The Potential of U.S. FOREST SOILS to Sequester Carbon and Mitigate the Greenhouse Effect

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CHAPTER 3

Carbon Trends in U.S. Forestlands: A Context for the Role of Soils in Forest Carbon Sequestration

Linda S. Heath, James E. Smith, and Richard A. Birdsey

CONTENTS

INTRODUCTION

Forestlands are unlike croplands and grazing lands, in that a large amount of carbon can be sequestered for long periods of time above ground by trees and below ground in coarse roots. Carbon in trees can also be harvested, and some of the harvested carbon can be stored for long periods of time as wood products or as waste wood or paper in landfills. As in croplands and grazing lands, most of the carbon in forests is usually in the soil, with some forest types having a greater percentage in the soil than other types. The density (metric ton per hectare — t/ha) of carbon stock in mature forests is usually greater than the carbon density of cropland or grazing land would be if it occupied the same site. Cultivating land for crops in the long-term, all other things being equal, usually means emitting carbon from the soil in the form of a greenhouse gas; growing forests on cropland usually means sequestering carbon aboveground and perhaps in the soil, and an increase in carbon density. Thus, forests have the potential to increase carbon in soils for a very long time, because of the long residence time of carbon in soils, and they may be the best available option for storing carbon in terrestrial ecosystems (US DOE, 1999). In addition, aboveground components and other nonsoil belowground components of the forest have the potential to sequester a substantial amount of carbon.

The purpose of this chapter is to discuss forest carbon budgets of U.S. forests, to provide the context in which to compare the soil carbon component of forests with other components of the

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forest ecosystem, such as trees. We present historical and current estimates of forest carbon and carbon in harvested wood, summarized by attributes such as region, forest type, and owner. Finally, we discuss uncertainties and needs for future research for national-level estimates. Although we include soil carbon estimates, our focus is on all forest carbon to highlight the importance of forest soils. For specific broad estimates of forest soil carbon, see Johnson and Kerns (2002).

METHODS

Fundamentally, one can estimate the amount of carbon in forests by multiplying the forestland area (for example, hectares) by the carbon density (t C/ha). To provide separate estimates for components of the forest (such as soil, forest floor, and trees), carbon densities must be known for each component. A total amount of carbon may be referred to as a reservoir, pool, stock, or inventory. If a second survey is conducted at a later time, then a change in the carbon inventories can be calculated as the difference between inventories, divided by length of time between inventories, with the resulting change reported in units of C per year. Some methods, such as eddy-covariance techniques (Barford et al., 2001), measure this change, also referred to as carbon flux, directly. In the estimates provided in this chapter, the flux is the exchange of carbon between forests and the atmosphere over a specified period of time, usually one year. A positive flux means net carbon is being sequestered from the atmosphere into forests; a negative means net carbon is being emitted from forests.

We are interested in providing estimates for forest components that account for all carbon stored in forest ecosystems. We partition the forest into the components: aboveground live trees, belowground live trees, aboveground standing dead trees, down deadwood (including stumps), belowground deadwood (i.e., dead roots), understory vegetation, forest floor, and soil. Figure 3.1 illustrates the major carbon pools and associated flows. Figure 3.1 also illustrates another important aspect of forests in the United States: summary pools for the fate of carbon of harvested wood.

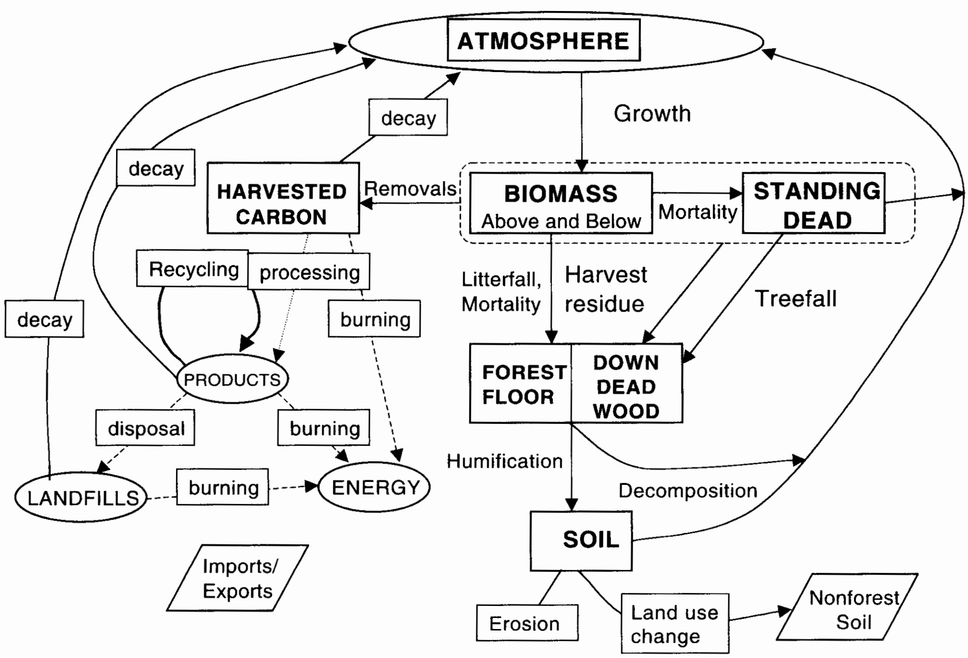

Figure 3.1 Diagram of stocks and flows of carbon in the forest sector.

The categories of harvested wood products commonly shown as summaries (Heath et al., 1996) for carbon purposes are:

1. Carbon in wood products in use
2. Carbon in landfills
3. Emissions from wood burned to produce energy
4. Emissions from wood either decaying or burned without producing energy

Wood can be burned for energy directly in the mill or used as fuelwood, or it can be converted into biofuels, which are then used for energy. Emissions from wood burned for energy are shown as a pool to account for the amount of fossil fuel offset by the use of wood. Biofuels currently play a small role in energy production from wood and account for only a small proportion of the total wood burned for energy. Furthermore, in many states of the United States, trees grown for biofuel are considered an agricultural crop, not forest. Imports and exports of harvested wood are shown as a disconnected box to emphasize that these pools should be accounted for. However, the debate continues as to how the accounting of these forest carbon pools should be recorded, and to which nations these pools should be attributed. The nonforest soil, also not connected to this system, indicates that carbon may transfer from the forest without entering the atmosphere or leaving the site; erosion is another process in which carbon leaves the site without necessarily being emitted to the atmosphere.

We use an inventory and modeling approach to estimate the forest ecosystem pools of carbon. Others have also used this approach for U.S. forests (Plantinga and Birdsey, 1993; Heath and Birdsey, 1993; Birdsey and Heath, 1995; Turner et al., 1995; and Houghton et al., 1999). Since the early 1950s, forests in the United States have been surveyed periodically state-by-state: States in the Southern region, where change occurs quickly, were surveyed every 5 to 7 years, while states in other regions were surveyed every 10 to 14 years. The survey is currently being updated to an annualized inventory (Gillespie, 1999), with a sample being conducted each year in a portion of every state. In addition, other attributes such as soil carbon and forest floor carbon will be sampled in the new inventory design. However, the data used here are from the periodic surveys. The surveys were designed for estimates of forest area and merchantable timber volume. For carbon estimates, tree volume can be converted to carbon with basic models or conversion factors. Carbon in other forest components can be estimated similarly based on forest attributes.

For estimates of carbon in harvested wood products, we adopt the estimates from Skog and Nicholson (1998). All wood harvested and removed from the site for processing is counted in one of these four categories, thus the sum of the four categories is equal to the amount of total carbon harvested. Any wood left on the site following harvest, such as logging residue, is counted as mass of deadwood in the forest ecosystem. Using historical data for the USDA Forest Service on wood harvest and end use starting in 1909, the flow of carbon was counted in primary products such as lumber, railway ties, paper and paperboard, through to end-use categories such as housing and office paper. Losses during processing were counted, as well as lifetime of the product and transfers from one category to another. Some end uses of wood are quite durable, such as single-family homes (those built after 1980), assumed to have a half-life of 100 years. Because of the relative size of the harvest in U.S. forests and the possible longevity of carbon in products and landfills, carbon in harvested wood products is an important aspect of carbon sequestration in forests.

Forest Inventory Databases

The forest inventory data are available for the last half of the 20th century at two different levels of detail: plot-level data, and aggregated across the landscape. The data were compiled for the years 1953, 1963, 1977, 1987, 1992, and 1997. The USDA Forest Service has a detailed plot-level database for the forest inventory data compiled for the years 1987, 1992, and 1997. For the other years, only forest statistics aggregated across the landscape are available (Smith et al., 2001). The inventories were conducted more intensively on certain broad classifications of forestland than on others and more intensively later in the time period. We refer to three forestland classes: timberland, other forest, and reserved. Reserved forestland is forest withdrawn from timber utilization by statute, administrative regulation, or designation. (For example, wilderness areas in U.S. national forests are reserved areas.) In the past, reserved forestland may have been surveyed only in terms of area. A second type of forestland is timberland, which is defined as nonreserved land capable of producing in excess of 20 cubic feet per acre per year of industrial wood products. Timberland comprises about 67% of U.S. forestland and has been consistently surveyed over the period. The third category, other forestland, refers to lands of low productivity and, like reserved lands, may have been surveyed only in terms of area. For more details about these and other forest survey definitions, see Smith et al. (2001).

Estimating Carbon from Forest and Soils Inventory Data — Equations and Assumptions

To estimate historical tree carbon mass, we used (1) generalized tree biomass equations (Jenkins et al., in press); (2) tables of volume distributed among diameter classes and forest areas (Smith et al., 2001); (3) relative effects of ownership and forest type on carbon content from the databases associated with the 1987 and 1997 U.S. forest statistics (Waddell et al., 1989; Smith et al., 2001); and (4) the equations of Smith et al. (in press) to estimate standing dead tree C associated with the detailed 1987 and 1997 data. The forest statistics discuss growing stock and nongrowing stock. Growing-stock volume is the volume of live trees, 5.0-in. diameter breast height (dbh) and larger, of commercial species meeting certain standards of quality. Carbon mass density of forest growing stock was estimated from average tree volumes, diameter distributions, and biomass equations. Carbon was estimated as 50% of biomass. Additional carbon mass in nongrowing stock and standing dead trees was estimated from similar relationships found in carbon estimates based on the detailed 1987 and 1997 databases. For example, carbon density of forest growing stock was increased according to the ratios of nongrowing-stock carbon to growing-stock carbon calculated for 1987; these ratios were specific to region, ownership, and forest type. Similar adjustments were made for carbon in standing dead trees and for carbon on nontimberlands relative to timberlands.

Carbon pools of down deadwood, above- and belowground, and understory vegetation were based on relationships obtained from simulated growth, management, and harvest of forests according to region, forest type, and ownership. Carbon in down deadwood — larger than 7.5-cm diameter — was simulated in two parts. First, logging residue was calculated as the difference in forest carbon density before harvest and the total amount of carbon removed from harvested areas; this removed carbon includes merchantable volume and other removals. Second, additional downed deadwood accumulation is based on influences of simulated mortality and amount of standing dead trees. Simulations include decay of woody residue (Turner et al., 1995). The estimates for woody residue presented here were from long-term simulated average ratios of woody-residue to live-tree carbon. Carbon in understory vegetation is based on Birdsey (1992).

For the purposes of this chapter, organic carbon mass in the top 100 cm of the soil were derived from the STATSGO (Soil Conservation Service, 1991) database using the methods outlined by Bliss et al. (1995). A digital forest-type coverage of the United States (Powell et al., 1993) was overlaid on the STATSGO coverage, and an average soil carbon estimate was assigned to each forest type (Iverson, 1997). We included carbon from Histosols because forests can contain small areas (less than 0.4 ha) of wetland-type areas and still be counted as forest. However, we are probably including some areas of nonforest within the forest-type map, and a more precise forest-type coverage would probably result in a smaller amount of organic carbon from Histosols. Carbon densities determined for the 1987 database were applied to earlier inventories after adjusting for relative proportion of each forest type within a region. Thus, our estimates of soil C are based on the assumption that harvesting had no effect on soil carbon unless the forest type of the regenerated stand was different from the harvested stand, and we assumed no direct past land-use effects except those captured in the data underlying STATSGO.

Forest-floor carbon is the pool of organic carbon above the mineral soil and includes woody fragments up to 7.5-cm diameter (Smith and Heath, in press). Estimates of forest-floor carbon were based on equations in Smith and Heath (in press), which predicted forest-floor carbon according to region, forest type, and age. The equations could be directly applied to the 1987 and 1997 forest inventory datasets because the datasets included the age of most forests. Because available inventory data for years prior to 1987 did not include age, carbon densities (t/ha) estimated using the 1987 data were applied to areas by region and forest type for 1953 through 1977.

RESULTS AND DISCUSSION

Forests of the conterminous United States contained 50,830 Mt of C on 250 million hectares (Mha) in 1997 (Table 3.1). Because there is little new Forest Inventory and Analysis (FIA) inventory data for the forests of Alaska and Hawaii, we included carbon estimates for these states from Birdsey (1992) to provide an estimate for all forests of the United States. Thus, we estimate carbon in all U.S. forests in approximately 1997 to be 71,034 Mt of C on 303 Mha. This is greater than previously reported estimates for a number of reasons: We are using new inventory data, which estimate that forests contain more volume than before, which means more carbon; we included organic soils (the soil order Histosol, not to be confused with the O horizon or forest floor, which is included in the dead-mass category in this study); we include additional deadwood components; and our biomass equations tend to estimate greater biomass, and therefore greater carbon, than previous work. Approximately 88% of the C inventory in the conterminous United States is on timberland, which has been more thoroughly inventoried. About 63% of the carbon in forests is on privately owned lands. Our estimates indicate that 51% of the carbon in forests is in the soil, with about 15% in dead mass. This is somewhat lower than the estimate of 58% from Birdsey (1992).

Table 3.1 Forest Ecosystem Carbon by Broad Forestland Classification, Owner, Component, and Forest Area in the Conterminous United States, 1997, and Alaska and Hawaii, 1987

Forestland Classification	Owner Group	C in Biomass (Mt)	C in Dead Mass[a] (Mt)	Soil Organic C (1-m depth)[b] (Mt)	Total Forest C (Mt)	Forest Area (thousand ha)
Timberland	private	9663	4454	15,888	30,005	143,080
	public	4616	2267	6112	12,996	55,453
	all	14,279	6721	22,000	43,001	198,533
Reserved	private	4	10	35	49	309
	public	1100	585	1776	3462	16,628
	all	1104	595	1811	3511	16,937
Other woodland	private	436	312	1186	1934	15,841
	public	645	473	1266	2384	18,724
	all	1081	785	2452	4318	34,565
48-state total		16,465	8102	26,262	50,830	250,036
1987 Alaska forest		2287	1386	10,068	13,741	52,223
1987 Hawaii forest		6395	8	60	6463	707
Total		25,147	9496	36,390	71,034	302,966

[a] Dead mass includes standing dead trees, down dead trees, and forest floor.
[b] Soil includes both mineral soil and organic soils (i.e., Histosols).
Source: Birdsey, R.A., Gen. Tech. Rep. WO-59, USDA Forest Service, Washington, D.C., 1992.

Table 3.2 Carbon Densities (t/ha) and Forest Area (thousand ha) for Major Forest Types of the Eastern United States, 1997, on Timberland Only

Forest Type	C in Biomass (t/ha)	C in Dead Mass[a] (t/ha)	Soil Organic C (1-m depth)[b] (t/ha)	Total Forest C (t/ha)	Forest Area (thousand ha)
White-red-jack pine	72.7	26.0	196.1	294.8	4795
Spruce-fir	52.9	53.9	192.9	299.8	7079
Longleaf-slash pine	43.6	19.1	136.3	199.0	5351
Loblolly-shortleaf pine	50.4	21.3	91.7	163.4	21,293
Oak-pine	56.9	26.5	82.3	165.7	13,766
Oak-hickory	73.1	22.6	85.0	180.6	52,972
Oak-gum-cypress	81.1	26.5	152.2	259.7	12,256
Elm-ash-cottonwood	61.5	37.9	118.1	217.6	5498
Maple-beech-birch	77.6	43.3	139.5	260.4	22,694
Aspen-birch	51.3	21.1	237.0	309.3	7278
Other forest types	1.8	2.9	99.6	104.4	1953
Nonstocked	3.1	5.1	99.6	107.9	2074
All eastern types	64.7	27.4	117.4	209.5	157,008

[a] Dead mass includes standing dead trees, down dead trees, and forest floor.
[b] Soil includes both mineral soil and organic soils (i.e., Histosols).

The carbon densities of forest components for major forest types on timberland in the eastern and western United States (excluding Alaska and Hawaii) are given in Tables 3.2 and 3.3, respectively, for the year 1997. Eastern timberland refers to the area east of and including the states of North and South Dakota, Nebraska, to Oklahoma and eastern Texas. The West includes the remaining conterminous states. Note that carbon in dead mass includes above- and belowground portions of standing dead trees, down deadwood including logging residue, and the forest floor. These estimates are means over stands of all ages and stocking levels; they also account for saplings and noncommercial species. The nonstocked type refers to areas of young forest that do not yet contain enough trees to assign a species-related forest type. Thus, there is a high percentage of soil carbon in relation to forest carbon because there is little vegetation on these areas. Over 60% of the land area of the 12 eastern types is found in three of the types: oak-hickory, maple-beech-birch, and

Table 3.3 Carbon Densities (t/ha) and Forest Area (thousand ha) for Major Forest Types of the Conterminous Western United States, 1997, on Timberland Only

Forest Type	C in Biomass (t/ha)	C in Dead Mass[a] (t/ha)	Soil Organic C (1-m depth)[b] (t/ha)	Total Forest C (t/ha)	Forest Area (thousand ha)
Douglas-fir	101.5	54.7	89.6	245.9	16,947
Ponderosa pine	62.6	37.3	70.4	170.3	13,534
Western white pine	173.0	46.6	68.3	287.9	239
Fir-spruce	94.1	64.9	137.5	296.5	11,845
Hemlock-Sitka spruce	123.4	73.1	157.1	353.6	3586
Larch	86.9	52.1	65.6	204.6	516
Lodgepole pine	52.8	39.9	62.7	155.3	7043
Redwood	150.6	77.8	85.8	314.2	371
Hardwoods	69.4	20.9	79.5	169.9	11,410
Other forest types	74.1	39.1	90.1	203.3	4544
Pinyon-juniper	24.5	24.0	56.3	104.8	19,999
Chaparral	17.5	29.3	58.7	105.6	2099
Nonstocked	11.4	32.7	90.1	134.1	895
All western types	67.8	40.8	84.2	192.8	93,028
All major U.S. types	65.9	32.4	105.0	203.3	250,036

[a] Dead mass includes standing dead trees, down dead trees, and forest floor.
[b] Soil includes both mineral soil and organic soils (i.e., Histosols).

loblolly-shortleaf pine. In fact, oak-hickory alone makes up 20% of the land area of U.S. timberland. Oak-hickory features the lowest percentage of soil carbon to forest ecosystem carbon, with aspen-birch having the highest percentage. In the West, about 55% of the timberland area is pinyon-juniper, Douglas-fir, and ponderosa pine. The soil carbon densities tend to be lower in the West than in the East; this is especially true because the Histosol soil order has been included. Overall, there is about twice the carbon in timberlands of the eastern United States than on western timberlands. Eastern timberland forest types have a lower percentage of carbon in dead mass, and a slightly lower percentage in live vegetation compared with western types; eastern types tend to have a higher percentage of carbon in soil.

Historic and current forest carbon inventory and net carbon flux for all forestlands of the conterminous United States are given in Table 3.4 every decade from 1953 to 1997. The regions are similar to those in Chapter 2, except Great Plains is included in the North Central region. As in previous studies, overall forest carbon increases over the period on average 155 Mt/year, not including carbon removed in harvested wood, while the land base decreases overall by 65,000 ha/year. In other words, wood harvested from the forest is not counted as being sequestered. This is a net change between inventories, not a gross increase calculated before the wood was harvested. The Northeast and North Central regions sequestered the most carbon over the period at an average annual estimate of 47 and 39 Mt/year sequestered, respectively. According to the data, the Pacific Coast region emitted an annual average of 3 Mt/year, although this may be due to changing the status of timberland to reserved forest. These rankings would change if net carbon flux in harvested wood were included by region.

With the approach we are using for this study, soil carbon changes only if the area of forestland changes during the period, or if the forest type changes. No changes are assumed due to land-use change from prior periods or due to harvesting, unless harvesting causes a change in forest type. Thus decreases in soil carbon are due to either a decrease in area of forestland or to a change in forest-type area from a forest type of high soil carbon density to a forest type of lower soil carbon density. We do this to simplify the analysis; there is evidence that soil carbon density changes over time, particularly following land-use change (see Chapter 12). The results illustrate the difficulty of forest carbon accounting. In regions with increasing area of forestland, the annual dead flux is positive before land is transferring into the forest sector, and therefore the soil carbon inventory increases. The reverse is true where forest area is declining, for instance, between the years 1962 and 1977 for the entire United States, when the annual dead flux shows emissions of 29 Mt/year. The Northeast region shows decreasing soil carbon in the last period, even with an increase in forested area, because forest types have changed, with more area allotted to forest types with lower soil carbon density. This results in the annual dead flux shifting quickly between positive and negative flux. This shift may have more to do with transfers of carbon between soil carbon in forests and soil carbon in croplands than with the change in emissions or sequestration between forests and the atmosphere. Thus, one must carefully interpret the flux estimates in Table 3.4. In a previous study using an inventory approach to forest carbon inventories, Turner et al. (1995) held their soil carbon densities constant by forest type, like we have here, and implied there was no soil carbon change over the period of the 1990s. However, the amount of forestland changed over the period, as did the areas of various forest types. Thus, the total inventory should have changed, along with flux estimates.

If past land-use changes were taken into account in our estimates, we would usually expect an increase in carbon densities for cropland that is regenerated to forest, and therefore carbon sequestration in soils. Even very small increases in soil carbon sequestration may be noticeable at a large scale. There are 303 Mha of forest in the United States. Increasing soil carbon densities by just 10 g/ha would sequester 3 Mt of carbon.

In addition to the amount of carbon storage in forest ecosystems, some of the carbon in harvested wood continues to be stored in products in use and in landfills. Figure 3.2 shows the pattern of carbon flux over select years in the time period 1950 to 1990 (Skog and Nicholson, 1998). At the

Table 3.4 Summary of Historical and Current Estimates of Carbon Storage (Mt) and Flux (Mt/year) by Geographic Region and Ecosystem Component, Conterminous U.S. Forestland, 1953–1997

Region	C pool (Mt) or C flux (Mt/yr)	Year 1953	1963	1977	1987	1997
Northeast	Soil	4289	4509	4685	4675	4637
	Forest floor	611	637	710	705	688
	Dead wood	268	324	423	479	527
	Understory	32	39	50	56	62
	Live trees	1392	1690	2203	2515	2784
	Total Storage	6592	7199	8071	8428	8697
	Annual Dead Flux		30	25	4	–1
	Annual Live Flux		30	37	32	28
	Total Flux		61	62	36	27
	Area (Thou. ha)	30,984	33,019	34,119	34,513	34,595
North Central	Soil	5091	5177	5050	5025	5173
	Forest floor	560	588	592	601	661
	Dead wood	220	279	350	417	492
	Understory	29	37	40	47	55
	Live trees	1021	1295	1612	1926	2274
	Total Storage	6920	7375	7644	8016	8654
	Annual Dead Flux		17	–4	5	28
	Annual Live Flux		28	23	32	36
	Total Flux		45	19	37	64
	Area (Thou. ha)	36,204	35,995	34,145	34,176	36,276
Southeast	Soil	4173	4220	3809	3767	3740
	Forest floor	283	289	285	277	284
	Dead wood	340	386	493	534	550
	Understory	68	75	90	95	94
	Live trees	1359	1541	1967	2144	2200
	Total Storage	6224	6509	6645	6818	6868
	Annual Dead Flux		10	–22	–1	0
	Annual Live Flux		19	32	18	5
	Total Flux		29	10	17	5
	Area (Thou. ha)	37,621	38,340	36,610	35,837	35,881
South Central	Soil	5378	5391	4974	4824	4951
	Forest floor	369	371	350	340	348
	Dead wood	532	631	793	874	954
	Understory	82	95	115	126	140
	Live trees	1678	1981	2473	2730	2981
	Total Storage	8039	8469	8706	8894	9375
	Annual Dead Flux		11	–20	–8	22
	Annual Live Flux		32	37	27	26
	Total Flux		43	17	19	48
	Area (Thou. ha)	53,850	54,100	51,225	49,611	50,764
Rocky Mountain	Soil	4136	4189	4173	4300	4481
	Forest floor	1346	1346	1332	1366	1409
	Dead wood	555	593	637	676	725
	Understory	105	109	126	132	131
	Live trees	2446	2605	2888	3051	3173
	Total Storage	8588	8843	9156	9526	9918
	Annual Dead Flux		9	1	20	27
	Annual Live Flux		16	21	17	12
	Total Flux		25	22	37	39
	Area (Thou. ha)	55,179	54,863	54,099	54,797	56,028
Pacific Coast	Soil	3310	3332	3315	3184	3324
	Forest floor	955	939	892	864	891
	Dead wood	823	806	732	753	771
	Understory	97	95	83	80	78
	Live trees	3702	3660	3506	3663	3670
	Total Storage	8886	8832	8528	8545	8733

Table 3.4 Summary of Historical and Current Estimates of Carbon Storage (Mt) and Flux (Mt/year) by Geographic Region and Ecosystem Component, Conterminous U.S. Forestland, 1953–1997 *(Continued)*

Region	C pool (Mt) or C flux (Mt/yr)	Year 1953	1963	1977	1987	1997
	Annual Dead Flux		–1	–10	–14	18
	Annual Live Flux		–4	–12	15	0
	Total Flux		–5	–22	2	19
	Area (Thou. ha)	39,121	38,984	37,694	36,695	36,486
Lower 48 States	Soil	26,377	26,817	26,006	25,775	26,306
	Forest floor	4124	4169	4161	4153	4281
	Dead wood	2739	3019	3428	3734	4018
	Understory	413	449	505	536	559
	Live trees	11,598	12,773	14,650	16,030	17,081
	Total Storage	45,250	47,227	48,750	50,228	52,245
	Annual Dead Flux		77	–29	7	94
	Annual Live Flux		121	138	141	107
	Total Flux		198	109	148	202
	Area (Thou. ha)	252,958	255,300	247,892	245,629	250,030

time of this work, the years after 1986 were based not on actual data but on projections of harvests. Removals in the first two decades totaled approximately 80 Mt/year, increasing to 90 Mt/year by 1970 and to 107 Mt/year by 1980. Recent inventory data indicate that the 145 Mt/year projected for 1990 would be closer to the 1980 estimate of 107 Mt/year. These numbers are net flux; emissions of carbon in wood harvested in years prior to these, and now decaying, have already been included in the calculation. Note that these are not a stock of carbon, but a flux. The estimates represent the change between inventories of carbon in harvested wood. In the later two decades, waste-management practices led to a threefold increase of carbon sequestration in landfills. These are expected to be long-term sequestrations. The relative amount of wood burned for energy increases in relation to emissions as companies actively look to save money by burning waste wood for energy and end up substituting fossil-fuel-based carbon with burning wood. The additional carbon sequestered by products in use and in landfills is about 20 Mt/year in the first three decades, rising to almost 40 Mt/year in the 1980s. For accounting purposes, these estimates can be added directly to the forest ecosystem carbon flux in Table 3.4.

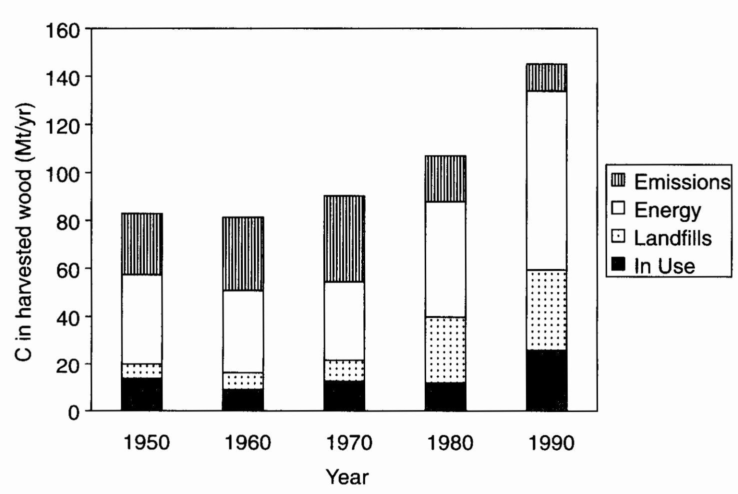

Figure 3.2 Carbon flux (Mt/year) in harvested wood products by disposition category. Note that all pools are listed as positive flux. This enables the height of the bar to equal the total removal of wood from the forest. However, emissions are negative.

The estimates in this chapter differ from those of Birdsey and Heath (1995). In this study, we use new conversion factors for forest carbon. The factors now explicitly separate live tree biomass and standing dead and down dead mass, along with more information about aboveground and belowground carbon. The tree biomass equations are specific to groups of species, and carbon density predictors were developed with the Eastwide (Hanson et al., 1992) and Westwide (Woudenberg and Farrenkopf, 1995) forest inventory databases. Thus, the new predictors reflect the current size and distribution of species in U.S. forests, while soil carbon estimates are now based on STATSGO. In addition, new forest inventory data are available for 1997.

The numbers presented in our tables are estimates, and there is some uncertainty about these estimates. Although we did not conduct an uncertainty analysis in this study, we have previously conducted an uncertainty analysis (Heath and Smith, 2000) on an older version of a similar forest carbon simulation model. Uncertainty in estimated carbon flux is greater than uncertainty in total carbon inventory, as is expected where net flux is the difference between two sampled inventories. The uncertainty analysis placed 80% of the repeatedly simulated estimates within 5% of the average total carbon inventory. The analogous uncertainty for net flux was just over 15%. (For more information about the interpretation of these uncertainty estimates, see Smith and Heath [2000].) In both cases, uncertainty in soil carbon had the greatest influence in overall uncertainty (Smith and Heath, 2001). However, confidence in values can increase and overall uncertainty can decrease with improvement in carbon pool inventories and predictions. The higher uncertainty in soil carbon estimates may indicate that more precisely designed inventories are needed for soil carbon than for other forest ecosystem components.

SUMMARY AND CONCLUSIONS

Forests occupy about 33% of the land area of the United States and are estimated to contain approximately 71,000 Mt of C. Over 50% is in the soil, with another 13% in dead mass in the forest, including the forest floor. Forests have sequestered a net annual average of 155 Mt/year over the period 1953 to 1997, not including increases to harvested-wood carbon pools or land-use and management changes to soil densities, although transfers of land are included as well as changes in forest type. Studies have shown that total soil carbon in U.S. forests can change dramatically, especially due to land-use history. Because of the magnitude of forest area, an increase of only 0.5% in soil carbon density would mean a total increase of 181 Mt. Products in use and in landfills have stored carbon at an average rate of approximately 31 Mt/year, while an average of 45 Mt/year of carbon in harvested wood was burned for energy or converted to an energy source, with the potential of substituting for the burning of fossil fuel.

Although forest carbon pools are often thought of as uncertain, permanent continuous inventory plots such as those measured in the United States provide estimates that are reliable and that feature the desired precision built in the sampling design. Soil carbon estimates will become more precise if planned samples are taken in the future on the FIA plots. Estimates of other forest-change components like growth and mortality will also become more precise with a greater percentage of permanent plots. Techniques are being developed to monitor soil carbon more easily, but more research would help. Using these techniques would then provide more information on specific activities and how those activities affect soil carbon and for how long.

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