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Carbon sequestration by forests of the United States. Current status and projections to the year 2040

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ABSTRACT

National-level forest carbon budgets are of interest in relation to understanding the global carbon cycle, comparing anthropogenic and biogenic sources of carbon, and developing possible strategies for conserving and sequestering carbon. In this study, forest carbon pools and flux for timberlands in the conterminous United States were projected over the coming 50 years by coupling a forest economics model, a forest inventory model and a forest carbon model. In the base case scenario, US forests sequestered carbon in the 1990s at a rate of 80 Tg yr^{-1} but came close to carbon equilibrium by the 2020s. The dominant factors driving this change were an increasing forest harvest, a decreasing forest land base, and a reduction in average stand age. Scenarios in which alternative forest policy options were implemented related to increased paper recycling and increased afforestation (5×10^6 ha) produced long-term increases in carbon sequestration on the forest land base of up to 15 Tg yr^{-1}. The carbon sink on the forest land base currently offsets 6% of US fossil carbon emissions but that proportion is likely to decrease over the coming decades.

1. Introduction

Carbon sources or sinks related to deforestation and forest management are a significant component of the global carbon cycle. Studies with atmospheric transport models have suggested that forests of the northern temperate zone are currently a carbon sink (Tans et al., 1990), however, earlier assessments have indicated an approximate carbon equilibrium (Houghton et al., 1987). In temperate zone forests, successive forest inventories based on repeated forest surveys (Kauppi et al., 1992), or modeling approaches which couple age class-based forest inventories with associated growth and yield tables (Turner et al., in press), offer opportunities for building annual carbon budgets at the regional to continental scale which could help resolve this issue. The framework convention for climate change (Parsons et al., 1992) calls for national greenhouse gas emission inventories and has recently provided impetus for development of national forest carbon budgets (Maclaren and Wakelin, 1991; Birdsey, 1992; Kurz et al., 1992; Kolchugina and Vinson, 1993).

Interest has also arisen in projecting forest carbon budgets into the future because forest management options have been included among potential strategies for moderating the rise in atmospheric CO_2 (Sampson and Hair, 1992). The halting of deforestation, the acceleration of afforestation, and alteration of management variables such as rotation age, have been proposed. These projections must be model-based and may require information on socioeconomic, as well as purely biological, factors. In this analysis, we employ economic, forest inventory, and forest carbon

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models to evaluate the current forest carbon budget of the United States (US) as well as project the forest carbon balance through the year 2040. We examine a base case, and two forest policy scenarios related to increased paper recycling and increased afforestation. These simulations do not treat the potential effects of climate change and increasing CO_2 on forest distribution and productivity, however, they provide a framework for doing so as improved climate scenarios at the regional scale become available.

2. Methods

Our approach to modeling the forest carbon budget was based on the combination of three components: a forest sector economic model, a forest inventory model, and a forest carbon model (Turner et al., 1993). The forest sector economic model (timber assessment market model [TAMM]; Adams and Haynes 1980) incorporates projections of population increase, land use change, and timber demand, to estimate future harvest levels by region, fiber type and forest type. The forest inventory model (aggregate timberland assessment system [ATLAS]; Mills and Kincaid, 1992) distributes a given harvest volume among the forest types and age classes based on the available inventory. The forest inventory is then advanced in a 5 or 10 year time step, depending on the region, by reference to a set of growth and yield tables which are associated with the different forest types. TAMM and ATLAS were used in a coupled mode by the US Department of Agriculture (USDA) Forest Service for the 1990–2040 projections associated with the 1989 Resources Protection Act (RPA) Assessment and are documented more fully in Haynes (1990).

The forest carbon model (Turner et al., 1993; in press) contains a set of stand level carbon budgets (Fig. 1) which relate the growth and yield tables from ATLAS to trends in total ecosystem carbon over the course of stand development. Allometric relationships are used for converting merchantable volume in the growth and yield tables into tree carbon. A modeling approach involving harvest residue, rates of tree mortality and rates of dead wood decay, is employed for estimating the pool of woody debris in each age class. Literature studies (Vogt et al., 1986) provide the basis for estimating

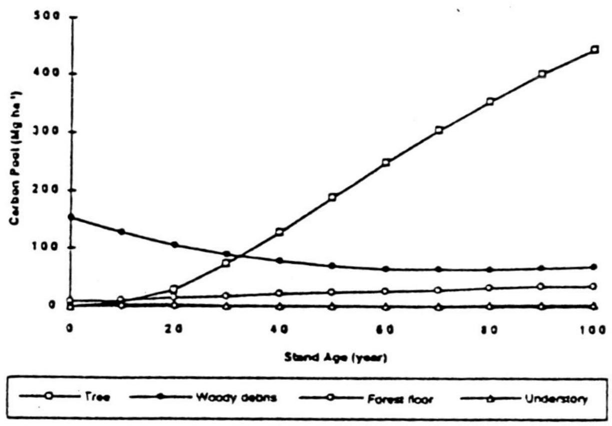

Fig. 1. Stand level carbon budget for the medium productivity Douglas-fir forest type of the Pacific Northwest region.

the carbon in the forest floor and understory. Soil carbon is assumed to be stable over the course of stand development in accord with the recent literature (Alban and Perala, 1992; Johnson, 1992).

In order to estimate carbon flux, the projected forest inventory from a TAMM/ATLAS run was coupled to the forest carbon model at decadal intervals. Differences in the total forest carbon storage between the decades provided the basis for estimating net carbon flux. These differences reflect both growth and harvest removals. Changes in soil carbon associated with gains or losses in the forest land base are excluded from the flux estimate.

Although disturbances (e.g., wildfire) produce carbon emissions, and alter growth rates and the age class distribution, they were not treated explicitly in this analysis. The effects of noncatastrophic disturbance are implicit in the ATLAS growth and yield tables because the tables are based on repeated measurement of permanent plots (USDA, 1992a). Catastrophic disturbances are not considered in ATLAS. However, such disturbances are usually salvage logged and the recovered merchantable wood contributes to the targeted harvest removals. Thus, to some degree these disturbances are analogous to harvests and are captured by our approach.

A second notable limitation in this analysis regards the potential changes in carbon storage in stands older than the maximum in the ATLAS yield tables. These stands are carried from decade to decade in the projections with no change in carbon storage. Limited observations indicate that old-growth stands may be accumulating both live and dead carbon (Franklin and Spies, 1991), thus we may be underestimating the carbon sink in some areas.

The projected inventory from ATLAS covers only private timberland (136.1×10^6 ha), i.e., 68% of total forested land in the conterminous US capable of producing $> 1.4\ m^3\ ha^{-1}\ yr^{-1}$ of merchantable wood. For the associated public timberland (62.9×10^6 ha), a current forest inventory was constructed based on USDA Forest Service reports (Waddell et al., 1989; Haynes, 1990; Turner et al., in press). Inventory projections in terms of total growing stock by region were based on Haynes (1990) and reflect projected rates of growth and harvest. The ratios of growing stock volume to total tree carbon derived from the current inventory were used with the volume projections to estimate future carbon storage on public lands.

Possible changes in the pool of carbon stored as forest products still in use or in landfills were not analyzed here. These pools may represent a significant carbon sink (Birdsey et al., 1993; Turner et al., 1993); however, a modeling approach which accounts for the historical inputs to these pools is needed to simulate changes over time.

The base case TAMM/ATLAS scenario in this study was similar to that in the 1989 USDA forest service RPA Assessment (Haynes, 1990) with some updating of the volume projections on public lands (R. Haynes, USDA Forest Service, Portland, OR, personal communication). The basic trends in that projection include a future with continued growth in consumption of forest products, rising real prices for timber, and attenuated growth in timber inventories. After 2020, increased timber production associated with forest areas now planted serves to stabilize the forest inventory.

In addition to the base case, 2 alternative policy scenarios were considered in order to evaluate the sensitivity of the carbon storage projections to forest policy options. The increased paper recycling scenario called for paper recycling in the US to increase approximately 20% above the levels assumed in the base case scenario (reaching 45% by 2000). Haynes (1990) discusses a similar scenario and its potential effects on harvest levels and inventories. In the afforestation scenario, 5 million ha of marginal pastureland or cropland are converted to forest, primarily in the South Central region of the US. The basis for locating the available land and determining the appropriate forest type was the study of Parks et al. (1992) which employed a current land cover database as well as maps of the distribution of different forest types. Soil carbon is assumed to increase on afforested lands, rising 20% over a base derived from Kern (1994) during the course of the first rotation. Management of public forest land in these scenarios is assumed to be the same as the base case. Further details of the these scenarios are described in Turner et al. (1993) and Winnett et al. (1993) along with a treatment of their projected economic impacts.

3. Results and discussion

In the base case scenario, the forest land base is a net carbon sink of 80 Tg yr^{-1} in the 1990s (Fig. 2). Growth of live tree carbon, particularly in the Northeast region, more than offsets reductions associated with natural mortality, harvests and land use change. An increase in the woody debris pool is also suggested (Table 1), although the complex history of forest management and fire in the United States makes it difficult to model woody debris rigorously. The difference approach to flux calculation used in this study tends to overestimate woody debris formation because land coming into the zero-year age class is assumed to have woody debris, whereas it may have orginated via land use change. The accumulation of tree carbon in the 1990s is a continuation of a trend over the last several decades in the US (Clawson, 1979; Birdsey

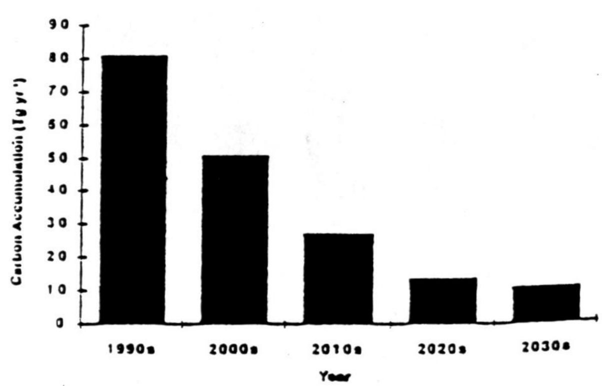

Fig. 2. Projected net carbon accumulation rate on the forest land base for timberland under the base case scenario.

Table 1. *Projected carbon pools (Tg) on private and public timberland*

		Private					Public	US
Year	Area (× 10^6 ha)	live tree	forest floor	coarse woody debris	understory	total	total[a]	total
1990	199.0	8,037	1,152	2,160	339	11,688	6,897	18,585
2000	197.4	8,269	1,188	2,346	342	12,145	7,247	19,392
2010	195.9	8,304	1,201	2,414	347	12,266	7,633	19,899
2020	194.8	8,166	1,193	2,440	351	12,150	8,021	20,171
2030	193.5	7,931	1,173	2,426	351	11,881	8,426	20,307
2040	192.6	7,655	1,143	2,438	350	11,586	8,831	20,417

[a] Projections on public lands are based on changes in tree carbon only (see text).

et al., 1993) and is associated with recovery of eastern forests from heavy cutting earlier in this century, reversion of land from agriculture to forest (Williams, 1988) and fire suppression (USDA, 1992b).

The projected net carbon sink declines over the following decades to 11 Tg yr^{-1} in the 2030s (Fig. 2). Changes in the tree carbon pool dominate the overall carbon sink and the most important factor in the declining strength of the forest land base sink is a relatively large increase in the harvest level. The tree carbon sink is essentially a function of the difference between net tree growth and harvest removals (Fig. 3). Tree growth increases moderately over the fifty year simulation because of the shift to a more productive age class distribution and more intensive management. Based on the ATLAS inventory projections, average tree growth on private timberland in the US rises from 204 g m^{-2} yr^{-1} in the 1990s to 229 g m^{-2} yr^{-1} in the 2030s or from 258 to 293 Tg yr^{-1}. However, the harvest level rises much faster, with tree carbon removals on private timberland increasing by 85 Tg yr^{-1} over the 50 year scenario (Fig. 3). Private timberland begins losing carbon midway through the scenario (Table 1).

Some of the reduction in the carbon sink is related to a 5% (6.4 × 10^6 ha) reduction in the projected area of private timberland over the 50-year scenario (Fig. 4). Because the carbon flux estimates are based on differences in pools between two points in time, reduction in the land base means all nonsoil carbon on those lands is assumed to be harvested or returned to the atmosphere. This source of carbon tends to offset sinks

Fig. 3. Projected tree growth and harvest removal on private timberland through 2040.

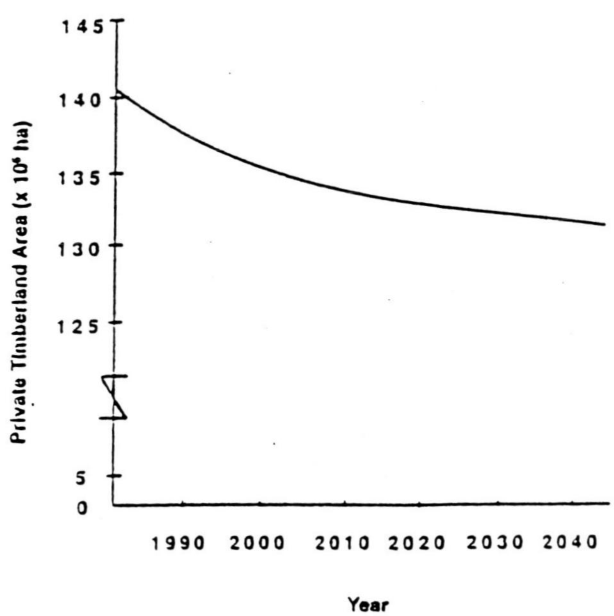

Fig. 4. The projected forest land base for private timberland through 2040.

elsewhere on the forest land base. The projected decline in timberland is driven primarily by conversion for agricultural and urban uses (Alig et al., 1990). At a mean nonsoil carbon storage of 8.5 kg m^{-2} for private timberland in 1990, this area loss represents a reduction in carbon storage of 544 Tg, or about 11 Tg yr^{-1} over the 50 year projection.

The trend towards more intensively managed forests which are characterized by younger average age classes and lower average carbon storage (Cooper, 1983; Harmon et al., 1990) also contributes to reducing the net sink. The ATLAS inventory model projections allow detailed examination of trends in age class distribution on private lands and for many forest types the trend is towards a lower average age. The trend is apparent even in the comparison of the age class distribution across all private timberland in the 1990s and 2030s (Fig. 5). In contrast, projections of increasing growing stock volume on public land suggest a gradual rise in the average age. Proposed changes in management of public lands (Brooks and Grant, 1992), including harvest reductions and more retention of woody debris after harvest, are likely to augment rates of carbon sequestration.

The general trend for the carbon sink in the increased paper recycling scenario was similar to the base case scenario, but with an additional carbon sequestration which averaged 8 Tg yr^{-1}

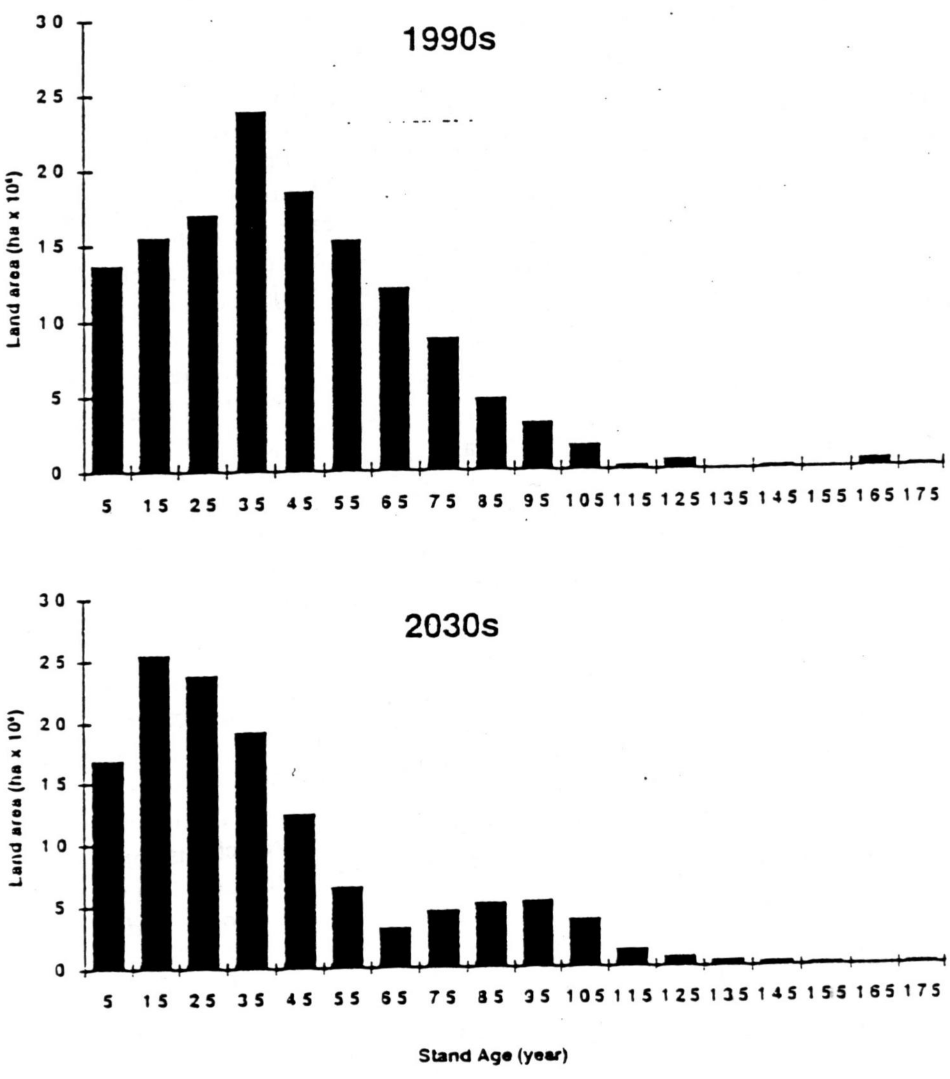

Fig. 5. Age class distribution in 1990s and projected for 2030s on private timberland.

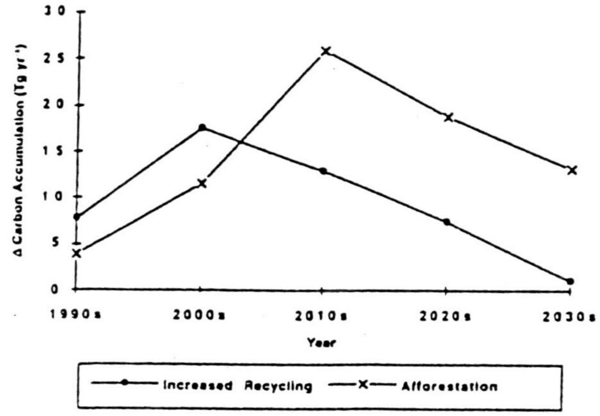

Fig. 6. The difference in carbon sequestration rate on the forest land base for the afforestation and increased paper recycling scenarios relative to the base case scenario.

(Fig. 6). This increased sequestration was driven by a modest reduction in harvest over the base case. There was not a direct relationship between increased paper recycling and increased carbon storage on the forest land base because of interactions between increased timber supply, lower timber prices, increased demand, and decreased timber imports (Winnett et al., 1993).

In the afforestation scenario, carbon sequestration was as much as 25 Tg yr^{-1} greater than the base case scenario in the early decades and averaged 14 Tg yr^{-1} higher over the 50 years (Fig. 6). The accumulation rate peaked midway through the scenario when the growth rates of the planted trees were at a maximum and harvest removals had not begun. Approximately 47 million ha of marginally productive, privately-owned crop and pasture land in the US is biologically capable of supporting tree growth (Parks et al., 1992). Thus, significantly higher carbon sequestration is possible from afforestation.

Opportunities for validating the modeling framework in this analysis are limited. The estimate for tree growth in the 1990s is close to that in Birdsey (1992) and, expressed in terms of an increase in growing stock volume, is 2% below the estimate in Powell et al. (1993) for US timberlands in 1991. The Forest Service estimates are based on repeated measurements over the set of permanent plots maintained by the USDA forest service inventory and analysis units (1992b). Subak et al. (1993) indicate a net carbon sink on commercial forests in the US of 60 Tg yr^{-1} based on inventory data from the UN FAO. The modeling study of Heath and Birdsey (1993) suggests a forest land base carbon sink of 73 Tg yr^{-1} over the period 1987–2010, close to the two decade average of 66 Tg yr^{-1} here. However, the sink for "dead carbon" was significantly larger in that study. Results of the two projections diverge over time because of a continued accumulation ($\sim$50 Tg yr^{-1}) in the "dead carbon" pool which is not found in this analysis. A long-term carbon sink of that magnitude, within the pool of woody debris, forest floor and soil organic matter, seems unlikely considering the general insensitivity of forest soil carbon in the temperate zone to stand age class (Alban and Perala, 1992; Johnson, 1992) and the way that harvesting resets the pools of forest floor and woody debris carbon.

Evidence for a contemporary forest carbon sink is common to several temperate zone countries which are responding to earlier periods of deforestation and heavy cutting (Sedjo, 1992; Dixon et al., 1994). The carbon sink associated with the forest land base of the US in the 1990s represents an offset of about 6% of the fossil carbon emissions ($\sim$1300 Tg in 1990). Projections of fossil carbon emissions for the US range from a stabilization at 1990 levels to a steady 1–2% increase per year. At the same time, the carbon sink associated with the forest land base is projected to decrease. The pool of forest products still in use or in landfills will tend to increase with the harvest level, however the majority of the current harvest does not go into long term storage (Harmon et al., 1990) and the magnitude of this sink is not large relative to fossil emissions. Thus, the carbon sink associated with the forest sector in the US will probably offset a decreasing proportion of national fossil carbon emissions over the coming decades.

Large uncertainties are inevitably associated with efforts to model at the spatial and temporal scale of this study and a number of specific issues relating to forest carbon dynamics need increased attention. For the US in particular, an improved forest inventory and inventory projections on public lands is needed, since historically, the USDA Forest Service forest inventory and analysis units have surveyed primarily private timberland (USDA, 1992b). A better understanding of soil carbon and woody debris dynamics following harvest is also needed. Assumptions of significant losses in soil carbon after harvest, and gains later in stand development, which have been employed in earlier carbon budget models (Houghton et al., 1983; Heath and Birdsey, 1993), may not be warranted in temperate zone forests. Any effort to model biologically-based processes over the coming decades should also treat the potential effects of higher CO_2 and projected climate change on forest productivity and distribution.

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