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Past and prospective carbon storage in United States forests

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ABSTRACT

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Global concern about increasing carbon dioxide concentrations in the atmosphere and the possible consequences of future climate changes have generated interest in understanding and quantifying the role of terrestrial ecosystems in the global carbon cycle. Historical changes in carbon storage in US forests have been estimated from periodic, comprehensive national inventories of forest resources. Since 1952, carbon stored on US timberland has increased by 38% or 8.8×10^{15} g, primarily in the East. This increase is consistent with recently reported trends in Europe and accounts for as much as 21% of a hypothesized carbon sink in Northern temperate forests. Projections of changes in carbon storage over long periods of time were made with a carbon budget model that has been integrated with econometric models of the forest sector. Carbon storage is expected to increase until 2040, but at a slower rate than at present.

INTRODUCTION

Prospective increases in atmospheric carbon dioxide (CO_2) have generated interest in strategies to reduce emissions of CO_2 into the atmosphere, or to offset emissions by storing additional carbon in forests or other terrestrial carbon sinks (Intergovernmental Panel on Climate Change, 1991). Forest ecosystems are capable of storing large quantities of carbon in solid wood and other organic matter. Forest disturbances may add to the pool of CO_2 in the atmosphere through burning of forest lands, deforestation, tree damage or

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death, and decomposition of wood products and byproducts. Forests may also reduce the amount of CO_2 in the atmosphere through increases in biomass and organic matter accumulation. Young growing forests take up carbon at high rates, while carbon uptake in mature forests is roughly balanced by carbon release. The end-use of timber harvested from forests is an additional factor in evaluating the contributions of forestry to the global carbon cycle. Carbon may be stored for long periods of time in durable goods such as furniture or timber bridges, or as discarded wood products in landfills. Eventually, most of the carbon contained in harvested wood or discarded wood products will return to the atmosphere.

Estimates of global fluxes of carbon among major components of the carbon cycle reveal that 1.2×10^{15} g year^{-1} carbon (Detwiler and Hall, 1988) to 2.0–3.4×10^{15} g year^{-1} carbon (Tans et al., 1990) has not been accounted for in annual sinks. It is increasingly accepted that an unidentified large Northern Hemisphere sink exists, and that it contains terrestrial and oceanic components (Intergovernmental Panel on Climate Change, 1992). A recent estimate of the temperate forest component gives a figure of 0.7×10^{15} g year^{-1} carbon of which 0.091×10^{15} g year^{-1} carbon is found in Europe and 0.153×10^{15} year^{-1} carbon is found in the USA (Sedjo, 1992). His estimate for Europe is within the 0.085–0.120×10^{15} g year^{-1} carbon range reported by Kauppi et al. (1992).

ESTIMATING CARBON STORAGE IN FORESTS

Detailed estimates of current carbon storage and accumulation rates were based on national compilations of forest inventory statistics (Waddell et al., 1989; Cost et al., 1990; Birdsey, 1992). These estimates provide a quantitative basis for estimating past carbon storage and projecting future changes. Estimates of past carbon storage in forests were derived from periodic assessments of forest resource conditions, each including a compilation of national inventory statistics (US Department of Agriculture, Forest Service, 1958, 1965, 1974, 1982). Separate estimates were made for major forest types and plantation species in eight geographical regions.

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 below-ground portions of all live and dead trees, including the merchantable stem, the limbs, tops, and cull sections, the stump, the foliage, the bark and rootbark, and the coarse tree roots (of diameter greater than 2 mm). The soil component includes all organic carbon in mineral horizons to a depth of 1 m, excluding coarse tree roots. The forest floor includes all dead organic matter above the mineral soil horizons except standing dead trees, i.e. litter, humus and other

woody debris. Understory vegetation includes all live vegetation except 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, and forest biomass (Waddell et al., 1989; Cost et al., 1990). Periodic estimates of the volume of growing stock were converted to estimates of carbon in complete trees using factors derived from comprehensive biomass studies. Simple models were devised to estimate carbon storage in the soil, forest floor and understory vegetation. Soil carbon for individual States and forest classes was related to mean annual temperature and precipitation using a model similar to that used by Burke et al. (1989) with coefficients derived from data in Post et al. (1982), and modified to account for successional forest development as estimated by average stand age. Estimates of carbon stored in the forest floor and understory vegetation were based on compilations by Vogt et al. (1986) and reviews of numerous intensive-site ecosystem studies.

To make projections of carbon storage, profiles of average changes in carbon storage over time for the four ecosystem components were made for 92 forest classes defined by region, forest type and land-use history. These stand profiles are the basis for a forest carbon budget model (FORCARB) that is linked with econometric models of the forest sector used to make projections of forest resource conditions (Adams and Haynes, 1980; Alig, 1985; Mills and Kincaid, 1992). Linkage with a forest sector model is critical for making valid projections because interactions with expected market responses can affect estimates of future forest harvest levels. The forest sector models provide periodic estimates of area, inventory volume, growth, and removals by age class and management intensity for the defined forest classes. The projected inventory estimates are the basis for estimating carbon storage in the four basic ecosystem components using the stand profiles.

The error associated with historical estimates varies for the different forest ecosystem components. Periodic, regional forest inventories have used a sampling procedure 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 estimating sampling errors for aggregations of inventories, the exact magnitude of the error in estimating tree carbon is unknown. Individual forest inventories have standard errors of the order of plus or minus 3% at the 95% confidence level, and it is not likely that the aggregated estimates of carbon storage in trees have errors exceeding this by much. The error associated with estimates of the other ecosystem components is likely to be much larger since there are no comprehensive, statisti-

cally valid inventories of non-tree organic matter for large areas of the USA. Although many intensive studies of organic matter in forest ecosystems were used in developing the model-based estimates, the representation of highly disturbed, managed and successional ecosystems is poor. A conservative estimate of the error associated with non-tree organic matter is plus or minus 15% at the 95% confidence level. Estimates of historical change from one period to the next do not have appreciably higher error estimates since successive estimates are highly correlated.

There are additional sources of error associated with making projections, largely owing to the uncertainty of the many assumptions in the econometric models which are linked to the carbon budget model. One critical assumption is that future growing conditions will be identical to past or current growing conditions. In fact, forest ecosystems are likely to be growing in very different environmental conditions brought about by increases in atmospheric CO_2, temperature and precipitation changes, and other interacting stresses. There are forest growth models available or under development that can predict the response of vegetation to a changing environment, but none has yet been validated for enough forest types and conditions to allow a comprehensive analysis.

TRENDS IN CARBON STORAGE IN UNITED STATES FORESTS

The amount of carbon currently stored in US forest ecosystems is approximately 52.5×10^{15} g — 4% of all the carbon stored in the World's forests (Ajtay et al., 1979). The total area of US forests is 296×10^6 ha, 32% of the US land area and about 5% of the World's forest area. Most of the carbon in US forest ecosystems is stored below the ground. Trees, including tree roots, account for 31% of all forest ecosystem carbon. The soil contains 59% of the carbon. The remaining 10% is found in litter, humus and coarse woody debris on the forest floor, and in understory vegetation. Live and standing dead trees contain 16.1×10^{15} g carbon. Of this total, 51% is in tree sections considered merchantable for roundwood products, 30% is in other solid wood above the ground, 17% is in the roots and 3% is in the foliage.

Since 1952, carbon stored on 196×10^6 h of US forest land classified as timberland[1] has increased by 38% or 8.8×10^{15} g (Table 1). This is equivalent to 0.251×10^{15} g year^{-1} carbon, over 60% greater than the amount estimated

[1]Timberland is defined as forest land that is capable of producing 1.4 m^3 year^{-1} of industrial wood, and is not withdrawn from timber utilization by statute or administrative regulation. Timberland, rather than the more comprehensive forest-land category, was used for estimating trends and making projections in order to be consistent with the availability of good quality estimates. Since much of the other forest land is in dry areas of slow growth, or reserved areas with mature forests, it is a reasonable assumption that these forest lands are neither accumulating nor releasing large amounts of carbon.

TABLE 1

Estimated carbon storage on US timberland by owner, 1952–2040 (10^{15} g)

Year	Private	National forest	Other public	Total
1952	14.1	6.6	2.5	23.1
1962	15.9	7.1	2.8	25.8
1970	17.4	7.2	3.0	27.7
1977	19.1	7.3	3.2	29.6
1987	21.2	7.0	3.6	31.9
2000	21.9	6.7	4.2	32.8
2010	22.2	6.7	4.7	33.6
2020	22.3	6.6	5.1	34.1
2030	22.2	6.7	5.6	34.6
2040	22.0	6.8	6.1	34.8

TABLE 2

Estimated carbon storage on US timberland by region, 1952–2040 (10^{15} g)

Year	North	South	West	Total
1952	6.8	6.2	10.1	23.1
1962	8.5	7.1	10.1	25.8
1970	9.6	8.1	10.0	27.7
1977	10.8	9.1	9.7	29.6
1987	12.5	10.0	9.4	31.9
2000	13.7	10.0	9.1	32.8
2010	14.5	10.0	9.1	33.6
2020	15.1	9.9	9.1	34.1
2030	15.6	9.8	9.2	34.6
2040	15.8	9.7	9.3	34.8

by Sedjo (1992) and enough to offset 21% of US emissions of carbon to the atmosphere for the period (Boden et al., 1990). Most of the increase occurred on private and other public timberland. By region, most of the increase in carbon storage was in the eastern USA, with the West showing a slight decline (Table 2). Estimates for the West as a whole mask increases in Rocky Mountain States and decreases in Pacific Coast States.

Estimates from the base run of the most recent assessment of US forest resources (US Department of Agriculture, Forest Service 1989) reveal that carbon storage on private timberlands is expected to increase by about 1.0×10^{15} g over the next 20 years, then to decline slightly by 2040 (Table 1). Carbon storage on other public timberland could increase by 2.5×10^{15} g by 2040. This ownership summary obscures divergent regional trends. For example, timberland in the Northern USA will continue to sequester carbon until 2040, giving a total addition of about 3.3×10^{15} g (Table 2). In the South, after a slight increase, carbon storage on timberland will decline slightly. These

changes reflect expected regional changes in the forest resource — an ageing, predominantly hardwood resource in the North, and increasing utilization of both softwoods and hardwoods on shorter rotations in the South. In the West, carbon storage may increase slightly owing to a continued build-up in the Rocky Mountain States.

TEMPERATE FORESTS AND THE GLOBAL CARBON CYCLE

If it is assumed that temperate forests in the Northern Hemisphere are releasing and absorbing the same amount of CO_2 each year, then an estimated 1.2×10^{15} g year^{-1} carbon (Detwiler and Hall, 1988) to $2–3.4\times10^{15}$ g year^{-1} carbon (Tans et al., 1990) has not been accounted for in global carbon budget calculations. This assumption has proved to be inaccurate, as European forests have been found to contribute 5–9% of the unexplained carbon flux during the period 1971–1990 (Kauppi et al., 1992), and this analysis shows that forests of the USA have been assimilating carbon at 12–21% of the unexplained flux since 1952. This supports the hypothesis that a large proportion of the gap in the carbon storage cycle can be explained by biomass accumulation in temperate forests (Kauppi et al., 1992). From 1970 to 1987, approximately 2.5 times as much carbon accumulated in US forests compared with European forests.

Not included in the analysis is the additional carbon stored in wood products and landfills as a result of the large volumes of wood harvested in the USA since 1952. Simple calculations suggest that there was a net annual accumulation of about 0.036×10^{15} g carbon in wood sinks between 1952 and 1987[1]. This is 14% of the net annual accumulation in forests during the same period.

In 1989, emissions from tropical deforestation were estimated at $2.0–2.8\times10^{15}$ g carbon (Intergovernmental Panel on Climate Change, 1991). The accumulation of biomass in forests in the USA has offset these emissions by 10% on average. Assuming that $2–3.4\times10^{15}$ g year^{-1} carbon are absorbed by temperate forests and wood sinks, emissions from tropical deforestation have been fully offset by carbon sequestration in Northern temperate regions.

Fossil fuel emissions in the USA release about half the carbon per year compared with releases from tropical deforestation. In 1985, 1.16×10^{15} g carbon were emitted (Boden et al., 1990; Plantinga and Birdsey, 1993) and this is expected to increase at an average rate of growth of 1.4% until 2025. Historically, accumulation in US forests offsets emissions from fossil fuels by 21%.

[1]Assume annual removals of 0.382×10^{9} m^3 year^{-1} from 1952–1987 (Waddell et al., 1989) to estimate total removals at 13.4×10^{9} m^3; assume that 40% of removed wood remains in wood products in 1987 (US Department of Agriculture, Forest Service, 1989), and multiply the result by 234 kg m^{-3} carbon (Birdsey, 1992) and divide by 35 to estimate 0.036×10^{15} g year^{-1} carbon.

However, our projections show that this offset will decline dramatically as accumulation in US forests drops to about 0.05×10^{15} g year^{-1} carbon on average between 2000 and 2040.

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