

A pre-publication version of Carbon Trends in U.S. forestlands: a context for the role of soils in forest carbon sequestration. The Potential of U.S. Forest Soils to Sequester Carbon. Chapter 3 in: Kimble, J M., Heath, Linda S., Richard A. Birdsey, and Rattan Lal, editors. 2003. "The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect", CRC Press, Boca Raton, FL. P. 35-45.

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

Linda S. Heath¹, James E. Smith², and Richard A. Birdsey³

¹Project Leader, USDA Forest Service, Northeastern Research Station, PO Box 640, Durham, NH 032824, Phone: 603-868-7612, e-mail: Lheath@fs.fed.us

²Research Plant Physiologist, USDA Forest Service, Northeastern Research Station, PO Box 640, Durham, NH 032824, Phone: 603-868-7663, e-mail: jsmith11@fs.fed.us

³Program Manager, USDA Forest Service, Northeastern Research Station, 11 Campus Blvd., Suite 200, Newtown Square, PA 19073, Phone: 610-557-4091, e-mail: rbirdsey@fs.fed.us

INTRODUCTION

Forestlands are unlike cropland 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, if they 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 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 to other components of the 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 forest soil carbon estimates, see Johnson and Kerns (2003).

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 of 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 (see Barford et al., 2001) measure this change, also referred to as carbon flux, directly. In the estimates 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 dead wood (including stumps), belowground dead wood (that is, 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.

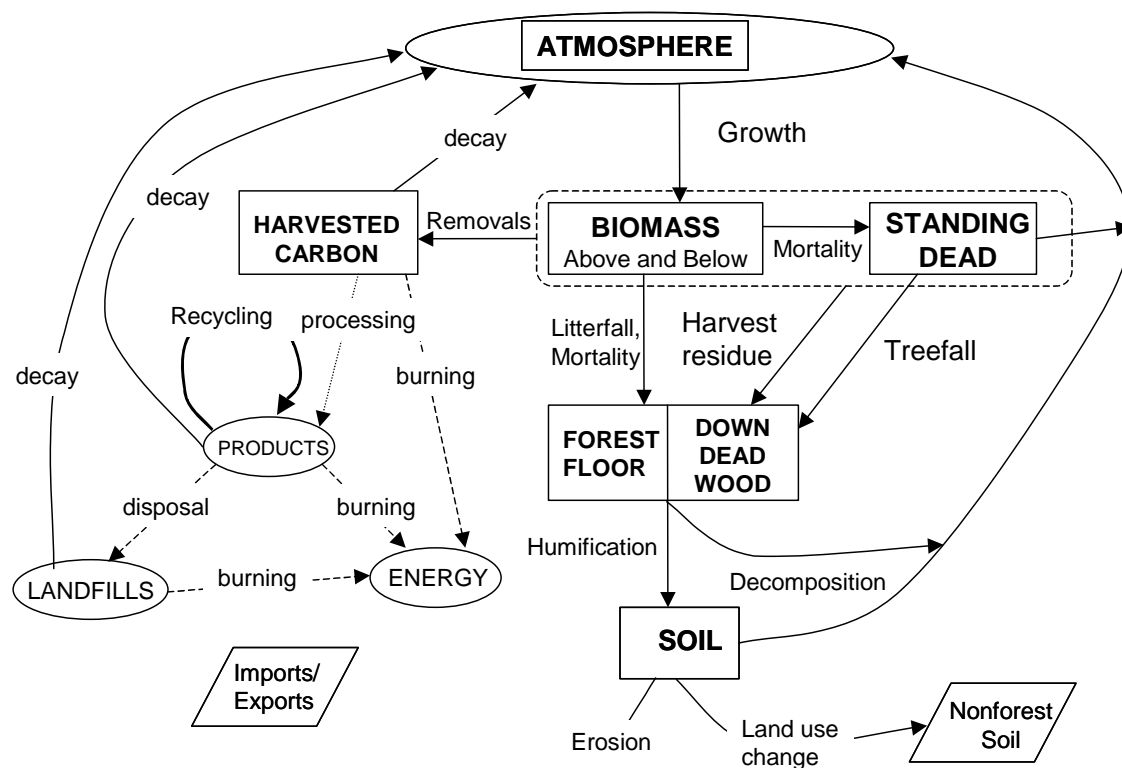


Figure 3.1 Diagram of stocks and flows of carbon in the forest sector.

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 may be burned for energy directly in the mill or used as fuelwood, or 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 plays 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, 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 1950's, forests in the U.S. were 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 we use 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 dead wood 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 harvest in US forests and the possible long-life 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 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 on U.S. national forests are reserved areas.) In the past, only the area of reserved lands may have been estimated. A second type of forestland is timberland, which is defined as land capable of producing in excess of 20 cubic feet per acre per year of industrial wood products and not designated as reserved. 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., 2003); (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. (2003) to estimate standing dead tree C associated with the detailed 1987 and 1997 data. The forest statistics discuss growing stock and non-growing stock. Growing stock volume is the volume of live trees, 5.0 inches at 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 non-growing 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 dead wood, above- and belowground, and understory vegetation were based on relationships obtained from simulated growth, management, and harvest of forests according region, forest type, and ownership. Carbon in down dead wood—larger than 7.5 cm diameter—was simulated in two parts. First, logging residue was essentially 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 dead wood 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 trees 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 U.S. (Powell et al., 1993) was overlaid on the STATSGO coverage, and an average soil carbon estimate assigned to each forest type (Dr. Louis Iverson, USDA Forest Service, Northeastern Research Station, Delaware, OH, personal communication). We included carbon from Histosols because forests can contain small areas (less than one 0.4 ha) of wetland-type areas and still be counted as forest. However, we are probably including some areas of non-forest 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, 2003). Estimates of forest floor carbon were based on equations in Smith and Heath (2003), 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 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 U.S. contain 50,830 Mt (megatonnes, million metric tons) C on 250 million hectares (Mha) in 1997 (Table 3.1). Because there is little new USDA Forest Service, 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 US forests in approximately 1997 to be 71,034 Mt 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, forest floor, which is included in the dead mass category in this study); we include additional dead wood 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

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	C in dead mass ^a	Soil organic C (1 m depth) ^b	Total forest C	Forest Area
		Mt				(thousand ha)
Timberland	Private	9,663	4,454	15,888	30,005	143,080
	Public	4,616	2,267	6,112	12,996	55,453
	All	14,279	6,721	22,000	43,001	198,533
Reserved	Private	4	10	35	49	309
	Public	1,100	585	1,776	3,462	16,628
	All	1,104	595	1,811	3,511	16,937
Other/Woodland	Private	436	312	1,186	1,934	15,841
	Public	645	473	1,266	2,384	18,724
	All	1,081	785	2,452	4,318	34,565
48-State Total		16,465	8,102	26,262	50,830	250,036
1987 Alaska Forest		2,287	1,386	10,068	13,741	52,223
1987 Hawaii Forest		6,395	8	60	6,463	707
Total		25,147	9,496	36,390	71,034	302,966

^aDead mass includes standing dead trees, down dead trees, and forest floor.

^bSoil includes both mineral soil and organic soils (i.e. Histosols).

Source: Birdsey, R.A. 1992. Gen.Tech. Rep. WO-59, USDA Forest Service, Washington, DC.

estimates indicate that 51 percent 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 3.2. 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) ^b (t/ha)	Total forest C (t/ha)	Forest area (thousand ha)
White-red-jack pine	72.7	26.0	196.1	294.8	4,795
Spruce-fir	52.9	53.9	192.9	299.8	7,079
Longleaf-slash pine	43.6	19.1	136.3	199.0	5,351
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	5,498
Maple-beech-birch	77.6	43.3	139.5	260.4	22,694
Aspen-birch	51.3	21.1	237.0	309.3	7,278
Other forest types	1.8	2.9	99.6	104.4	1,953
Nonstocked	3.1	5.1	99.6	107.9	2,074
All Eastern types	64.7	27.4	117.4	209.5	157,008

^aDead mass includes standing dead trees, down dead trees, and forest floor.

^bSoil 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 dead wood 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 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 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 U.S. than on western timberlands. Eastern timberland forest types have a lower percentage of carbon in dead mass, and slightly lower percentage in live vegetation compared to western types; eastern types tend to have a higher percentage of carbon in soil.

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) ^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	3,586
Larch	86.9	52.1	65.6	204.6	516
Lodgepole pine	52.8	39.9	62.7	155.3	7,043
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	4,544
Pinyon-juniper	24.5	24.0	56.3	104.8	19,999
Chaparral	17.5	29.3	58.7	105.6	2,099
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 US types	65.9	32.4	105.0	203.3	250,036

^aDead mass includes standing dead trees, down dead trees, and forest floor.

^bSoil includes both mineral soil and organic soils (i.e. Histosols).

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 1952 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 C/yr, not including carbon removed in harvested wood, while the land base decreases overall 65,000 ha/yr. 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 C/yr sequestered respectively. According to the data, the Pacific Coast region emitted an annual average of 3 Mt C/yr, 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, nor due to harvesting unless harvesting causes a forest type change. Thus decreases in soil carbon are due to either a decrease in area of forestland, or 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 C/yr. The Northeast region shows decreasing soil carbon in the last period, even with an increase in 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, which 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 area of forest type. 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 grams/ha will sequester 3 Mt C.

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 landfills. Figure 3.2 shows the pattern of carbon flux over select years in the time period 1950-1990 (Skog and Nicholson, 1998). At the time of this work, the years after 1986 were based not on actual data, but projections of harvests.

Table 3.4. Summary of Historical and Current Estimates of Carbon Storage (Mt C) and Flux (Mt C/yr) by Geographic Region and Ecosystem Component, Conterminous U.S. Forestland, 1952-1997

Region	C pool (Mt) or C flux (Mt/yr)	Year				
		1953	1963	1977	1987	1997
Northeast	Soil	4,289	4,509	4,685	4,675	4,637
	Forest floor	611	637	710	705	688
	Dead wood	268	324	423	479	527
	Understory	32	39	50	56	62
	Live trees	1,392	1,690	2,203	2,515	2,784
	TOTAL STORAGE	6,592	7,199	8,071	8,428	8,697
	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	5,091	5,177	5,050	5,025	5,173
	Forest floor	560	588	592	601	661
	Dead wood	220	279	350	417	492
	Understory	29	37	40	47	55
	Live trees	1,021	1,295	1,612	1,926	2,274
	TOTAL STORAGE	6,920	7,375	7,644	8,016	8,654
	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	4,173	4,220	3,809	3,767	3,740
	Forest floor	283	289	285	277	284
	Dead wood	340	386	493	534	550
	Understory	68	75	90	95	94
	Live trees	1,359	1,541	1,967	2,144	2,200
	TOTAL STORAGE	6,224	6,509	6,645	6,818	6,868
	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	5,378	5,391	4,974	4,824	4,951
	Forest floor	369	371	350	340	348
	Dead wood	532	631	793	874	954
	Understory	82	95	115	126	140
	Live trees	1,678	1,981	2,473	2,730	2,981
	TOTAL STORAGE	8,039	8,469	8,706	8,894	9,375
	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

(cont'd)

Table 3.4 (Continued). Summary of Historical and Current Estimates of Carbon Storage (Mt C) and Flux (Mt C/yr) by Geographic Region and Ecosystem Component, Conterminous U.S. Forestland, 1952-1997

Region	C pool (Mt) or C flux (Mt/yr)	Year				
		1953	1963	1977	1987	1997
Rocky	Soil	4,136	4,189	4,173	4,300	4,481
Mountain	Forest floor	1,346	1,346	1,332	1,366	1,409
	Dead wood	555	593	637	676	725
	Understory	105	109	126	132	131
	Live trees	2,446	2,605	2,888	3,051	3,173
	TOTAL STORAGE	8,588	8,843	9,156	9,526	9,918
	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	3,310	3,332	3,315	3,184
Forest floor		955	939	892	864	891
Dead wood		823	806	732	753	771
Understory		97	95	83	80	78
Live trees		3,702	3,660	3,506	3,663	3,670
TOTAL STORAGE		8,886	8,832	8,528	8,545	8,733
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	4,124	4,169	4,161	4,153	4,281
	Dead wood	2,739	3,019	3,428	3,734	4,018
	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

Removals in the first two decades totaled approximately 80 Mt C/yr, increasing to 90 Mt C/yr by 1970, and to 107 Mt C/yr by 1980. Recent inventory data indicate that the 145 Mt C/yr projected for 1990 would be closer to the 1980 estimate of 107 Mt C/yr. 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 three-fold increase of carbon sequestration in landfills. These are expected to be long-term storage. 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 using substituting more fossil-fuel-based carbon with burning wood. The additional carbon sequestered by products in use and landfills is about 20 Mt C/yr in the first three decades, rising to almost 40 Mt C/yr in the 1980s. For accounting purposes, these estimates can be added directly to the forest ecosystem carbon flux in Table 3.4.

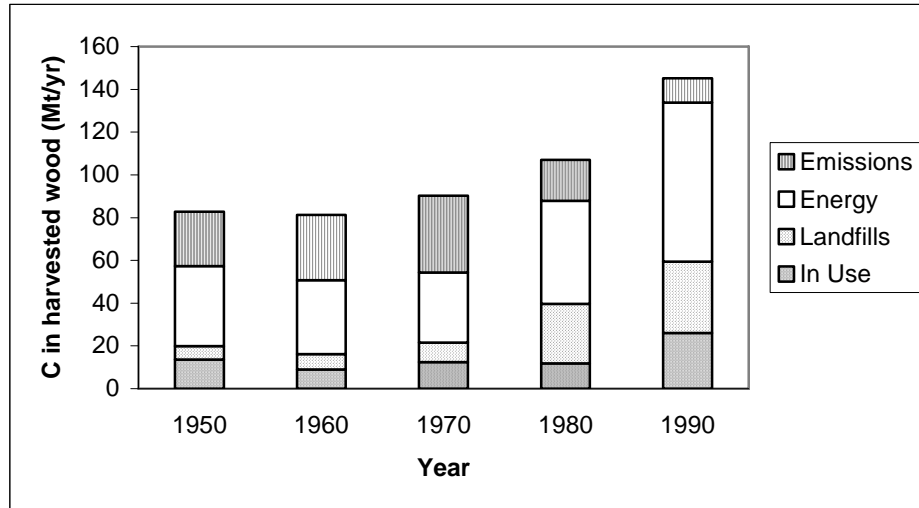


Figure 3.2. Carbon flux (Mt/yr) in harvested wood products by disposition category. Note that all pools are listed as positive flux. This enables the height of the bar to equal the total removal of wood from the forest. However, emissions are negative.

The estimates in this chapter differ from those in Birdsey and Heath (1995). In this study, we use new forest carbon conversion factors. 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 forest (Woudenberg and Farrenkopf, 1995) inventory databases. Thus, the predictors reflect the current size and distribution of species in U.S. forests, while soil carbon estimates are now based on STATSGO. Finally, new forest inventory data are available for 1997.

The numbers presented in our tables are estimates: 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 percent of the average total carbon inventory. The analogous uncertainty for net flux was just over 15 percent. (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 C. Over 50% is in the soil, with another 13% in dead mass in the forest, including forest floor. Forests have sequestered a net annual average of 155 Mt C/yr over the period 1952 to 1997, not including increases to harvested wood carbon pools, nor land use and management changes to soil densities, although transfers of land are included, as well as forest type changes. 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 one-half percent in soil carbon density would mean a total increase of 181 Mt C. Carbon in products in use and landfills have stored an average of approximately 31 Mt C/yr, while an average of 45 Mt C/yr 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 U.S., provide estimates that are reliable and that feature the desired precision built in to 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.

REFERENCES

- Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L.Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore. 2001. Factors controlling long- and short-term sequestration of atmospheric CO₂ in a mid-latitude forest. *Science* 294: 1688-1691.
- Birdsey, R.A. 1992. Carbon Storage and Accumulation in United States Forest Ecosystems. USDA Forest Service, Gen. Tech. Rep. WO-59. Washington, DC. 51 p.
- Birdsey, R.A. and L.S. Heath. 1995. Carbon changes in U.S. forests. In L.A. Joyce (ed), *Climate Change and the Productivity of America's Forests*. Gen. Tech. Rep. RM-271, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO, p. 56-70.
- Bliss, N.B., S.W. Waltman, and G.W. Peterson. 1995. Preparing a soil carbon inventory for the United States using geographic information systems. In: Lal, R, J. Kimble, E. Levine, and B.A. Stewart (eds), *Soils and Global Change*, Lewis Publishers, CRC Press, Inc. 440 p.
- Gillespie, A.J.R. 1999. Rationale for a national annual forest inventory program. *Journal of Forestry* 97(12): 16-20.

Hanson, M.H., T. Frieswyk, J.F. Glover, J.F. Kelly. 1992. The Eastwide Forest Inventory Data Base: Users Manual. Gen. Tech. Rep. NC-151, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN. 48 p.

Heath, L.S., and J. E. Smith. 2000. An assessment of uncertainty in forest carbon budget projections. *Environmental Science & Policy* 3: 73-82.

Heath, L. S., R. A. Birdsey, C. Row, and A. J. Plantinga. 1996. Carbon pools and flux in U.S. forest products. Pages 271-278 in M. J. Apps and D. T. Price, editors. *Forest Ecosystems, Forest Management, and the Global Carbon Cycle*. NATO ASI Series I: Global Environmental Changes. 40. Springer Verlag.

Heath, L.S., and R.A. Birdsey. 1993. Carbon trends of productive temperate forests of the coterminous United States. *Water, Air, and Soil Pollution* 70: 279-293.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence. 1999. The U.S. carbon budget: contributions from land-use change. *Science* 285: 574-578.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey. 2003. National-level biomass estimators for United States' tree species. *Forest Science* 49(1): 12-35.

Johnson, M., and J. Kerns. 2003. Carbon pools in forestland soils. In: J. Kimble, R. Birdsey, R. Lal, and L. Heath (eds). *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers. Boca Raton, FL, p. 47-72.

Plantinga, A.J., and R.A. Birdsey. 1993. Carbon Fluxes Resulting from U.S. Private Timberland Management. *Climatic Change* 23:37-53.

Powell, D. S., J.L. Faulkner, D.R. Darr, Z. Zhu, D. MacCleery. 1993. Forest resources of the United States, 1992, Gen. Tech. Rep. RM-234, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. Fort Collins, CO. 132 p.

Skog, K.E., and G.A. Nicholson. 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal* 48: 75-83.

Smith, J. E., and L. S. Heath. 2000. Considerations for interpreting probabilistic estimates of uncertainty of forest carbon, In L. Joyce and R. Birdsey (eds.) *The Impact of Climate Change on America's Forests*. Gen. Tech. Rep. RMRS-GTR-59. USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, p. 102-111.

Smith, J. E., and L. S. Heath. 2001. Identifying influences on model uncertainty: an application using a forest carbon budget model. *Environmental Management* 27:253-267.

Smith, J.E., L.S. Heath, J.C. Jenkins. 2003. Forest Tree Volume-to-Biomass Models and Estimates for Live and Standing Dead Trees of U.S. Forests, Gen. Tech. Rep. NE-238, USDA Forest Service, Northeastern Research Station. Newtown Square, PA. 57 p.

Smith, J.E., and L.S. Heath. 2003. A Model of Forest Floor Carbon Mass for U.S. Forest Types. Res. Pap. NE-722, USDA Forest Service, Northeastern Research Station, Newtown Square, PA. 37 p.

Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield. 2001. Forest Resources of the United States, 1997. USDA Forest Service, North Central Research Station, Gen. Tech. Rep. NC-219. St. Paul, MN. 190 p.

Soil Conservation Service. 1991. State Soil Geographic Data Base (STATSGO): Data users guide. U.S. Department of Agriculture, Soil Conservation Service, Miscellaneous Publication Number 1492, U. S. Government Printing Office.

Turner, D. P., G. J. Koerper, M. E. Harmon, and J. J. Lee. 1995. A carbon budget for forests of the conterminous United States. *Ecological Applications* 5:421-436.

U.S. Department of Energy. 1999. Carbon Sequestration Research and Development. US Department of Energy, Office of Science, Office of Fossil Energy. Also available http://www.ornl.gov/carbon_sequestration/carbon_seq.htm. (December 10, 2001).

Waddell, K.L; D.D. Oswald; D.D. Powell. 1989. Forest Statistics of the United States, 1987. USDA Forest Service, Pacific Northwest Research Station, Res. Bull. PNW-168. Portland, OR. 106 p.

Woudenberg, S.W., and T.O. Farenkopf. 1995. The Westwide Forest Inventory Data Base: user's manual. USDA Forest Service, Intermountain Research Station, Gen. Tech. Rep. INT-317. 67 p.