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4. Carbon Changes in U.S. Forests

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INTRODUCTION

Global concern about increasing atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO_2), and the possible consequences of future climate changes, has generated interest in understanding and quantifying the role of terrestrial ecosystems in the global carbon cycle. Recent efforts to quantify the global carbon budget have revealed an unknown carbon sink of 2.0-3.4 billion metric tons/yr, of which some may be accounted for by changes in northern temperate forests (Tans *et al*. 1990). Estimates for European forests show a possible contribution of 5-9% of the "missing" carbon (Kauppi *et al*. 1992), and similar estimates for U.S. forests show a possible contribution of 12-21% of the unexplained flux since 1952 (Birdsey *et al*. 1993).

Forest ecosystems are capable of storing large quantities of carbon in solid wood and other organic matter. Forest disturbances such as fire or timber harvest may add to the pool of CO_2 in the atmosphere, while growing forests may reduce atmospheric CO_2 through increases in biomass and organic matter accumulation. Carbon in wood products may be effectively stored for long periods of time depending on the end use of the wood. By accounting for all of the forest changes and effects on carbon in each of the components of the system, it is possible to determine whether a land area containing forests is a net source or sink of CO_2.

As a consequence of expected increases in emissions of greenhouse gases, analysts have proposed various strategies to reduce emissions of CO_2 to the atmosphere, or to offset emissions by storing additional carbon in forests or other terrestrial carbon sinks (Intergovernmental Panel on Climate Change 1991). Carbon sinks are a likely component of any U.S. strategy for limiting national contributions to greenhouse gas concentrations in the atmosphere. Of particular interest in the U.S. are options for increased tree planting, increased recycling, changes in harvesting and ecosystem management practices, and combinations of options, all within the context of the economic, demographic, and political assumptions that comprise the management and use of the Nation's forest resources.

To analyze these options, the Forest Service has developed a carbon accounting model that is linked with a socioeconomic model of the forest sector used for national assessments of forest resources. For the first time, the linked carbon accounting and forest sector models have been used with several climate change scenarios. This has been accomplished with a link between the Terrestrial Ecosystem Model (Raich *et al*. 1991, McGuire *et al*. 1992, 1993) and the forest sector model that allowed changes in forest productivity to alter projected timber supplies and affect the amount of carbon stored in U.S. forests. Although current models of global change effects on forests contain much uncertainty, analyses such as this give some indication of the magnitude of possible effects under different scenarios.

METHODS AND MODELS

Estimates of carbon storage for a base year (1992) were derived from national compilations of forest inventory statistics (Cost et al. 1990, Powell *et al*. 1993, Waddell *et al*. 1989), supplemented with information from ecosystem studies. These derived estimates provide a quantitative basis for calculating past carbon storage and projecting future changes. Estimates for the base year include all forest land classes and all 50 States. Past trends and projections focus on the conterminous U.S. where periodic inventories have been conducted over a long period of time, and where inventory projection models are well developed and linked with economic models. The general methods to calculate the past, current, and future estimates of carbon storage at periodic intervals are discussed in the following section. Additional details of the assumptions, estimation methods, and models can be found in Birdsey (1992a, 1992b) and Heath and Birdsey (1993).

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Carbon flux is estimated by calculating the change in carbon storage over a specified period of time. In the absence of harvesting or other disturbance, forests change relatively slowly and the changes are difficult to measure over a short time period. Statewide forest inventories are conducted in cycles of approximately 10 years which also is the average time period between major compilations of national forest statistics and the time period used in projections of forest inventories. To estimate the rate of carbon flux for a specified year, the total change in storage over the preceding and subsequent periods is divided by the total elapsed time, approximately 20 years. This method ties the rate of change closely to the reporting year, and avoids unrealistic changes in estimates between consecutive time periods.

Estimates for the Base Year

Carbon storage was estimated separately for several forest ecosystem components: trees, soil, forest floor, and understory vegetation. The definitions of these components are broad enough to include all sources of organic carbon in the forest ecosystem. The tree portion includes all above- and belowground portions of all live and dead trees, including the merchantable stem; limbs, tops, and cull sections; stump; foliage; bark and rootbark; and coarse tree roots (greater than 2 mm). The soil component includes all organic carbon in mineral horizons to a depth of one meter, excluding coarse tree roots. The forest floor includes all dead organic matter above the mineral soil horizons except standing dead trees: litter, humus, and other woody debris. Understory vegetation includes all live vegetation besides live trees.

Carbon storage was estimated in a four-stage process corresponding to the four major forest ecosystem components. Estimates of carbon storage in trees were based on periodic forest inventories designed to provide statistically valid estimates of timber volume, growth, removals and mortality (Waddell *et al.* 1989). Timber volume included merchantable live tree, 12.8 cm and larger at diameter breast height. Aboveground tree biomass was calculated by multiplying timber volume by conversion factors derived from the national biomass inventory (Cost *et al*. 1990). Belowground tree biomass was similarly calculated using conversion factors that range from 0.155 in northern hardwoods to 0.197 in southern hardwoods (Koch 1989).

Simple models were devised to estimate carbon storage in the forest floor and understory vegetation, based on the compilation by Vogt *et al.* (1986) and reviews of numerous intensive-site ecosystem studies (Birdsey 1992a). It was assumed that understory biomass peaked at age 5 and declined to between 1% or 2 % of the tree carbon by age 50 in the South and age 55 elsewhere. Forest floor estimates from forest ecosystems studies were applied to related forest types. Soil carbon for individual States and forest types was related to mean annual temperature and precipitation using a model similar to Burke *et al.* (1989) with coefficients derived from data in Post *et al.* (1982). The estimation process accounted for forest disturbance and regrowth as described by average stand age. Estimates of carbon in the soil and forest floor components were calibrated with the projections for private timberland by equating current (1992) estimates with a base year from the projections (1990).

Historical Estimates

Estimates of past carbon storage in forests were derived from periodic assessments of forest resource conditions, each including a compilation of national inventory statistics (USDA Forest Service, 1958,1965, 1974,1982, Waddell *et al*. 1989). Generalized factors to convert growing stock volume to carbon for each ecosystem component were derived from current estimates and applied retroactively without adjustment to previous estimates of growing stock volume by region and species group (softwoods and hardwoods). Past estimates for carbon in the forest floor, soil, and understory vegetation vary proportionally to changes in tree carbon. Lack of detailed information about past age class distributions precluded the inclusion of age class effects in the historical estimates. The effects cause estimates of carbon flux to appear more variable than would be expected if the periodic inventory system were implemented continuously across the U.S.

Methods for Projections

Carbon in Forest Ecosystems

The projection model uses detailed information about current age class distributions to simulate the effects of harvesting on future age class distributions. For private timberlands, profiles of average carbon storage by age of forest stands (carbon yield tables) were composed for each ecosystem component for forest classes defined by region, forest type, and land use history. The profiles were developed using methods similar to those used in estimating carbon storage in the base year. However, additional assumptions were required to estimate changes in soil and forest floor carbon over time. A search of the literature indicated that a major forest disturbance, such as a clearcut harvest, can increase coarse litter and oxidation of soil organic matter. The balance of these two processes can result in a net loss of 20% of the initial carbon over a 10-15 year period following harvest (Pastor and Post 1986, Woodwell *et al*. 1984), although a recent review suggested that the net effect may be less or even positive in many cases (Johnson 1992). There are indications that site preparation before replanting can cause a major loss of carbon in the southern U.S. (Johnson 1992). Recovery of carbon begins after an initial decline unless the harvest is followed by conversion to agricultural use, in which case loss could reach 60% under intensive cultivation (Anderson 1992, Johnson 1992).

Tree plantations established on agricultural land with depleted carbon stores can cause a substantial accumulation of soil organic matter, depending on species, soil characteristics, and climate (Johnson 1992). For example, *Populus* spp. established on sandy soils showed large increases in soil and forest floor carbon due to high litter production (Dewar and Cannell 1992). Expected changes in carbon storage for soil and forest floor components were derived by assuming a linear transition from average nonforest to average forest conditions.

After the initial 20% loss of soil carbon after harvest, it was assumed that soil carbon would return to pre-harvest levels by age 50 in the South and 55 elsewhere. If the forest land had reverted from agriculture, soil carbon was assumed to accumulate over time to levels similar to forest land that had never been cultivated. Then, after harvest, this forest land was treated the same as forest land that was never cultivated.

Carbon in Wood Products

The cumulative fates of carbon from projected harvests on private lands were estimated with a model based on the work of Row and Phelps (1991). The eventual disposal of all carbon removed from timberland since 1900 is included, based on data from detailed historical records of harvest volumes. There are four disposition categories: products, landfills, energy, and emissions. Products are goods, manufactured or processed from wood including lumber and plywood for housing and furniture, and paper for packaging and newsprint. Landfills store carbon as discarded products that eventually decompose and are released as emissions. Emissions also include carbon from wood burned without generation of usable energy, or from decomposing wood. Energy is a separate category from emissions because wood used for energy may be a substitute for fossil fuels.

The Modeling System for Projections

Equations derived from carbon storage profiles form the basis of a forest carbon model, FORCARB (Plantinga and Birdsey 1993), which is linked with a forest sector model, TAMM/ATLAS (Adams and Haynes 1980, Alig 1985, Haynes and Adams 1985, Mills and Kincaid 1992). The forest sector model is linked with the Terrestrial Ecosystem Model (TEM - Raich *et al*. 1991, McGuire *et al*. 1992,1993). The forest sector model provides an economic framework through which price, consumption, and production of timber and wood products are projected. Linkage with a forest sector model is critical for making valid projections because interactions with expected market responses will affect estimates of future forest harvest levels. Timber harvest on U.S. timberlands is currently the dominant cause of forest disturbance, accounting for 75% of the timber volume lost to all causes (Powell *et al*. 1993). Timber harvests from public lands are incorporated into the forest sector model as exogenous variables, because public lands are not managed to maximize economic return. The model ATLAS provides periodic estimates of area, inventory volume, growth, and removals by age class and management intensity for defined forest classes on private timberlands. The projected estimates of area, volume, growth, and removals for forest classes defined by region, owner, forest type, site class, stocking class, and age class are the basis for estimating carbon storage and fluxes in the four basic ecosystem components on private timberland using FORCARB.

TEM is an ecosystem-level process-based model that estimates potential changes in net primary productivity (NPP) for different ecosystem types as a function of atmospheric CO_2, climate, and other limiting factors such as nutrient and water resources. The values for each factor are set at current and future (doubled atmospheric CO_2 and associated climate changes) equilibrium levels. Transition levels are estimated as a linear interpolation between present and future levels. Actual changes in NPP during a transition to a new equilibrium would likely be quite different than the estimated changes based on the assumption of simple linear interpolation.

TEM was linked with the ATLAS portion of the forest sector model by altering volume growth functions for different forest types. Changes in volume were then reflected in the conversion of volume to carbon in FORCARB. Since FORCARB estimates carbon storage in all forest ecosystem components, the proportional changes in carbon storage are consistent with the change in net primary productivity projected with TEM.

For public lands, reserved timberland, and other forest land, projections of timber volume are made with simple growth and removal models based on expected harvest levels and growth rates, since the forest sector model TAMM/ ATLAS is used for private timberland only. Projected forest inventories are converted to carbon estimates using volume-to-carbon conversion factors derived from the base year for each ecosystem component.

The effects of climate change are analyzed only for private timberland because of the lack of complete integration of all models for public forest land and other forest land. Furthermore, the link between TEM and FORCARB is not sufficiently well established at this time to allow FORCARB to account for prospective changes in carbon allocation between components of the ecosystem; yet this is a likely important consequence of changes in atmospheric CO_2. Therefore, when comparing the climate change scenarios to the base scenario, only carbon in trees is included in the results even though both FORCARB and TEM can project changes in other ecosystem components.

In estimating carbon for the reforestation scenarios, all land in the base scenario was accounted for in all scenarios even if that land was assumed to change from timberland to reserved status. This accounting avoided a sudden loss in carbon when there was only a classification change and not a true disturbance. For additions to forest land through reforestation programs, the initial quantity of soil carbon was not added, to avoid the appearance of a pulse of carbon caused simply by reclassification. However, after a change in status, all increments of carbon in all components were accounted for in each scenario.

Uncertainty of the Estimates

Regional forest inventories are based on a statistical sample designed to represent the broad range of forest conditions actually present in the landscape. Therefore estimates of carbon storage in forest trees are representative of the true average values, subject to sampling errors, estimation errors, and errors in converting data from one reporting unit to another. Because of the complexity of making the estimates, the magnitude of the error in estimating tree carbon has not been estimated; but it is likely quite small, because the forest inventories used to derive the estimates have very small sampling errors over large areas.

Most regional estimates of carbon storage in the soil and forest floor are not based on a statistical sample but on compilations of the results of many separate ecological studies of specific ecosystems. Published estimates for soil carbon show wide variation for terrestrial ecosystems (Houghton *et al*. 1985). In an extensive literature review of the effects of forest management on soil carbon, Johnson (1992) highlighted the difficulties of aggregating estimates when sampling protocols and definitions generally are inconsistent among individual studies.

Problems with aggregation apply to this study because estimates of carbon storage in the soil, forest floor, and understory vegetation were developed through the use of models based on data from forest ecosystem studies. Uncertainty also is introduced into the estimation process by assuming that the results of specific ecosystem studies are representative of regional or national averages without being part of a statistical sample that represents a large geographical area. Therefore, estimates of carbon storage in the soil, forest floor, and understory vegetation are subject to the following errors: bias from applying data from past studies that do not represent all forest conditions, modeling errors (imperfect assumptions), and errors in converting estimates from one reporting unit to another. No attempt has been made to estimate the magnitude of these errors.

For the projections, all of the above uncertainties apply, and the errors are propagated through the model. To this basic uncertainty contained within FORCARB can be added the substantial uncertainty of projected forest inventories from TAMM/ATLAS, a function of uncertain economic, technological, and resource supply assumptions. Finally, uncertainties in projecting atmospheric greenhouse gas concentrations, associated climate changes, and forest ecosystem responses are quite high and therefore all results should be interpreted with great caution, as scenarios instead of predictions.

RESULTS

Base-year Estimates

Carbon Storage in the United States

Forest ecosystems in the United States contain approximately 54.6 billion metric tons of organic carbon above and below the ground (table 4.1). This is about 5% of all the carbon stored in the world's forests (Dixon *et al*. 1994). The area of U.S. forests is 298 million hectares, or 6% of the world's forest area.

Table 4.1. Area of forest land and carbon storage by region, forest class, and forest ecosystem component, 1992.

			-------------- Forest Ecosystem Component --------------				
Region	Forest Class	Area[1]	Soil	Forest Floor	Under-story	Trees	Total
		1000 ha	*---------------------- million metric tons ----------------------*				
Northeast	Timberland	32,153	4,348	562	53	2,041	7,004
	Reserved	1,841	315	44	4	163	526
	Other	559	68	8	1	35	113
	Total	34,554	4,731	615	59	2,239	7,643
North Central	Timberland	31,708	3,192	460	45	1,573	5,270
	Reserved	1,211	151	23	2	60	235
	Other	715	152	22	2	46	222
	Total	33,634	3,495	505	48	1,679	5,727
Southeast	Timberland	34,316	2,411	197	106	2,017	4,730
	Reserved	809	75	9	3	60	147
	Other	520	32	3	2	10	47
	Total	35,645	2,518	210	111	2,086	4,924
South Central	Timberland	46,344	3,044	230	155	2,691	6,121
	Reserved	425	42	4	2	33	81
	Other	3,316	205	17	13	102	337
	Total	50,085	3,292	251	170	2,825	6,539
Rocky Mountains	Timberland	25,346	2,164	452	29	1415	4,060
	Reserved	4,971	479	86	7	328	901
	Other	26,233	1,248	185	30	970	2,432
	Total	56,549	3,891	723	65	2,713	7,393
Pacific Coast	Timberland	22,158	2,334	492	92	1,631	4,548
	Reserved	2,695	319	69	12	211	612
	Other	10,555	743	73	41	396	1,252
	Total	35,408	3,396	634	145	2,237	6,413
Alaska	Timberland	6,098	2,002	250	19	319	2,590
	Reserved	2,439	1,706	214	16	263	2,198
	Other	43,723	8,305	1,161	169	1,573	11,207
	Total	52,259	12,013	1,624	203	2,155	15,996
United States	Timberland	198,123	19,495	2,644	499	11,685	34,323
	Reserved	14,391	3,088	450	46	1,118	4,701
	Other	85,620	10,753	1,469	256	3,133	15,611
	Total	298,133	33,336	4,562	801	15,936	54,635

[1]From Powell et al. 1993. Estimates may differ slightly due to rounding.

The average forest in the United States contains 18.3 kg/m^2 of organic carbon. Trees, including tree roots, account for 29% of all forest ecosystem carbon (fig. 4.1). Live and standing dead trees contain 15.9 billion metric tons of carbon, or an average of 5.3 kg/m^2. Of this total, 50% is in live tree sections classified as growing stock, 30% is in other live solid wood above the ground, 17% is in the roots, 6% is in standing dead trees, and 3% is in the foliage.

The largest proportion of carbon in the average U.S. forest is found in the soil, which contains 61 % of the carbon in the forest ecosystem, or approximately 11.2 kg/m^2. About 8% of all carbon is found in litter, humus, and coarse woody debris on the forest floor, and about 1 % is found in the understory vegetation. By adding carbon in tree roots to the carbon in the soil, the average proportion of carbon below the ground in the United States is estimated to be 66%.

Carbon Storage by Region and Forest Class

Carbon storage and accumulation rates in a particular region or forest are influenced by many factors such as climate, solar radiation, disturbance, land use history, age of forest, species composition, site and soil characteristics. Even though all trees have similar physiological processes, there are significant differences in growth rates and wood density between species and individual organisms. The combination of species and site differences produces a wide variety of carbon densities across a landscape. Historical land use patterns and landscape attributes produce characteristic regional profiles of carbon storage.

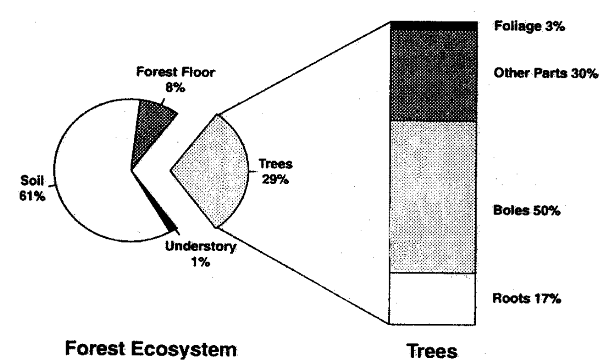


Figure 4.1. Allocation of carbon in forest ecosystems and in trees, U.S. forests, 1992. Total storage in the U.S. is 54.6 billion metric tons.

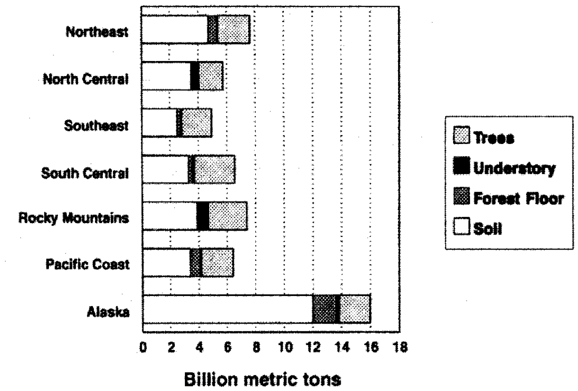


Figure 4.2. Total carbon storage by region and ecosystem components, U.S. forest, 1992.

The proportion of carbon in the different ecosystem components varies considerably between regions (fig. 4.2). Alaska has the highest estimated amount of carbon in the soil, about 75% of the total carbon. The Southeast and South Central States each have about 50% of total carbon in the soil, but have a higher percentage in the trees. Soil carbon is closely related to temperature and precipitation, with higher amounts of soil carbon found in regions with cooler temperatures and higher precipitation. Cooler temperatures slow the oxidation of soil carbon, while higher rainfall tends to produce greater growth of vegetation, fine roots, and litter, which are the main sources of organic soil carbon. Carbon in the forest floor varies by region in a way similar to carbon in the soil. Western and Northern States contain the most carbon on the forest floor, and Southern States contain the least.

Two-thirds of all carbon in U.S. forests is on land classified as timberland. Most of the remainder is on land classified as other forest, primarily in the drier forests of the Western U.S. and the interior of Alaska.

Recent and Projected Trends In Carbon Storage and Flux

U.S. forests are constantly changing. The total area of forest land declined by 1.6 million hectares between 1977 and 1987 (Waddell *et al.* 1989) and increased by 2.4 million hectares between 1987 and 1992. These relatively small changes in the total area do not reflect the larger underlying gains and losses that create a dynamic forest landscape. Each year forests are permanently lost to clearing for urban and suburban development, highways, and other rights-of-way. A larger area is typically cleared for agricultural use, but roughly balanced by agricultural land that was planted with trees or allowed to revert naturally to forest. In addition to land-use changes, each year about 1.6 million hectares of timberland are harvested for timber products and regenerated to forests, 1.6 million hectares are damaged by wildfire, and 1 million hectares are damaged by insects and diseases. And of course, all forests change continually as individual trees and other vegetation germinate, grow, and die.

Between 1952 and 1992, carbon stored on forest land in the conterminous U.S. has increased by an estimated 11.3 billion metric tons (table 4.2, fig. 4.3). This is an average of 281 million metric tons of carbon sequestered each year over the 40-year period, an amount that has offset about one fourth of U.S. emissions of carbon to the atmosphere (Boden *et al*. 1990). Most of the increase occurred in the Eastern and Central regions of the U.S., offsetting a much smaller decline in the West. Over the past 100 years or more, large areas of the East have reverted from agricultural use to forest. As these reverted forests have grown, biomass has increased substantially, and according to the assumptions described earlier, soil organic matter has increased proportionally.

In the South, increased harvesting and intensive forest management have significantly slowed the rate of increase in carbon storage. Northeastern and North Central forests have continued to accumulate carbon at a rapid rate since the mixed hardwood forests are less intensively utilized or managed for wood products. Although the West has not had the major land use shifts characteristic of the East, forest disturbance nonetheless has dominated the landscape as the original forests have been harvested and converted to second-growth forests. Declining carbon storage in the Pacific Coast region reflects the smaller amount of carbon contained in regenerating younger forests.

Projections through 2040 show an additional increase of 8.5 billion metric tons of carbon storage, or an average of 177 million metric tons per year (table 4.2, fig. 4.3). This projected trend reflects (1) a slowdown in the rate of accumulation in the North as the average forest has reached an age of slower growth relative to the past, and increases in soil carbon on reverted land are less; (2) increasingly intensive use of forests for wood products in the South so that accumulation is balanced by removal; and (3) reduced harvest of public forests in the West coupled with a large area of younger, more vigorous and intensively managed forests on former old-growth forest land.

Estimates of carbon flux, in which a positive flux represents a net increase of carbon storage in forest ecosystems, highlight the relative contribution of forest floor and soil carbon to the estimated annual increases in carbon storage (table 4.3, fig. 4.4). Nationally, about 2/3 of the historical and projected positive flux is carbon buildup in the soil and forest floor. Despite the exaggerated variability in the past estimates, the trends over the whole period from 1952-1992 are representative of true changes in biomass, limited by assumptions about organic matter in the soil and forest floor.

Regionally, both the North and the South are expected to accumulate less carbon in forests, while Western forests will accumulate more carbon (fig. 4.4). The reasons for these changes, as discussed earlier, are related to changing levels of harvest and trends in land use.

Past and projected changes in forest carbon storage vary significantly by ownership group (table 4.3, fig. 4.5). Most of the historical increase in carbon storage has been on private timberland in the East. As these lands approach full stocking of relatively large trees with low rates of biomass accumulation (primarily in the North), or are more intensively used for timber products (primarily in the South), accumulation of carbon is expected to decline to near zero by 2040. Carbon storage on forest industry lands has increased slightly in the past, and is expected to remain relatively constant over the projection period. Carbon storage on National Forests has declined in the recent past, a consequence of harvesting old-growth stands in the far western U.S. High rates of harvest on National Forest lands appear as a negative carbon flux, mirroring the positive carbon flux evident on private lands during the same period (fig. 4.5). With restrictions on harvest levels, carbon storage on National Forests is expected to increase substantially, with an average annual addition to carbon storage of about 83 million metric tons per year between 2000 and 2040. Other public forests show similar but less pronounced changes.

Table 4.2. Summary of historical estimates and projections of carbon storage and flux (in million metric tons) by geographic region and ecosystem component, conterminous U.S. forest land,1952-2040.[1]

Region	Ecosystem Component	1952	1962	1970	1977	1978	1992	2000	2010	2020	2030	2040
Northeast	Soils	2,438	2,961	3,418	3,901	4,349	4,731	5,016	5,278	5,532	5,786	6,033
	Forest Floor	317	385	442	507	567	615	661	686	704	716	727
	Understory	30	36	43	49	54	59	66	68	73	73	76
	Trees	1,133	1,380	1,582	1,814	2,054	2,239	2,512	2,686	2,811	2,912	2,986
	TOTAL STORAGE	3,918	4,762	5,484	6,270	7,024	7,643	8,255	8,717	9,119	9,487	9,821
	Annual Dead Flux[2]		61	71	62	63	58	34	28	27	26	
	Annua Llive Flux[3]		26	30	28	29	36	25	15	12	9	
	TOTAL FLUX		87	101	91	92	95	60	43	38	35	
North Central	Soils	1,643	2,083	2,347	2,695	3,224	3,495	3,724	3,999	4,271	4,549	4,829
	Forest Floor	236	303	341	393	468	505	519	551	581	612	640
	Under story	24	29	32	38	46	48	57	61	62	66	67
	Trees	794	1,000	1,122	1,280	1,536	1,679	1,793	1,895	1,987	2,070	2,157
	TOTAL STORAGE	2,697	3,414	3,842	4,406	5,273	5,727	6,093	6,506	6,901	7,297	7,692
	Annual Dead flux		45	47	59	61	42	31	30	31	31	
	Annual Live Flux		19	19	25	27	21	13	10	9	9	
	TOTAL FLUX		64	66	84	88	63	43	40	40	40	
Southeast	Soils	1,602	1,810	2,039	2,314	2,514	2,518	2,532	2,566	2,590	2,625	2,671
	Forest Floor	130	147	166	190	209	210	198	195	192	191	195
	Understory	71	80	91	103	111	111	108	112	116	118	120
	Trees	1,299	1,469	1,664	1,895	2,079	2,086	2,059	2,005	1,904	1,830	1,776
	TOTAL STORAGE	3,102	3,507	3,960	4,503	4,912	4,924	4,897	4,878	4,802	4,764	4,762
	Annual Dead Flux		26	36	30	15	1	2	3	3	4	
	Annua Live Flux		21	30	26	13	(2)	(4)	(7)	(8)	(6)	
	TOTAL FLUX		48	66	56	28	(1)	(3)	(5)	(6)	(2)	
South Central	Soils	1,894	2,274	2,550	2,868	3,153	3,292	3341	3,414	3,482	3,552	3,620
	forest Floor	143	173	192	218	240	251	249	261	276	281	276
	Understory	99	118	133	148	164	170	158	162	169	172	177
	Trees	1,626	1,906	2,111	2,369	2,651	2,825	2,903	3,110	3,204	3,175	3,071
	TOTAL STORAGE	3,762	4,470	4,985	5,602	6,208	6,539	6,651	6,947	7,131	7,180	7,145
	Annual Dead Flux		39	43	38	31	15	7	8	8	7	
	Annual Live Flux		29	33	34	32	19	15	16	4	(6)	
	TOTAL FLUX		68	75	72	62	34	23	24	12	1	
Rocky Mtns.	Soils	3,623	3,507	3,510	3,708	3,898	3,891	3,983	4,242	4,514	4,788	5,071
	Forest Floor	650	641	645	679	711	723	747	794	845	896	946
	Understory	66	63	62	64	67	65	80	84	87	92	95
	Trees	2,571	2,469	2,463	2,606	2,735	2,713	2,737	2,931	2,129	3,329	3,528
	TOTAL STORAGE	6,911	6,679	6,680	7,057	7,410	7,393	7,547	8,051	8,574	9,105	9,639
	Annual dad Flux		(7)	16	27	15	9	23	31	32	33	
	Annual Live Flux		(6)	9	16	7	1	13	20	20	20	
	TOTAL FLUX		(13)	25	43	22	11	37	51	53	53	
Pacific Coast	Soils	3,168	3,077	2,976	2,936	2,872	2,859	2,880	3,059	3,250	3,456	3,654
	Forest Floor	650	630	607	600	583	578	587	622	658	698	737
	Understory	129	125	121	119	117	117	111	116	122	128	135
	Trees	2,135	2,074	2,011	1,979	1,953	1,943	2,075	2,222	2,373	2,533	2,671
	TOTAL STORAGE	6,083	5,907	5,714	5,634	5,526	5,498	5,653	6,019	6,403	6,815	7,198
	Annual Dead Flux		(13)	(11)	(7)	(7)	1	14	22	24	24	
	Annual Live Flux		(7)	(7)	(4)	(3)	(9)	15	15	16	16	
	TOTAL FLUX		(20)	(18)	(11)	(9)	10	29	38	40	40	
TOTAL	Soils	14,368	15,711	16,840	18,422	20,009	20,785	21,475	22,557	23,638	24,757	25,878
	Forest Floor	2,126	2,279	2,394	2,585	2,778	2,882	2,960	3,109	3,256	3,393	3,521
	Understory	419	451	480	521	558	570	580	604	628	649	669
	Trees	9,560	10,298	10,953	11,943	13,009	13,487	14,079	14,849	15,407	15,849	16,188
	TOTAL STORAGE	26,473	28,738	30,666	33,471	36,353	37,724	39,094	41,119	42,930	44,647	46,257
	Annual Dead Flux		152	201	209	177	127	111	123	124	125	
	Annual Live Flux		81	114	126	106	84	78	69	52	41	
	TOTAL FLUX		233	316	335	284	211	189	192	176	166	

[1]Assumptions about forest land area used the in projecting carbon storage and flux: (1) Area of other forest land, reserve lands, and National Forest timberland are unchanged after 1992, (2) volume on reserve lands assumed to grow at the same rate as volume on similar unreserved lands, (3) area for private lands and other public lands are equal to projections from the 1993 RPA Assessment update, (4) for National Forest lands, harvest and growth rate projections are from National Forest lands and from previous RPA projections.

[2] Dead flux refers to average annual change in carbon in soils and the forest floor for the preceding and following periods. A positive flux indicates increase in carbon storage in dead organic matter.

[3] Live flux refers to average annual change in carbon in understory and trees for the preceding and following periods. A positive flux indicates increasing carbon storage in life organic matter.

Table 4.3. Summary of historical estimates and projections of carbon storage and flux (in million metric tons) by ownership group and ecosystem component, conterminous U.S. timberland,1952-2040.[1]

Region	Ecosystem Component	1952	1962	1970	1977	1978	1992	2000	2010	2020	2030	2040
National Forest	Soils	5,183	5,458	5,482	5,439	4,824	4,585	4,621	5,031	5,472	5,949	6,440
	Forest Floor	837	882	882	875	784	760	771	842	917	997	1,080
	Understory	101	108	109	109	99	99	101	112	123	135	145
	Trees	2,294	2,482	2,512	2,540	2,456	2,458	2,554	2,826	3,110	3,408	3,714
	TOTAL STORAGE	8,415	8,930	8,985	8,963	8,163	7,902	8,047	8,111	9,622	10,489	11,379
	Annual Dead Flux[2]		19	(2)	(44)	(65)	(17)	29	50	54	57	
	Annual Live Flux[3]		13	4	(4)	(6)	8	21	29	30	31	
	TOTAL. FLUX		32	2	(48)	(71)	(9)	51	79	84	88	
Other Public	Soils	1,954	2,177	2,359	2,510	2,380	2,311	2,595	2,912	3,212	3,510	3,811
	Forest Floor	302	332	357	378	369	350	392	439	485	530	578
	Understory	36	39	42	44	48	46	51	56	63	68	74
	Trees	818	914	993	1,066	1,178	1,145	1,263	1,391	1,523	1,662	1,810
	TOTAL STORAGE	3,110	3,462	3,751	3,998	3,975	3,852	4,301	4,798	5,283	5,770	6,273
	Annual Dead Flux		26	25	2	(15)	18	38	36	34	35	
	Annual Live Flux		10	10	11	5	7	14	14	14	15	
	TOTAL FLUX		36	35	13	(10)	(25)	53	49	49	50	
Forest Industry	Soils	1,997	2,220	2,419	2,561	2,579	2,559	2,536	2,523	2,543	2,584	2,626
	Forest Floor	306	318	333	341	342	338	297	296	309	314	314
Understory	62	68	70	75	76	73	88	87	87	86	87	
	Trees	1,208	1,324	1,392	1,470	1,501	1,473	1,464	1,587	1,733	1,822	1,855
TOTAL STORAGE	3,573	3,930	4,214	4,447	4,498	4,443	4,385	4,493	4,672	4,806	4,882	
	Annual Dead Flux		25	24	10	0	(7)	(4)	1	4	4	
	Annual Live Flux		11	10	7	0	(2)	7	13	12	6	
	TOTAL FLUX		36	34	17	0	(9)	3	14	16	11	
Other Private	Soils	5,480	6,296	6,998	7,751	9,254	10,040	10,253	10,575	10,843	11,083	11,306
	Forest Floor	663	756	828	906	1,081	1,196	1,237	1,258	1,256	1,247	1,228
	Understory	165	186	210	232	265	281	265	273	275	277	279
	Trees	3,840	4,338	4,815	5,308	6,090	6,609	6,885	7,056	6,971	6,797	6,559
	TOTAL STORAGE	10,148	11,576	12,851	14,197	16,691	18,126	18,640	19,162	19,345	19,404	19,372
	Annual Dead Flux		94	107	148	172	89	33	30	25	22	
	Annual Live Flux		57	68	78	90	61	2	5	(13)	(20)	
	TOTAL FLUX		150	175	226	262	150	58	35	12	1	
TOTAL	Soils	14,614	16,151	17,258	18,261	19,037	19,495	20,005	21,041	22,070	23,126	24,183
	Forest Floor	2,108	2,288	2,400	2,500	2,576	2,644	2,697	2,835	2,967	3,088	3,200
	Understory	364	401	431	460	488	499	505	528	548	566	585
	Trees	8,160	9,058	9,712	10,384	11,225	11,685	12,166	12,860	13,337	13,689	13,938
	TOTAL STORAGE	25,246	27,898	29,801	31,605	33,327	34,323	35,373	37,264	38,922	40,469	41,906
	Annual Dead Flux		163	155	115	92	84	97	117	117	117	
	Annual Live Flux		90	92	92	89	74	67	61	43	32	
TOTAL FLUX		253	247	207	181	157	163	177	160	149		

[1]Assumptions about forest land area used in projecting carbon storage and flux: (1) area of National Forest timberland are unchanged after 1992, (2)area for private lands and other public lands are equal to projection form the 1993 RPA Assessment update, (3) for National Forest lands, harvest and growth rate projections are from National Forest plans and from previous RPA projections.
[2] Dead flux refers to average annual change in carbon in soils and the forest floor for the preceding and following periods. A positive flux indicates increase in carbon storage in dead organic matter.
[3] Live flux refers to average annual change in carbon in understory and trees for the preceding and following periods. A positive flux indicates increasing carbon storage in life organic matter.

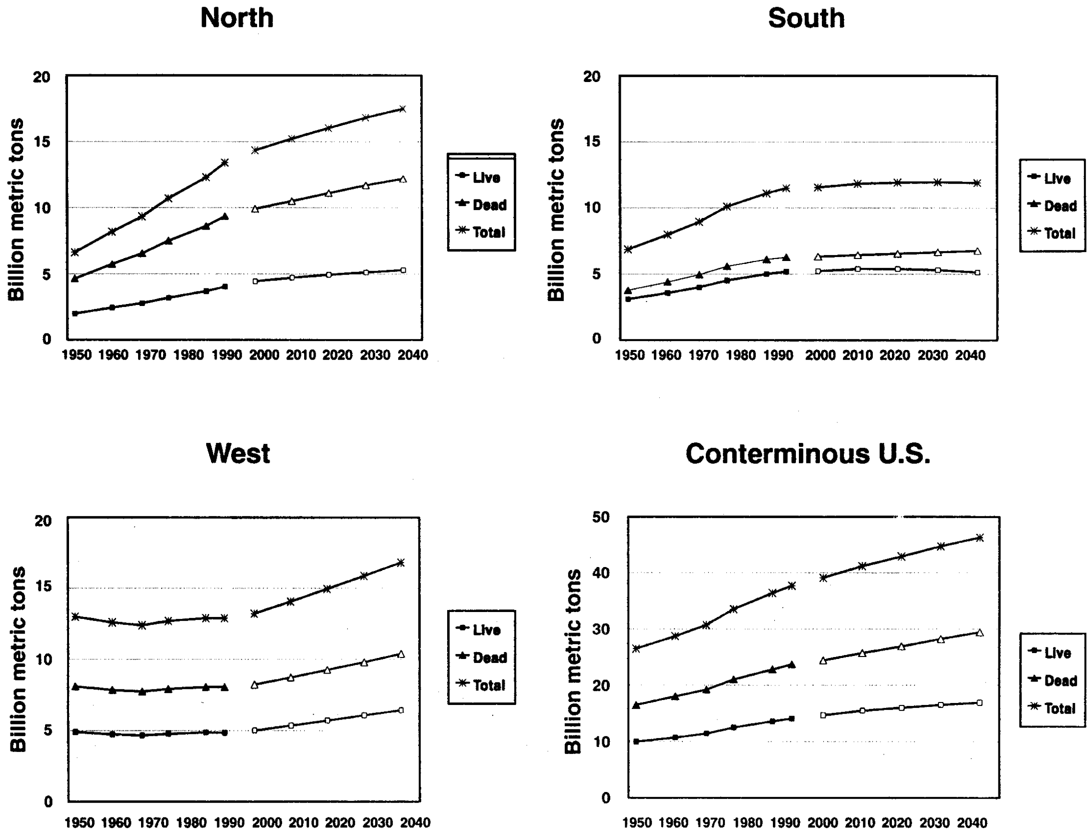


Figure 4.3. Carbon storage in live (tree and understory) and dead (soil and forest floor) organic matter, conterminous U.S. forests, 1952-2040.

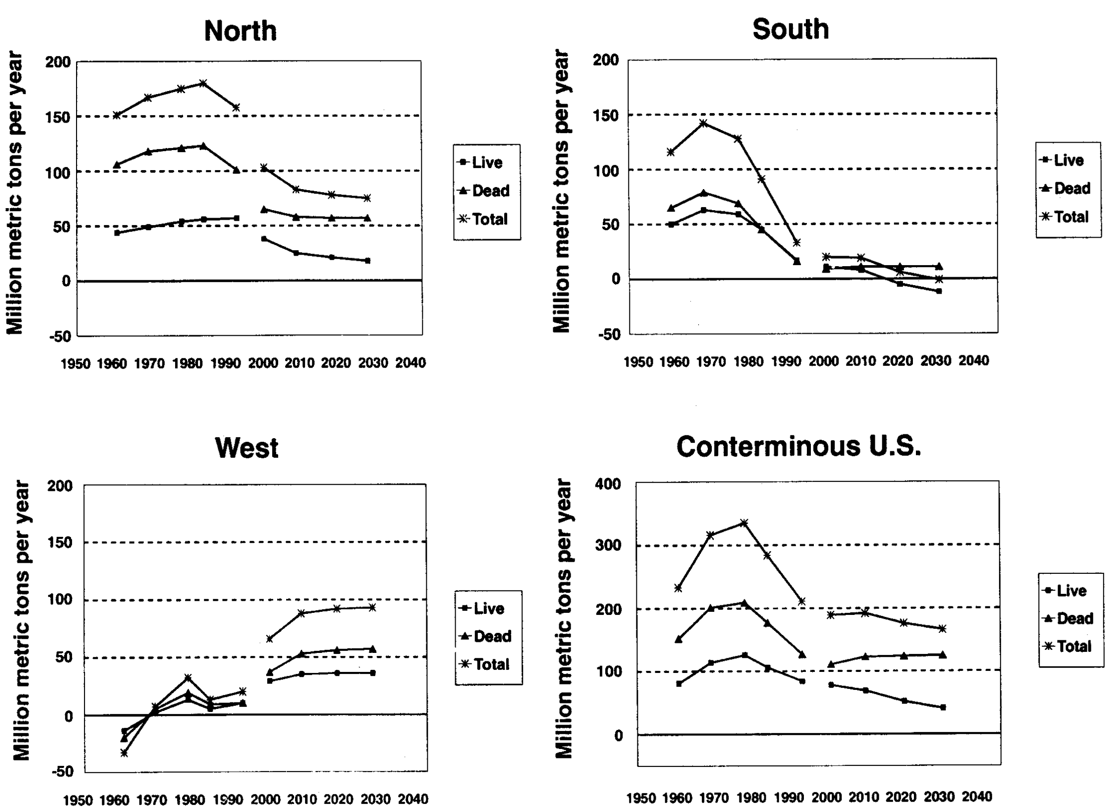
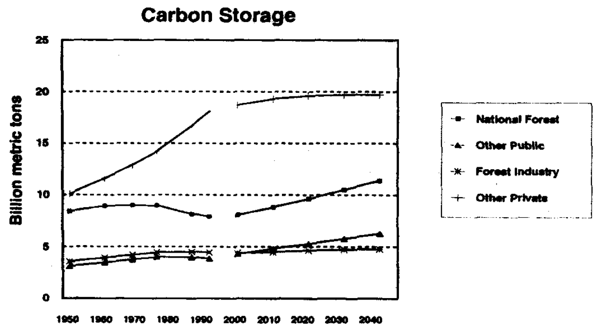


Figure 4.4. Carbon flux in live (tree and understory) and dead (soil and forest floor) organic matter, conterminous U.S. forests, 1952-2040. A positive flux indicates increasing carbon storage in forest ecosystems.



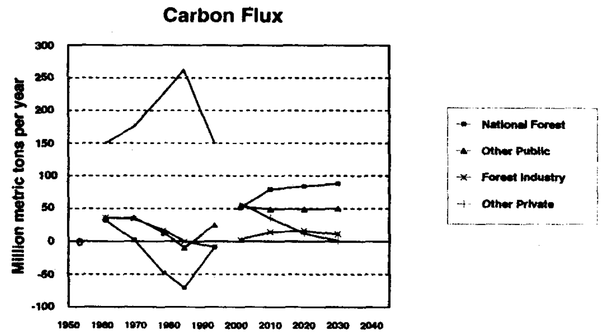


Figure 4.5. Carbon storage and flux by owner, U.S. timberland, 1952-2040. A positive flux indicates increasing carbon storage in forest ecosystems.

Carbon in Harvested Wood Products

Harvested wood can represent a substantial carbon sink (Heath *et al.* 1995). Based on harvests for the period 1900-2040 on private timberland, an estimated 27-39 million metric tons per year of additional carbon may be added to physical storage in wood products and landfills (table 4.4). Larger amounts of the harvested carbon are used for energy or decomposition and returned to the atmosphere. These estimates are sensitive to assumptions about recycling, age of trees at harvest, and other factors that affect the amount of wood and the retention periods in various pools. A comprehensive analysis of alternative scenarios should account for harvested carbon; however, a lack of quantitative information about how this carbon will change under the different assumptions has precluded full use of this modeling capability.

Alternative Scenarios

The effects of increasing atmospheric CO_2 and prospective climate change on productivity could have a significant impact on carbon storage in forests (table 4.5). Responses range from minor with a minimum increase in productivity, to an increase over the base of 67 million metric tons per year by 2040 with a maximum increase in productivity. This amount is significant enough on private timberland to reverse the projected decline in carbon storage that would begin by 2020 under baseline conditions. The increase also is equivalent to that projected by 2040 under a massive reforestation program (table 4.6). The estimates for climate change scenarios represent only the increase in tree carbon. Based on the increases in productivity, there was a small increase in the amount of carbon stored in wood products and landfills as more timber was available for harvest.

Table 4.4. Cumulative disposition of carbon harvested from private timberland in the conterminous U.S., 1980-2040.[1]

Year/Period	Wood in use	Landfill	Used for energy	Emitted
	-------------- millon metric tons -----------			
Storage:				
1980	1,272	1,236	3,642	3,129
1990	1,407	1,374	4,129	3,598
2000	1,520	1,533	4,647	4,109
2010	1,662	1,734	5,269	4,683
2020	1,804	1,954	5,942	5,314
2030	1,948	2,185	6,656	5,911
2040	2,097	2,426	7,416	6,719
	------- million metric tons per year -------			
Flux:[2]				
1990	12	15	50	49
2000	13	18	57	54
2010	14	21	65	60
2020	14	23	69	65
2030	15	24	74	70

[1]Includes carbon removed from timberland after 1990.
[2]Calculated as average annual change over the preceding and following periods.

Table 4.5. Comparison of carbon storage and flux for base run and climate change scenarios, trees only, private timberland in the conterminous U.S., 1990-2040.

		Change in productivity		
Year/Period	Base Run	Minimum	Average	Maximum
	------------------million metric tons -------------			
Storage:				
1990	7,838	7,838	7,838	7,838
2000	8,266	8,232	8,313	8,351
2010	8,554	8,501	8,728	8,876
2020	8,610	8,584	8,998	9,312
2030	8,516	8,533	9,202	9,732
2040	8,303	8,398	9,375	10,193
	--------- million metric tons per year ----------			
Flux:[1]				
1990-2000	43	39	48	51
2000-2010	29	27	42	53
2010-2020	6	8	27	44
2020-2030	(9)	(5)	20	42
2030-2040	(21)	(14)	17	46

[1]Positive flux indicates net transfer of carbon from atmosphere to trees.

One mitigation option favored for increasing carbon sinks is an increase in reforestation of marginal cropland and pasture. Several scenarios investigated in previous studies show the possibility of medium- to long-term gains in carbon storage, on the order of 5-10 million metric tons per year for a relatively low-cost program treating about 20 million acres of timberland that would also produce an economic return on investment (table 4.6). A more ambitious program treating all biologically suitable land in the U.S. could achieve substantially higher gains, on the order of those attainable under a major climate shift.

Table 4.6.—Comparison of carbon storage and flux for current base run, reforestallon and recycling scenarios,[1] all ecosystem components, private timberland In the conterminous U.S., 1980-2040.

Year/Period	Base Run	Planting M/R	Planting AF-I	Planting AF-2
	-------------- million metric tons			---------------------
Storage:				
1980	20,308	20,308	20,308	20,308
1990	21,471	21,471	21,514	21,569
2000	22,102	22,135	22,198	22,467
2010	22,515	22,649	22,691	23,303
2020	22,715	23,042	22,860	23,982
2030	22,790	23,241	22,878	24,511
2040	22,839	23,342	23,161	25,332
	----------- million metric tons per year			------------
Flux:				
1980-1990	116	116	121	126
1990-2000	63	66	68	90
2000-2010	41	51	49	84
2010-2020	20	39	17	68
2020-2030	8	20	2	53
2030-2040	5	10	28	82

[1]These scenarios were run on an earlier base prior to the 1993 RPA Update. M/R refers to a study by Moulton and Richards (1990) to estimate the amount of land and cost of reforestation for carbon storage. A $220 million investment level is assumed here. AF-1 refers to implementation of The “economic opportunities” described in Sampson and Hair (1992). AF-2 refers to implementation of the “biological opportunities” described in the same study.

A moderate tree planting scenario affecting only the South Central region, and a separate recycling scenario, were run using the new base projections (table 4.7). Small gains were estimated from tree planting, appearing by 2030 when the trees were sufficiently grown to make some difference. Increased recycling produced a more immediate and larger gain; however, this analysis included only the effects on forest carbon storage, which may be partly increased or offset by changes in the carbon held in product pools.

Table 4.7.—Comparison of carbon storage and flux for previous base run and reforestation scenarios,[1] all ecosystem components, private timberland in the conterminous U.S., 1990 - 2040.

Year/Period	Base Run	Planting M/R	Recycling
	--------------	million metric tons	--------------
Storage:			
1990	21,621	21,621	21,621
2000	22,394	22,356	22,421
2010	22,964	22,913	23,108
2020	23,271	23,306	23,552
2030	23,401	23,468	23,795
2040	23,390	23,492	23,874
	---------- million metric tons per year ----------		
Flux:			
1990-2000	77	74	80
2000-2010	57	56	69
2010-2020	31	39	44
2020-2030	13	16	24
2030-2040	(1)	2	8

[1]M/R refers to a study by Moulton and Richards (1990) to estimate the amount of land and cost of reforestation for carbon storage. A $110 million investment level is assumed here. For the recycling run (described in the 1993 RPA Update), only changes in forest carbon are included. Changes in the disposition of harvested carbon, not simulated here, could offset some of the changes in forest carbon storage and flux.

CONCLUSIONS

This analysis has shown that U.S. forests have been a significant carbon sink since 1952, and that additional carbon sequestration will likely occur through 2040 but at a slower rate. Between 1952 and 1992, carbon stored on forest land in the conterminous U.S. increased by 11.3 billion metric tons, an average of 281 million metric tons for each year, and an amount that offset about one quarter of U.S. emissions of carbon for the period. Most of the historical increase in carbon storage has been on private timberland. Base projections through 2040 show an additional increase of 8.5 billion metric tons of carbon storage, and average accumulation of 177 million metric tons per year.

Most of the projected increase in carbon storage is expected on public forest land. The effects of global change and alternative forest management strategies could result in additional carbon storage through 2040. Carbon in harvested wood, the effects of increased CO_2 in the atmosphere, and large reforestation programs may all have a substantial effect on the rate of carbon sequestration.

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