due to activities in that year, as well as fluxes due to activities in previous years (i.e., delayed fluxes). Carbon stocks on reserved forests and other forests are believed to be stable, so their inclusion in the Inventory only affects carbon stocks, not fluxes. The inclusion of fluxes due to activities prior to 1990 in the Inventory results in higher annual emission estimates (i.e., lower net sequestration) for harvested wood and logging residue pools compared to the U.S. Submission.

Second, the methodologies used to estimate harvested wood and soil carbon pools vary between the two documents. The harvested wood carbon pools in the U.S. Submission on LULUCF are based on disposition coefficients that were derived using the method of Skog and Nicholson (1998) and a run of the integrated forestry model system (FORCARB/TAMM/ATLAS/NAPAP) with 1992 and earlier forest inventory data as inputs. The estimates of harvested wood carbon pools used in the Inventory are also based on the method of Skog and Nicholson (1998), but with a rerun of the integrated forestry model system with the 1997 forest inventory data as input. Also, the carbon stocks in the U.S. Submission were derived using a new soils method, which is not yet available for reserved forests and other forests, so an older method was used in the Inventory. This resulted in higher soil carbon stock estimates in the U.S. Submission compared to the Inventory, but did not affect the estimated fluxes.

carbon following the methods described in the methodology section. Soil carbon estimates are based on data from the STATSGO database (USDA 1991). Carbon stocks in wood products in use and wood stored in landfills are based on historical data from the USDA Forest Service (Powell et al. 1993, Smith and Sheffield 2000), and historical data as implemented in the framework underlying the NAPAP (Ince 1994) and TAMM/ATLAS (Adams and Haynes 1980, Mills and Kincaid 1992) models.

Uncertainty

This section discusses uncertainties in the results, given the methods and data used. There are likely sampling and measurement errors associated with forest survey data that underlie the forest carbon estimates. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Although newer inventories are being conducted annually in every state, much of the data currently used may have been collected over more than one year in a state, and data associated with a particular year may actually have been collected over several previous years. Thus, there is uncertainty in the year associated with the forest inventory data. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska, Hawaii, and the U.S. territories, and trees on non-forest land (e.g., urban trees). However, net carbon fluxes from these stocks are believed to be minor. The assumptions that were used to calculate carbon stocks in reserved forests and other forests in the coterminous United States also contribute to

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[4] Although forest carbon stocks in Alaska, Hawaii, and U.S. territories are large compared to the U.S. total, net carbon fluxes from forest stocks in these areas are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

the uncertainty. Although the potential for uncertainty is large, the sample design for the forest surveys contributes to limiting the error in carbon flux. Re-measured permanent plot estimates are correlated, and greater correlation leads to decreased uncertainties in change estimates. For example, in a study on the uncertainty in the forest carbon budget of U.S. private timberlands, Smith and Heath (2000) estimated that the uncertainty of the flux increased about 3.5 times when the correlation coefficient dropped from 0.95 to 0.5.

The second source of uncertainty results from deriving carbon storage estimates for the forest floor, understory vegetation, and soil from models that are based on data from forest ecosystem studies. To extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially introduce the following errors: 1) bias from applying data from studies that inadequately represent average forest conditions; 2) modeling errors (e.g., erroneous assumptions); and 3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. For example, Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while Johnson (1992) found little or no net change in soil carbon following harvest. Heath and Smith (2000) noted that the experimental design in a number of soil studies was such that the usefulness of the studies may be limited in determining harvesting effects on soil carbon. Soil carbon impact estimates need to be very precise because even small changes in soil carbon may sum to large differences over large areas.

Recent studies have looked at quantifying the amount of uncertainty in national-level 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 private timberlands. These studies are not strictly comparable to the estimates in this chapter because they used an older version of the FORCARB model, and were based on older data. However, the magnitudes of the uncertainties should be instructive. Their results indicate that the carbon flux of private timberlands, not including harvested wood, was approximately the average carbon flux (271 Tg CO_2 Eq. per year) ±15 percent at the 80 percent confidence level for the period 1990 through 1999. The flux estimate included the tree, soil, understory vegetation, and forest floor components only. The uncertainty in the carbon inventory of private timberlands for 2000 was approximately 5 percent at the 80 percent confidence level. It is expected that the uncertainty should be greater for all forest lands (i.e., private and public timberlands, and reserved and other forest land).

Changes in Agricultural Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of photosynthetically fixed carbon (i.e., organic matter such as decayed detritus and roots) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and the 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 each responds differently to land-use practices.

Mineral soils contain comparatively low amounts of organic matter, much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic matter (by weight); mineral subsoils contain even lower amounts of organic matter (Brady and Weil 1999). When mineral soils undergo conversion from their native state to agricultural use, as much as half of 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 biomass production or decreased oxidation (e.g., 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, which are also referred to as histosols, include all soils with more than 20 to 30 percent organic matter by weight (depending on clay content) (Brady and Weil 1999). The organic matter 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, tilling or mixing of the soil aerates the soil, thereby accelerating 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. Conversion of organic soils to agricultural uses typically involves drainage as well, which also causes soil carbon oxidation. 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, the composition (i.e., decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for upland crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and/or 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. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for applied limestone and dolomite to degrade completely.

Of the three activities, use and management of mineral soils was by far the most important in terms of contribution to total flux during the 1990 through 1999 period (see Table 6-6). Carbon sequestration in mineral soils in 1999 was estimated at about 109.3 Tg CO_2 Eq., while emissions from organic soils were estimated at about 22.4 Tg CO_2 Eq. and emissions from liming were estimated at about 9.9 Tg CO_2 Eq. Together, the three activities accounted for net sequestration of 77.0 Tg CO_2 Eq. in 1999. Total annual net CO_2 flux was negative each year over the 1990 to 1999 period. Between 1990 and 1999, total net carbon sequestration in agricultural soils increased by 90 percent.

The flux estimates and analysis for this source are restricted to CO_2 fluxes associated with the use and management of agricultural soils. However, it is important to note that land use and land-use change activities may also result in fluxes of non-CO_2 greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO), to and from soils. For example, when lands are flooded with freshwater, such as during hydroelectric

Table 6-6: Net CO_2 Flux From Agricultural Soils (Tg CO_2 Eq.)

Description	1990	1995	1996	1997	1998	1999
Mineral Soils	(71.9)	(100.1)	(100.1)	(100.1)	(109.3)	(109.3)
Organic Soils	22.0	22.4	22.4	22.4	22.4	22.4
Liming of Soils	9.5	8.9	8.9	8.7	9.6	9.9
Total Net Flux	**(40.4)**	**(68.8)**	**(68.9)**	**(69.0)**	**(77.3)**	**(77.0)**

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

dam construction, CH_4 is produced and emitted to the atmosphere due to anaerobic decomposition of organic material in the soil and water column. Conversely, when flooded lands, such as lakes and wetlands, are drained, anaerobic decomposition and associated CH_4 emissions will be reduced. Dry soils are a sink of CH_4, so eventually, drainage may result in soils that were once a source of CH_4 becoming a sink of CH_4. However, once the soils become aerobic, oxidation of soil carbon and other organic material will result in elevated emissions of CO_2. Moreover, flooding and drainage may also affect net soil fluxes of N_2O and CO, although these fluxes are highly uncertain. The fluxes of CH_4, and other gases, due to flooding and drainage are not assessed in this inventory due to a lack of activity data on the extent of these practices in the United States as well as scientific uncertainties about the greenhouse gas fluxes that result from these activities.[5]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except where noted below.

The estimates of annual net CO_2 flux from mineral soils were taken from Eve et al. (2000a) and U.S. Department of State (2000). The approach used to derive these estimates is described in Eve et al. (2000b). Total mineral soil carbon stock estimates for 1982, 1992, and 1997 were developed by applying the default IPCC carbon stock and carbon adjustment factors (with one exception), to cropland and grazing land area estimates, classified by climate, soil type, and management regime. The exception is the base factor for lands set aside for less than 20 years. The IPCC default value is 0.8, but recent research in the United States (Paustian et al. 2001, Follett et al. 2001, Huggins et al. 1997, and Gebhart et al. 1994) indicates that 0.9 is a more accurate factor for the United States. Therefore, 0.9 was used instead of 0.8 for the base factor for grassland set aside through the Conservation Reserve Program. Areas of non-federal cropland and grazing land, by soil type and land management regime, in 1982, 1992, and 1997 were taken from USDA (2000a).[6] These were assigned to climatic regions using the climate mapping program in Daly et al. (1994). Estimates of tillage practices were derived from data collected by the Conservation Technology Information Center (CTIC).[7] The carbon flux estimate for 1990 is based on the change in stocks between 1982 and 1992, and the carbon flux estimate for 1995 through 1997 is based on the change in stocks between 1982 and 1997. The IPCC base, tillage, and input factors were adjusted to account for use of a ten-year and a fifteen-year accounting period, rather than the 20-year period used in the *IPCC Guidelines*. The carbon flux estimate for 1998 and 1999 is based on the change in stocks between 1982 and a projection for 2008. The 2008 projection is based on the estimated 1997 stock, adjusted to account for additional acres expected to be enrolled in the Conservation Reserve Program by 2008 (USDA 2000b).

The estimates of annual CO_2 emissions from organic soils were also taken from Eve et al. (2000a) and U.S. Department of State (2000), and are based on an approach described in Eve et al. (2000b). The IPCC methodology for organic soils utilizes annual CO_2 emission factors, rather than a stock change approach. Following the IPCC methodology, only organic soils under intense management were included, and the default IPCC rates of carbon loss were applied to the total 1992 and 1997 areas for the climate/land-use categories defined in the IPCC Guidelines. The area estimates were derived from the same climatic, soil, and land-use/land management databases that were used in the mineral soil calculations (Daly et al. 1994, USDA 2000a). The annual flux estimated for 1992 is applied to 1990, and the annual flux estimated for 1997 is applied to 1995 through 1999.

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[5] However, methane emissions due to flooding of rice fields are included, as are nitrous oxide emissions from agricultural soils. These are addressed under the Rice Cultivation and Agricultural Soil Management sections, respectively, of the Agriculture chapter.

[6] Soil carbon stocks on federal grazing lands were assumed to be stable, and so are not included in the flux estimates.

[7] See <www.ctic.purdue.edu>.

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 6-7) by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[8] 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; USGS 2000). 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 total 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 were equal to the fraction of "specified" production that was applied to agricultural soils. In addition, data were not available in 1990, 1992, and 1999 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 1999 data, the 1998 fractions were applied to a 1999 estimate of total crushed stone found in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2000* (USGS 2000).

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.

Uncertainty

Uncertainties in the flux estimates for mineral and organic soils result from both the activity data and the carbon stock and adjustment factors. Each of the datasets used in deriving the area estimates has a level of uncertainty that is passed on through the analysis, and the aggregation of data over large areas necessitates a certain degree of generalization. The default IPCC values used for estimates of mineral soil carbon stocks under native vegetation, as well as for the base, tillage and input factors, carry with them high degrees of uncertainty, as these values represent broad regional averages based on expert judgment. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an

Table 6-7: Quantities of Applied Minerals (Thousand Metric Tons)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Limestone	19,012	20,312	17,984	15,609	16,686	17,297	17,479	16,539	14,882	15,375
Dolomite	2,360	2,618	2,232	1,740	2,264	2,769	2,499	2,989	6,389	6,600

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[8] Note: 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.

order of magnitude. In addition, 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 also result from both the methodology and the activity data. It can take several years for agriculturally-applied limestone and dolomite to degrade completely. The IPCC method assumes that the amount of mineral applied in any year is equal to the amount that degrades in that year, so annual application rates can be used to derive annual emissions. Further research is required to determine actual degradation rates, which would vary with varying soil and climatic conditions. However, application rates are fairly constant over the entire time series, so this 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.

Changes in Yard Trimming Carbon Stocks in Landfills

As is the case with landfilled forest products, carbon contained in landfilled yard trimmings can be stored indefinitely. In the United States, yard trimmings (i.e., grass clippings, leaves, branches) comprise a significant portion of the municipal waste stream. In 1990, the EPA estimated discards of yard trimmings to landfills at over 21 million metric tons (EPA 1999). Since then, programs banning or discouraging disposal, coupled with a dramatic rise in the number of composting facilities, have decreased the disposal rate for yard trimmings. In 1999, the landfill disposal of yard trimmings was about 9 Tg (EPA 1999). The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from about 17.8 Tg CO_2 Eq. in 1990 to 7.7 Tg CO_2 Eq. in 1999 (see Table 6-8).

Methodology

Table 6-8: Net CO_2 from Landfilled Yard Trimmings

Year	Tg CO_2 Eq.
1990	(17.8)
1995	(12.0)
1996	(10.0)
1997	(9.4)
1998	(8.8)
1999	(7.7)

Note: Parentheses indicate net storage. Lightly shaded area indicates values based on projections.

The methodology for estimating carbon storage is based on a life cycle analysis of greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). According to this methodology, carbon storage is the product of the mass of yard trimmings disposed, on a wet weight basis, and a storage factor. The storage factor, which is the fraction of total carbon that is assumed to be stored permanently, is based on a series of experiments designed to evaluate methane generation and residual organic material in landfills (Barlaz 1997). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

For purposes of this analysis, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches on a wet weight basis. A different storage factor was used for each component. The weighted average carbon storage factor is 0.23 (metric ton of carbon stored indefinitely per metric ton [wet weight] of yard trimmings landfilled), as shown in Table 6-9.

Data Sources

The yard trimmings discard rate was taken from the EPA report *Characterization of Municipal Solid Waste in the U.S.: 1998 Update* (EPA 1999), which provides

Table 6-9: Composition of Yard Trimmings in MSW and Carbon Storage Factor (Gg C/Gg yard trimmings)

Component	Percent	Storage Factor
Grass	50	0.13
Leaves	25	0.43
Branches	25	0.23
Total/Weighted Average	**100**	**0.23**

estimates for 1990 through 1998 and forecasts for 2000 and 2005. Yard trimmings discards for 1999 were projected using the EPA (1999) forecast of generation and recovery rates (i.e., decrease of 6 percent per year, increase of 8 percent per year, respectively) for 1999 through 2000. This report does not subdivide discards of individual materials into volumes landfilled and combusted, although it does provide an estimate of the overall distribution of solid waste between these two management methods (i.e., 76 percent and 24 percent, respectively) for the waste stream as a whole.[9] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills (see Table 6-10). The carbon storage factors were obtained from EPA (1998).

Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stems from an incomplete understanding of the long-term fate of carbon in landfill environments. Although there is ample field evidence that many landfilled organic materials remain virtually intact for long periods, the quantitative basis for predicting long-term storage is based on limited laboratory results under experimental conditions. In reality, there is likely to be considerable heterogeneity in storage rates, based on 1) actual composition of yard trimmings (e.g., oak leaves decompose more slowly than grass clippings) and 2) landfill characteristics (e.g., availability of moisture, nitrogen, phosphorus, etc.) Other sources of uncertainty include the estimates of yard trimmings disposal rates, which are based on extrapolations of waste composition surveys, and the extrapolation of a value for 1999 disposal from estimates for the period from 1990 through 1998.

Table 6-10: Yard Trimmings Disposal to Landfills

Year	Gg (wet weight)
1990	21,200
1991	20,800
1992	20,400
1993	18,200
1994	16,200
1995	14,300
1996	12,000
1997	11,200
1998	10,500
1999	9,200

Note: Lightly shaded area indicates values based on projections.

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[9] Note that this calculation uses a different proportion for combustion than an earlier calculation in the Waste Combustion section of the Waste chapter. The difference arises from different sources of information with different definitions of what is included in the solid waste stream.

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