Inventory of U.S. Greenhouse Gas Emissions and Sinks:

1990 — 2000

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Preface

The United States Environmental Protection Agency (EPA) prepares the official *U.S. Inventory of Greenhouse Gas Emissions and Sinks* to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC).[1] Under a decision of the UNFCCC Conference of the Parties, national inventories for most UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document is announced via Federal Register Notice and is posted on the EPA web page.[2] Copies are also mailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report. The EPA's policy is to allow at least 60 days for public review and comment when proposing new regulations or documents supporting regulatory development – unless statutory or judicial deadlines make a shorter time necessary – and 30 days for non-regulatory documents of an informational nature such as the Inventory document.

[1] See http://www.unfccc.de

[2] See http://www.epa.gov/globalwarming/emissions/national

6. 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. 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 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 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 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. 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. As a result of this data structure, estimated CO_2 fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are constant over multi-year intervals, with large discontinuities between intervals. For the landfilled yard trimmings, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. In addition, because the most recent national forest, land-use, and municipal solid waste surveys were completed for the year 1997, the estimates of CO_2 flux from forests, agricultural soils, and landfilled yard trimmings are based in part on modeled projections. Carbon dioxide fluxes from urban trees are based on neither annual data nor periodic survey data, but instead is data collected over the decade 1990 through 2000. Therefore, this flux has been applied to the entire time series.

Land use, land-use change, and forestry activities in 2000 resulted in a net sequestration of 903 Tg CO_2 Eq. (246 Tg C) (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 18 percent between 1990 and 2000. 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 also slowed over this period, while annual carbon accumulation in agricultural soils increased. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for the decade).

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

Sink Category	**1990**		**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Forests	(982.7)		(979.0)	(979.0)	(759.0)	(751.7)	(762.7)	(770.0)
Urban Trees	(58.7)		(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Agricultural Soils	(37.3)		(60.2)	(60.2)	(60.4)	(67.2)	(67.7)	(67.4)

[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."

Landfilled Yard Trimmings	(19.1)		(12.2)	(10.2)	(9.5)	(8.3)	(7.3)	(6.4)
Total	**(1097.7)**		**(1110.0)**	**(1108.1)**	**(887.5)**	**(885.9)**	**(896.4)**	**(902.5)**

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)

Sink Category	1990		1995	1996	1997	1998	1999	2000
Forests	(268)		(267)	(267)	(207)	(205)	(208)	(210)
Urban Trees	(16)		(16)	(16)	(16)	(16)	(16)	(16)
Agricultural Soils	(10)		(16)	(16)	(17)	(18)	(19)	(18)
Landfilled Yard Trimmings	(5)		(3)	(3)	(3)	(2)	(2)	(2)
Total	**(299)**		**(303)**	**(302)**	**(242)**	**(242)**	**(245)**	**(246)**

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. 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

Carbon in forests can be described as the total of several interrelated carbon storage pools, including:

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

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, clearing, and replanting), carbon is continuously cycled through and among these storage pools, as well as between the forest ecosystem and the atmosphere. For example, as trees 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 carbon storage slows. 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 stocks.

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. 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.

This section of the Land-Use Change and Forestry chapter tracks 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.

An illustration of forest carbon storage pools, and flows between them via emissions, sequestration, and transfers, is presented in Figure 6-1. In this illustration, 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 boxes are not identical with storage pools identified in this chapter. The storage pools identified in this chapter have been arranged to better illustrate the processes that result in transfers of carbon from one pool to another, and that result in emissions to the atmosphere (adapted from Birdsey and Lewis 2001).

Figure 6-1: Forest Sector Carbon Pools and Flows

Approximately 33 percent (747 million acres) of the U.S. land area is forested (Smith et al. 2001). Between 1977 and 1987, forest land declined by approximately 5.9 million acres, and between 1987 and 1997, the area increased by about 9.2 million acres. These 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 recent 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 through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils. The net effect of both forest management and land-use change involving forests is captured in these estimates.

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 (i.e., net sequestration) of carbon during the period from 1990 through 2000. 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, carbon fluxes from Eastern forests have been affected by a trend toward managed growth on private land. Collectively, these changes have produced 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.

Changes in carbon stocks in U.S. forests and harvested wood were estimated to account for an average annual net sequestration of 899 Tg CO_2 Eq. (245 Tg C) over the period 1990 through 2000 (see Table 6-3 and Table 6-4).[3] The net sequestration is a reflection of net forest growth and increasing forest area over this period, particularly from 1987 to 1997, as well as net accumulation of carbon in harvested wood pools. The rate of annual sequestration, however, declined by 22 percent between 1990 and 2000. This is due to a greater rate of forest area increase between 1987 and 1997 than between 1997 and 2001. Most of the decline in annual sequestration occurred in the forest soil carbon pool. This is a reflection of modeling assumptions used in this analysis, specifically that soil

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

[3] This average annual net sequestration is based on the entire time series (1990 through 2000), rather than the abbreviated time series presented in Table 6-3 and Table 6-4. Results for the entire time series are presented in Annex N (Methodology for Estimating Net Changes in Forest Carbon Stocks).

carbon stocks for each forest type are constant over time, rather than varying by age, whereas biomass carbon stocks are a function of forest type and age class. Therefore, as lands are converted from non-forest to forest, there is a relatively large immediate increase in soil carbon stocks compared to the increase in biomass carbon stocks. The relatively large shifts in annual net sequestration from 1996 to 1997 are the result of calculating average annual forest fluxes from periodic, rather than annual, activity data.

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

Description	1990	1995	1996	1997	1998	1999	2000
Forest Carbon Stocks	**(773.7)**	**(773.7)**	**(773.7)**	**(546.3)**	**(546.3)**	**(546.3)**	**(546.3)**
Trees	(469.3)	(469.3)	(469.3)	(447.3)	(447.3)	(447.3)	(447.3)
Understory	(11.0)	(11.0)	(11.0)	(14.7)	(14.7)	(14.7)	(14.7)
Forest Floor	(25.7)	(25.7)	(25.7)	29.3	29.3	29.3	29.3
Down Dead Wood	(55.0)	(55.0)	(55.0)	(58.7)	(58.7)	(58.7)	(58.7)
Forest Soils	(212.7)	(212.7)	(212.7)	(55.0)	(55.0)	(55.0)	(55.0)
Harvested Wood Carbon Stocks	**(209.0)**	**(205.3)**	**(205.3)**	**(212.7)**	**(205.3)**	**(216.3)**	**(223.7)**
Wood Products	(47.7)	(55.0)	(55.0)	(58.7)	(51.3)	(62.3)	(66.0)
Landfilled Wood	(161.3)	(150.3)	(150.3)	(154.0)	(154.0)	(154.0)	(157.7)
Total	**(982.7)**	**(979.0)**	**(979.0)**	**(759.0)**	**(751.7)**	**(762.7)**	**(770.0)**

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. 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	2000
Forest Carbon Stocks	**(211)**	**(211)**	**(211)**	**(149)**	**(149)**	**(149)**	**(149)**
Trees	(128)	(128)	(128)	(122)	(122)	(122)	(122)
Understory	(3)	(3)	(3)	(4)	(4)	(4)	(4)
Forest Floor	(7)	(7)	(7)	8	8	8	8
Down Dead Wood	(15)	(15)	(15)	(16)	(16)	(16)	(16)
Forest Soils	(58)	(58)	(58)	(15)	(15)	(15)	(15)
Harvested Wood Carbon Stocks	**(57)**	**(56)**	**(56)**	**(58)**	**(56)**	**(59)**	**(61)**
Wood Products	(13)	(15)	(15)	(16)	(14)	(17)	(18)
Landfilled Wood	(44)	(41)	(41)	(42)	(42)	(42)	(43)
Total	**(268)**	**(267)**	**(267)**	**(207)**	**(205)**	**(208)**	**(210)**

Note: Note: 1 Tg C = 1 Tg carbon = 1 million metric tons carbon. Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or harvest from the carbon pool). The sum of the net stock changes in this table (i.e., total) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. 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.

Methodology

The approach to calculating changes in carbon stocks in forests can generically be described as sampling the forest carbon at one time, sampling the forest carbon a second time at a later date, and then subtracting the two estimates for the net stock change. Historically, the main purpose of the national forest inventory has been to estimate areas, volume of growing stock, and timber products output and utilization factors. Growing stock is simply a classification of timber inventory that includes live trees of commercial species meeting specified standards of quality (Smith et al. 2001). Timber products output refers to the production of industrial roundwood products such as logs and other round timber generated from harvesting trees, and the production of bark and other residue at processing mills. Utilization factors relate inventory volume to the volume cut or destroyed when producing roundwood (May 1998). Growth, harvests, land-use change, and other estimates of change are derived from repeated surveys. The inventory data are converted to carbon using conversion factors or a model that estimates basic relationships between forest characteristics and carbon pools like forest floor. Historical carbon stock changes are derived from USDA Forest Service, Forest Inventory & Analysis inventory data (Smith et al. 2001, Frayer and Furnival 1999). Projected carbon stock changes are derived from areas, volumes, growth, land-use changes and other forest characteristics projected in a system of models (see Haynes et al. 2001a) representing the U.S. forest sector, including a model (FORCARB) that estimates carbon for merchantable and non-merchantable tree pools, and other forest carbon pools.

The USDA Forest Service, Forest Inventory & Analysis (FIA) has conducted consistent scientifically designed forest surveys of much of the forest land in the United States since 1952. Historically, these were conducted periodically, state-by-state within a region. One state within a region would be surveyed, and when finished, another state was surveyed. Eventually (every 5-14 years, depending on the state), all states within a region would be surveyed, and then states would be resurveyed. FIA has adopted a new annualized design, so that a portion of each state will be surveyed each year (Gillespie 1999); however, data are not yet available for all states. 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. Characteristics that are measured and readily available from some surveys include individual tree diameter and species, and forest type and age of the plot. For more information about forest inventory data and carbon flux, see Birdsey and Heath (2001).

The USDA Forest Service periodically compiles and reports survey data for a specific base year. Available years relevant to CO_2 flux estimates are 1987 and 1997. Live tree carbon and dead tree carbon are estimated from the inventory data using the conversion factors by forest type and region in Smith et al. (in review). Understory carbon is estimated from forest inventory data and equations based on estimates in Birdsey (1992). Forest floor carbon is estimated from the forest inventory data using the equations listed in Smith and Heath (in review). Projections produce estimates of areas and volumes; carbon estimates are produced using this information using procedures similar to those used to produce carbon estimates from forest inventory data. For a detailed description of the modeling system, see Annex N.

In the past, FIA surveyed all productive forest land, which is called timberland, and some reserved forest land and some other forest land.[4] With the introduction of the annualized design (Gillespie 1999), all forest lands will feature the same type of information. Forest carbon stocks on non-timberland forests were estimated based on average carbon estimates derived from representative timberlands. Reserved forests were assumed to contain the same average carbon densities 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 were derived for other forest land by using average carbon stocks for timberlands, which were multiplied by 50 percent to simulate the effects of lower productivity.

Estimates of carbon stock changes in wood products and wood discarded in landfills are based on the methods described in Skog and Nicholson (1998). 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 net carbon stock changes presented here represent the amounts of carbon that are stored (i.e., not released to the atmosphere). Annual historical estimates and projections of detailed 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 production approach to accounting for imports and exports was used. Thus, carbon in exported wood is included using the same disposal

[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 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.

rates as in the United States, while carbon in imported wood is not included. Over the period 1990 to 2000, carbon in exported wood accounted for an average of 22 Tg CO_2 Eq. storage per year, with little variation from year to year. For comparison, imports—which are not included in the harvested wood net flux estimates—increased from 26 Tg CO_2 Eq. per year in 1990 to 46 Tg CO_2 Eq. per year in 2000.

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.[5] 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 to calculate forest carbon fluxes are based largely 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 1987and 1997 are given in Waddell et al. (1989) and Smith et al. (2001), respectively, with trends discussed in the latter citation. The timber volume data used here include timber volumes on forest land classified as timberland, as well as on some reserved forest land and other forest land. Timber volumes on forest land in Alaska, Hawaii, and the U.S. territories are not sufficiently detailed to be used here. Also, timber volumes on non-forest land (e.g., urban trees, rangeland) are not included. The timber volume data include estimates by tree species, size class, and other categories. The forest inventory data are augmented or converted to carbon following the methods described in the methodology section. The carbon storage factors applied to these data are described in Annex N. 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 (USDA 1964, Ulrich 1989, Howard 2001), and historical data as implemented in the framework underlying the NAPAP (Ince 1994) and TAMM/ATLAS (Haynes et al. 2001a, Mills and Kincaid 1992) models. The carbon conversion factors and decay rates for harvested carbon removed from the forest are taken from Skog and Nicholson (1998).

Table 6-5 presents the carbon stock estimates for forest and harvested wood storage pools. Together, the tree and forest soil pools account for over 80 percent of total carbon stocks. Carbon stocks in all pools, except forest floor, increased over time, indicating that, during these periods, all storage pools except forest floor accumulated carbon (e.g., carbon sequestration by trees was greater than carbon removed from the tree pool through respiration, decay, litterfall, and harvest). Figure 6-2 shows 1997 carbon stocks by the regions that were used in the forest carbon analysis.

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

Description	**1987**	**1997**	**2001**
Forests	**47,594**	**49,694**	**50,291**
Trees	15,168	16,449	16,937

[5] 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).

Understory	448	473	489
Forest Floor	4,240	4,306	4,274
Down dead wood	2,058	2,205	2,269
Forest Soils	25,681	26,262	26,322
Harvested Wood	**1,920**	**2,479**	**2,712**
Wood Products	1,185	1,319	1,384
Landfilled Wood	735	1,159	1,328
Total	**49,514**	**52,173**	**53,003**

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. Totals may not sum due to independent rounding. Note that the stock is listed for 2001 because stocks are defined as of January 1 of the listed year.

Figure 6-2: Forest Carbon Stocks, 1997
This graphic shows total forest carbon stocks in 1997, by region. Harvested wood carbon stocks are not included.

Uncertainty

There are sampling and measurement errors associated with the 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 have been collected over several earlier 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 most forest land in Alaska, Hawaii, U.S. territories. The assumptions that were used to calculate carbon stocks in reserved forests and other forests in the coterminous United States also contribute to 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 of the forest carbon budget of private timberlands of the United States, 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.

Additional sources of uncertainty come from the models used to estimate carbon storage in specific ecosystem components, such as forest floor, understory vegetation, and soil. Extrapolating results of separate ecosystem studies to all forest lands, introduces uncertainty through the necessary assumption that the studies adequately describe regional or national averages. These assumptions can potentially introduce the following errors: (1) bias from applying data from studies that inadequately represent average forest conditions, (2) modeling errors (e.g., relying on coefficients or relationships that are not known), 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, 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 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 precise; even small changes in soil carbon may sum to large differences over large areas. This analysis assumes that soil carbon density for each forest type stays constant over time. In the future, land-use effects will be incorporated into the soil carbon density estimates.

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, which was based on older data and produced decadal estimates. 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. These estimates did not include all uncertainties, such as the ones associated with public timberlands, and reserved and other forest land, but they did include many of the types of uncertainties listed previously. It is expected that the uncertainty should be greater for all forest lands.

Changes in Carbon Stocks in Urban Trees

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). It was estimated that urban areas (cities, towns, and villages), which cover 3.5 percent of the continental United States, contained about 3.8 billion trees. With an average tree canopy cover of 27.1 percent, urban areas accounted for approximately 2.8 percent of total tree cover in the continental United States.

Trees in urban areas of the continental United States were estimated by Nowak and Crane (2001) to account for an average annual net sequestration of 59 Tg CO_2 Eq. (16 Tg C). This estimate is representative of the period from 1990 through 2000, as it is based on data collected during that decade. Annual estimates of CO_2 flux have not been developed (see Table 6-6).

Table 6-6: Net CO_2 Flux From Urban Trees (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	(58.7)
1995	(58.7)
1996	(58.7)
1997	(58.7)
1998	(58.7)
1999	(58.7)
2000	(58.7)

Note: Parentheses indicate net sequestration.

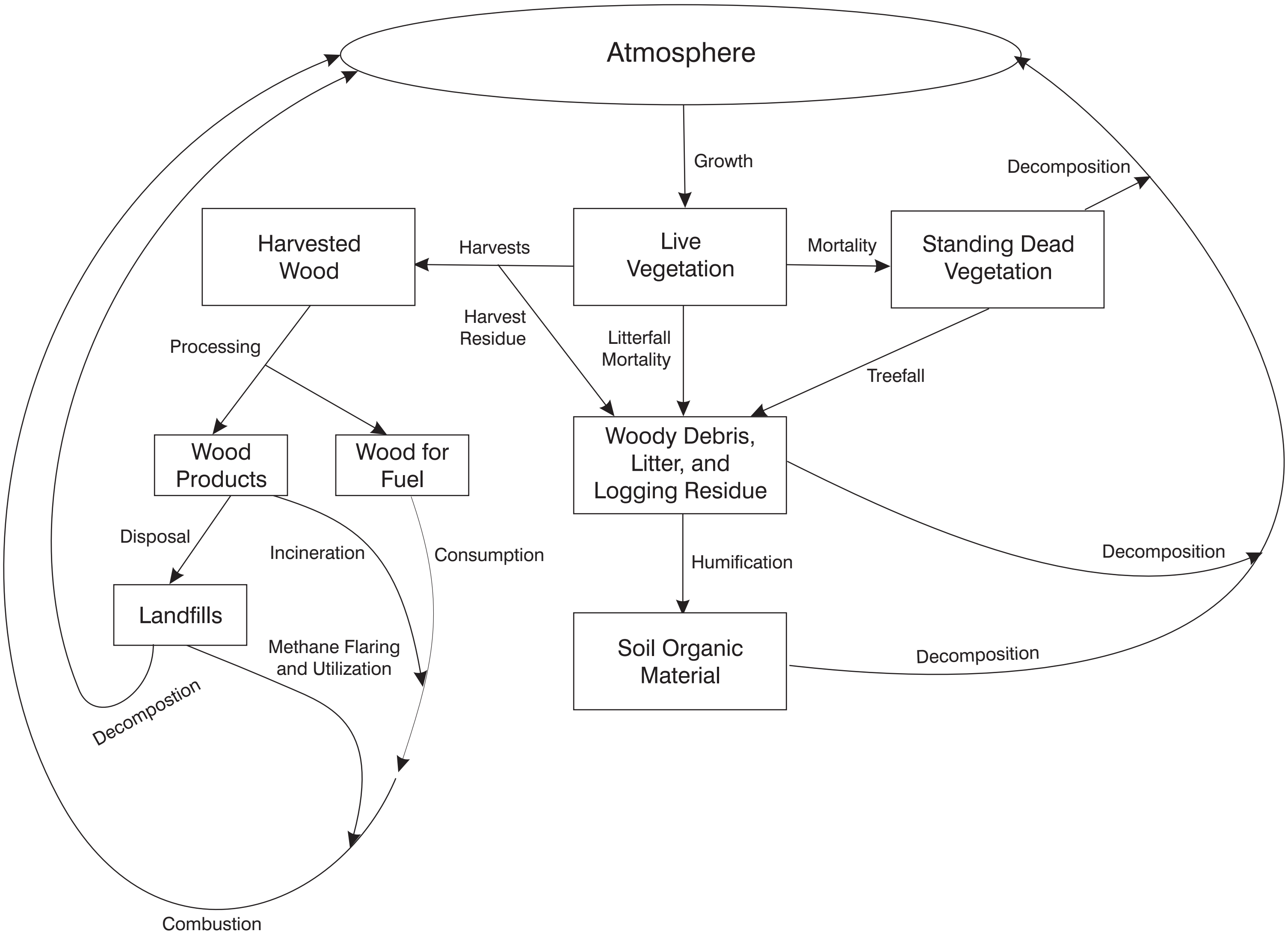
Methodology

The methodology used by Nowak and Crane (2001) 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).[6]

Nowak and Crane (2001) 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 1990 through 2000, 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

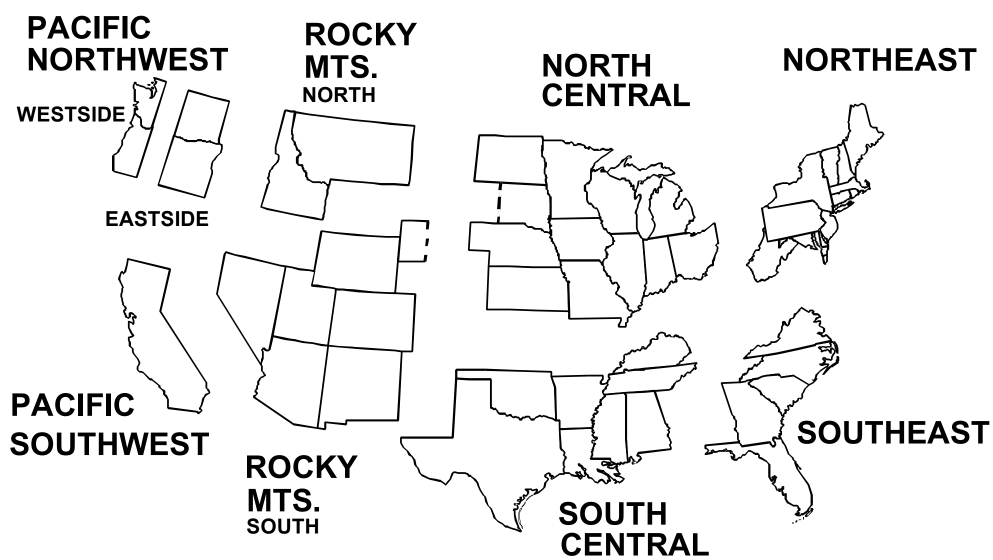
[6] It is more robust in that both growth and decomposition are accounted for, and data from individual trees are scaled up to state and then national estimates based on data on urban area and urban tree canopy cover.

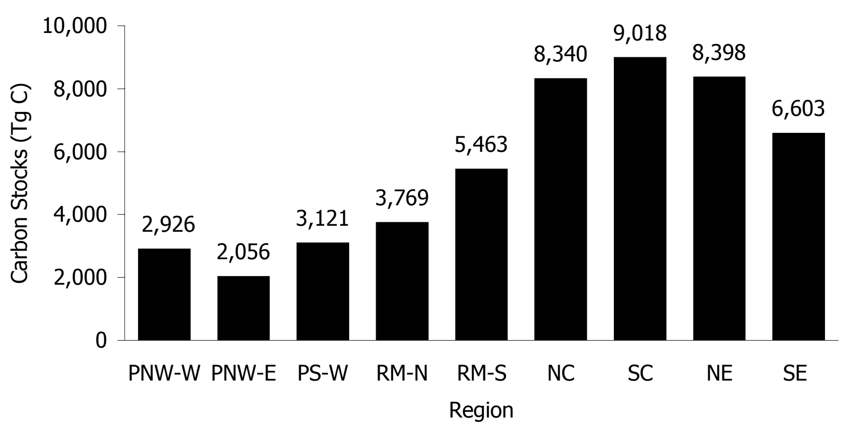
Figure 6-1: Forest Sector Carbon Pools & Flows



Source: Adapted from Birdsey and Lewis (2001)

Figure 6-2: Forest Carbon Stocks, 1997





ANNEX N

Methodology for Estimating Net Changes in Forest Carbon Stocks

This annex presents a discussion of the methodology used to calculate net changes in carbon stocks in trees, understory, forest floor, down dead wood, forest soils, and harvested wood (i.e., wood products and landfilled wood). More detailed discussions of selected topics may be found in the references cited in this annex.

The details of carbon conversion factors and step-by-step details of calculating net CO_2 flux for forests are given in three steps. In addition, the modeling projection system is briefly described.

Step 1: Estimate Forest Carbon Stocks and Net Changes in Forest Carbon Stocks

Step 1a: Obtain Forest Inventory Data

Forest survey data in the United States by broad forest type and region for 1987 and 1997 were obtained from U.S. Forest Service, Forest Inventory & Analysis (FIA) estimates of forest resources, published in Waddell et al. (1989) and Smith et al. (2001). The FIA data include: (1) growing stock volume per acre by forest type (referred to hereinafter as "growing stock volumes"); and (2) area by Timberland and other forest land, for general forest types by region (referred to hereinafter as "forest areas"). For 2001, the same variables were obtained from model results as described in Haynes et al. (2001b). (See The Forest Sector Modeling Projection System below). This information was combined with separate estimates of carbon density (carbon mass per unit area) to compile estimates of carbon stocks.

Step 1b: Estimate Carbon in Living and Standing Dead Trees

To estimate live tree biomass, equations that convert forest tree volumes to total live tree dry biomass (Smith et al. in review) were applied to the growing stock volumes by forest type and region (obtained in Step 1a). Tree biomass includes aboveground biomass and belowground biomass of coarse roots. The minimum size tree is one-inch diameter at diameter breast height (1.3 meter). Trees less than one-inch diameter are counted as carbon in understory vegetation. 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). Standing dead tree biomass was calculated by applying equations that estimate biomass for standing dead trees (Smith et al. in review) from growing stock volumes. Again, standing dead tree biomass was divided by two to estimate carbon in standing dead trees. Table N-1 lists the average living and standing dead tree carbon densities by forest type, as calculated by applying the equations to the 1997 data.

Table N-1: Average U.S. Carbon Densities of Forest Components* (metric tons C/ha)

Region[a]/Forest Type	Live and Standing Dead Tree Carbon	Forest Floor Carbon	Soil Organic Carbon[b]
Eastern			
White-red-jack pine	77.1	13.8	196.1
Spruce-fir	59.8	40.2	192.9
Longleaf-slash pine	42.4	9.2	136.3
Loblolly-shortleaf pine	49.3	9.1	91.7
Oak-pine	57.3	11.6	82.3
Oak-hickory	76.3	6.6	85.0
Oak-gum-cypress	86.0	6.0	152.2
Elm-ash-cottonwood	67.6	23.0	118.1
Maple-beech-birch	82.5	28.0	139.5
Aspen-birch	56.0	7.6	237.0
Other forest types	1.8	2.1	99.6
Nonstocked	3.7	3.5	99.6
Western			
Douglas-fir	110.8	30.7	89.6
Ponderosa pine	66.3	20.3	70.4
Western white pine	69.2	25.8	68.3
Fir-spruce	113.0	37.4	137.5
Hemlock-Sitka spruce	152.4	34.1	157.1
Larch	97.0	30.2	65.6
Lodgepole pine	67.8	23.9	62.7
Redwood	186.6	26.9	85.8
Hardwoods	89.0	9.9	79.5
Other forest types	55.4	28.2	90.1
Pinyon-juniper	20.8	21.1	56.3
Chaparral	17.5	25.7	58.7
Nonstocked	18.1	24.4	90.1

* Based on 1997 data for major forest types of the conterminous United States.

[a]Eastern United States is defined as states east of, and including North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. Western United States includes the remaining conterminous States.

[b]Soil includes both mineral soils and organic soils (i.e., histosols); carbon densities are to a depth of 1 meter.

Step 1c: Estimate Carbon in Understory Vegetation

To estimate carbon in understory vegetation, equations based on Birdsey (1992) were applied to the database that was used to produce the compiled forest statistics in Smith et al. (2001). Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch diameter, measured at breast height. A ratio of understory carbon to live tree carbon was calculated, and multiplied by 100 to display the percent that understory carbon is as related to live tree carbon. The average percent understory carbon to live tree carbon was calculated by region and forest type. This percent was multiplied by the live tree carbon data in 1987 and 1997 to calculate understory carbon. These percentages are given in Table N-2. This procedure was used instead of applying the Birdsey equations directly, because detailed databases are not available for inventory years prior to 1987. Using average estimates results in consistent historical carbon estimates for all survey years.

Table N-2: Ratios of Understory and Down Dead Wood Carbon to Live Tree Carbon* (percent)

Region/Forest Type	Ratio of Understory Carbon to Live Tree Carbon	Ratio of Down Dead Wood Carbon to Live Tree Carbon
Northeast		
White-red-jack pine	2.5	10.8
Spruce-fir	2.6	13.3
Longleaf-Slash pine	2.5	10.8
Loblolly-shortleaf pine	2.5	10.8
Oak-pine	2.8	12.9

Oak-hickory	2.4	10.9
Oak-gum-cypress	2.6	11.1
Elm-ash-cottonwood	2.6	11.1
Maple-beech-birch	1.9	11.1
Aspen-birch	2.7	13.6
Other Forest Types	8.9	3.8
Nonstocked	8.9	3.8
North Central		
White-red-jack pine	1.8	9.8
Spruce-fir	2.2	17.4
Longleaf-Slash pine	2.4	7.4
Loblolly-shortleaf pine	2.4	7.4
Oak-pine	1.9	7.2
Oak-hickory	2.3	9.6
Oak-gum-cypress	2.3	9.6
Elm-ash-cottonwood	2.2	10.8
Maple-beech-birch	2.2	10.8
Aspen-birch	2.8	13.3
Other Forest Types	5.5	4.1
Nonstocked	5.5	4.1
Southeast		
White-red-jack pine	6.8	23.9
Spruce-fir	6.8	23.9
Longleaf-Slash pine	6.8	23.9
Loblolly-shortleaf pine	6.8	23.9
Oak-pine	5.2	28.0
Oak-hickory	4.4	24.2
Oak-gum-cypress	2.2	21.8
Elm-ash-cottonwood	2.2	21.8
Maple-beech-birch	4.4	24.2
Aspen-birch	2.2	21.8
Other Forest Types	11.9	2.0
Nonstocked	11.9	2.0
South Central		
White-red-jack pine	5.9	18.6
Spruce-fir	5.9	18.6
Longleaf-Slash pine	5.9	18.6
Loblolly-shortleaf pine	5.9	18.6
Oak-pine	4.4	17.3
Oak-hickory	3.7	15.0
Oak-gum-cypress	2.2	15.7
Elm-ash-cottonwood	2.2	15.7
Maple-beech-birch	3.7	15.0
Aspen-birch	2.2	15.7
Other Forest Types	16.9	1.7
Nonstocked	16.9	1.7
Pacific Northwest Eastside of Cascades		
Douglas-fir	1.6	10.0
Ponderosa Pine	2.5	12.6
Western White Pine	1.6	10.0
Fir-Spruce	1.1	15.7
Hemlock-Sitka spruce	1.6	10.0
Larch	1.6	10.0
Lodgepole pine	2.6	21.3
Redwood	1.9	25.8
Other hardwoods	1.4	8.9
Unclassified & other	2.5	12.6
Pinyon-Juniper	10.7	3.7
Chaparral	9.7	2.1
Nonstocked	9.7	2.1
Pacific Northwest Westside of Cascades		
Douglas-fir	2.0	11.9

Ponderosa Pine	2.5	18.1
Western White Pine	2.5	18.1
Fir-Spruce	1.0	13.7
Hemlock-Sitka spruce	1.0	13.7
Larch	2.0	11.9
Lodgepole pine	1.7	16.4
Redwood	2.0	11.9
Other hardwoods	4.5	3.9
Unclassified & other	1.7	16.4
Pinyon-Juniper	20.2	3.7
Chaparral	14.2	3.0
Nonstocked	14.2	3.0
Rocky Mountain, Northern		
Douglas-fir	2.6	19.2
Ponderosa Pine	2.4	19.6
Western White Pine	2.2	9.7
Fir-Spruce	1.7	14.8
Hemlock-Sitka spruce	2.0	18.7
Larch	2.2	9.7
Lodgepole pine	2.4	19.6
Redwood	2.2	9.7
Other hardwoods	1.9	14.2
Unclassified & other	2.2	9.7
Pinyon-Juniper	16.1	3.2
Chaparral	16.1	3.2
Nonstocked	16.1	3.2
Rocky Mountain, Southern		
Douglas-fir	2.8	19.4
Ponderosa Pine	4.1	21.6
Western White Pine	2.8	19.4
Fir-Spruce	2.2	17.4
Hemlock-Sitka spruce	2.8	19.4
Larch	2.8	19.4
Lodgepole pine	3.1	12.8
Redwood	2.8	19.4
Other hardwoods	9.2	26.7
Unclassified & other	10.7	3.3
Pinyon-Juniper	9.8	3.9
Chaparral	9.8	3.9
Nonstocked	2.6	15.2
Pacific Southwest		
Douglas-fir	2.3	15.5
Ponderosa Pine	2.6	15.2
Western White Pine	2.2	11.5
Fir-Spruce	2.6	15.2
Hemlock-Sitka spruce	2.6	15.2
Larch	4.6	10.8
Lodgepole pine	2.6	15.2
Redwood	4.4	9.7
Other hardwoods	2.8	11.5
Unclassified & other	9.9	3.1
Pinyon-Juniper	15.3	3.5
Chaparral	15.3	3.5
Nonstocked	2.5	10.8

* Based on data from 1997. Regions are defined in Figure 6-2 of the Land-Use Change and Forestry Chapter.

Step 1d: Estimate Carbon in Forest Floor

To estimate forest floor carbon, the forest floor equations (Smith and Heath, in review) were applied to the dataset described in Step 1a. Forest floor carbon is the pool of organic carbon (litter, duff, humus, and small woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Table N-1 shows the average forest floor carbon densities by forest type, as calculated by applying the equations to the 1997 data.

Step 1e: Estimate Carbon in Down Dead Wood

To estimate carbon in down dead wood, a procedure similar to estimating carbon in understory vegetation was used. Down dead wood is defined as dead wood pieces not attached to trees, greater than 7.5 cm diameter, including stumps and roots of harvested trees. Down dead wood was estimated in the projections by using decay rates applied to logging residue, along with equations that estimate down dead wood not related to harvesting. The ratio of down dead wood carbon to live tree carbon was calculated, and multiplied by 100 to display the ratio as a percentage. The average percentage of down dead wood carbon as compared to live tree carbon was calculated by region and forest type. The percent was multiplied by the live tree carbon data based on the dataset described in step 1a to calculate down dead wood carbon. These percentages are given in Table N-2. This procedure was used because detailed databases are not available for older data. By using average estimates, carbon estimates from historical data are consistent with carbon estimates from current FIA data.

Step 1f: Estimate Forest Soil Carbon

To estimate forest soil carbon, soil carbon estimates for 1 meter depth were obtained from the STATSGO database (USDA 1991). A forest type coverage (Powell et al. 1993) was overlaid onto the soil carbon estimates derived from STATSGO. An average soil carbon estimate was then calculated by forest type. Soil organic carbon of both mineral soils and organic soils (histosol soil order, characterized as soils that develop in wetland areas, and have greater than 20 to 30 percent organic matter by weight, depending on clay content) was included. Coarse roots were included with tree carbon estimates rather than with soils. The soil carbon estimates are given in Table N-1. These estimates were multiplied by the area of forest land in each forest type for all years. Thus, any change in soil carbon is purely a reflection of the changing forest land base.

Step 1g: Calculate Net Carbon Stock Changes

The next step was to calculate the average annual net carbon stock change for each forest carbon pool for the years from 1990 through 2000. The net annual stock change for each pool for 1987 through 1997 was derived by subtracting the 1987 stock from the 1992 stock, and dividing by the number of years between estimates (10 years). The stocks, by definition, correspond to the stock as of January 1 of the given year. The net annual stock changes for 1997 through 2000 were derived in the same way using the 1997 and 2001 stocks.

Step 2: Estimate Harvested Wood Carbon Fluxes

The first step in estimating harvested wood (i.e., wood products and landfilled wood) carbon flux estimates was to compile historical data on: the production of lumber, plywood and veneer, pulp and other products; product and log imports and exports; and fuelwood (in terms of million cubic feet of roundwood equivalent beginning in the year 1900, as described in Skog and Nicholson 1998). Data were obtained from USDA (1964), Ulrich (1989), and Howard (2001). Projected products and roundwood use were obtained from the models used for the USDA Forest Service 2000 Resource Planning Act Assessment (Haynes et al. 2001b, Ince 1994). Roundwood products include logs, bolts, and other round timber generated from harvesting trees for industrial or consumer use. The harvested wood-to-carbon conversion factors (as listed in Skog and Nicholson 1998) were applied to annual estimates and projections to produce an estimate for carbon in roundwood in products. Roundwood consumed was categorized according to product, such as lumber, railroad ties, and paper, because the time carbon remains in those products differs substantially. The dynamics of carbon loss through decay or through disposal of the product is summarized as the half-life of each product (Skog and Nicholson 1998). The resulting estimates can be applied to products to derive the net carbon change in wood products and landfills. Note that, unlike forest carbon stock estimates, carbon in harvested wood products estimates are derived as a carbon stock change. In other words, the annual roundwood production is a change variable already before it is converted to carbon.

Step 3: Sum the Results from Step 1 and Step 2 for the Total Net Flux from U.S. Forests

In the final step, net changes in forest carbon stocks are added to net changes in harvested wood carbon stocks, to obtain estimates of total net forest flux (see Table N-3).

Table N-3: Net CO_2 Flux from U.S. Forest Carbon Stocks (Tg CO_2 Eq.)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Forests	**(773.7)**	**(773.7)**	**(773.7)**	**(773.7)**	**(773.7)**	**(773.7)**	**(773.7)**	**(546.3)**	**(546.3)**	**(546.3)**	**(546.3)**
Trees	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(469.3)	(447.3)	(447.3)	(447.3)	(447.3)
Understory	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(11.0)	(14.7)	(14.7)	(14.7)	(14.7)
Forest Floor	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	(25.7)	29.3	29.3	29.3	29.3
Down Dead Wood	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)	(58.7)	(58.7)	(58.7)	(58.7)
Forest Soils	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(212.7)	(55.0)	(55.0)	(55.0)	(55.0)
Harvested Wood	**(209.0)**	**(198.0)**	**(202.8)**	**(203.9)**	**(210.5)**	**(205.3)**	**(205.3)**	**(212.7)**	**(205.3)**	**(216.3)**	**(223.7)**
Wood Products	(47.7)	(40.7)	(46.6)	(54.6)	(60.9)	(55.0)	(55.0)	(58.7)	(51.3)	(62.3)	(66.0)
Landfilled Wood	(161.3)	(157.3)	(156.2)	(149.2)	(149.6)	(150.3)	(150.3)	(154.0)	(154.0)	(154.0)	(157.7)
Total	**(982.7)**	**(971.7)**	**(976.4)**	**(977.5)**	**(984.1)**	**(979.0)**	**(979.0)**	**(759.0)**	**(751.7)**	**(762.7)**	**(770.0)**

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total net flux) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. 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.

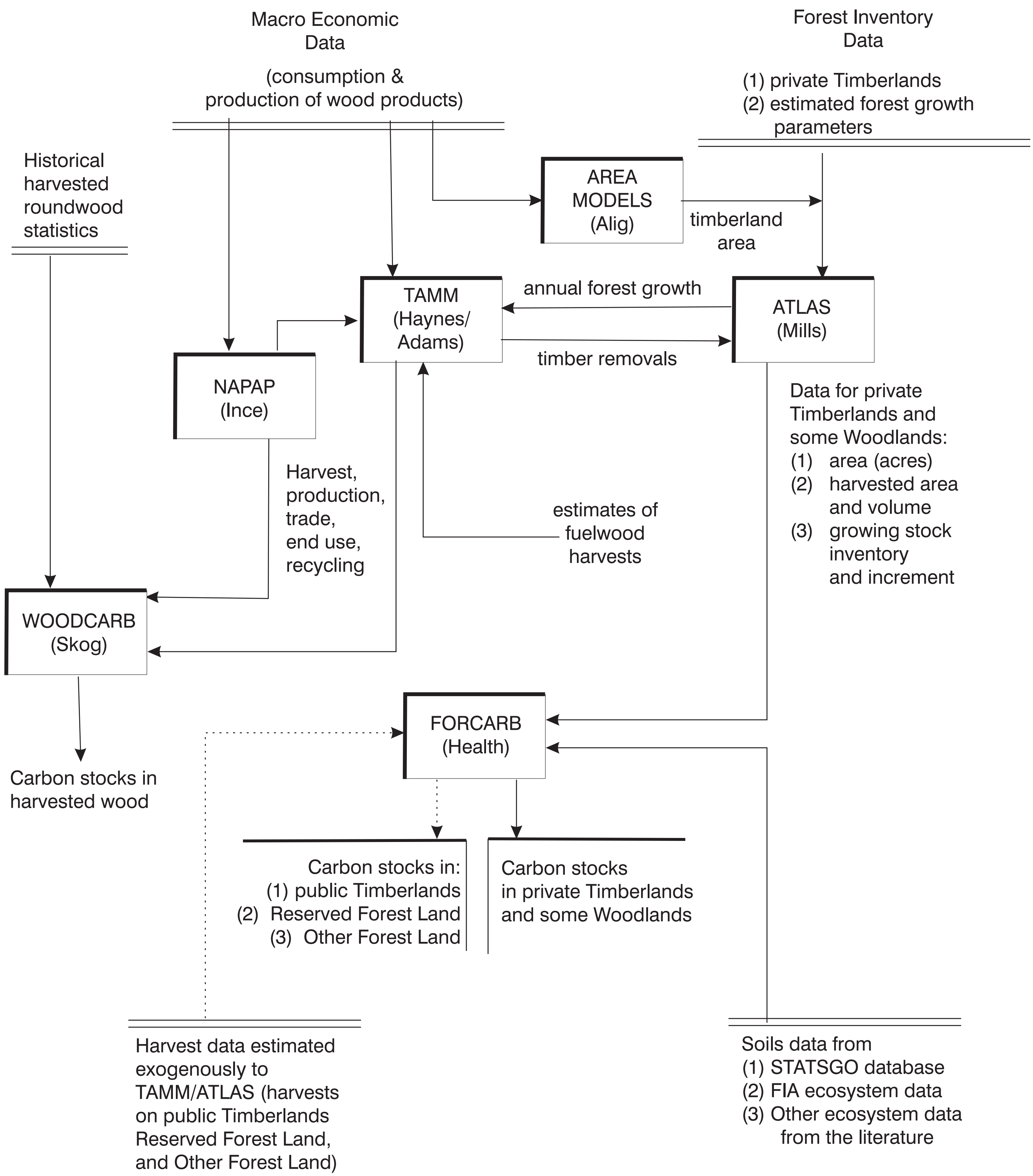
The Forest Sector Modeling Projection System

The modeling projection system is a set of models that has been used for the USDA Forest Service, Resource Planning Act Assessment since the late 1980's (see Figure N-1). The models include 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 model (ATLAS; Mills and Kincaid 1992). Many of these models are econometric models, designed to project the demand and supply and prices in the forest sector. Results of the projection include timber volume, forest areas, harvests, and primary product production. To see all the assumptions and results of the modeling system for 2001, see Haynes et al. (2001b).

The FORCARB model (Plantinga and Birdsey 1993, Heath and Birdsey 1993, and Heath et al. 1996) uses data on timber volume, forest areas, and harvests from the modeling system to estimate carbon in trees using biometrical relationships between carbon and live tree volume. FORCARB estimates carbon in all other forest ecosystem components, producing carbon density estimates similar to those in Table N-1 and Table N-2. The model WOODCARB (Skog and Nicholson 1998) uses harvested roundwood product statistics, along with end-use, decay rate, and duration information to estimate carbon in harvested wood.

This figure illustrates the models, data inputs, and data outputs that compose the forest sector modeling projection system. Names of model authors are in parentheses in each model box to facilitate identification of model citations. Data that are external to the models are marked with double lines.

Figure N-1: Forest Sector Modeling Projection System



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