# CARBON FLUXES RESULTING FROM U.S. PRIVATE TIMBERLAND MANAGEMENT

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**Abstract.** A carbon budget model was developed to examine the effects of forest management practices on carbon storage in U.S. private timberlands. The model explicitly incorporates the demand for wood products and its impact on harvesting and other management decisions. Forest carbon is divided into four components: carbon stored in trees, soils, forest litter, and understory vegetation. Changes in the forest carbon inventory result from tree growth and management activities, in particular harvesting. Harvesting of timber for wood products is determined by demand and supply forces. The model then tracks carbon in timber removals through primary and secondary processing and disposal stages. Harvesting also has effects on carbon in soils, forest litter, and understory vegetation. A base-run scenario projects increases in carbon storage in U.S. private timberlands by 2040; however, this increase is offset by carbon emissions resulting from harvesting.

## Introduction

Since trees convert carbon dioxide to fixed carbon through photosynthesis, forests can act as large carbon sinks and thereby mitigate the build up of atmospheric carbon, the principal greenhouse gas. However, forests also can be significant carbon sources, primarily as a result of anthropogenic activities. Deforestation in tropical countries has contributed to increasing atmospheric carbon concentrations (Houghton *et al.*, 1987) and in temperate forests, management practices such as logging old growth can release significant amounts of carbon (Harmon *et al.*, 1990). Yet while tropical forests appear to be a carbon source (Detwiler and Hall, 1988), there is evidence suggesting that temperate forests are a carbon sink. A recent analysis by Tans *et al.* (1990) points to the existence of a terrestrial carbon sink at mid-northern latitudes of between 2.0 and 3.4 Gigatons (Gt) per year. Conceivably, forests are a large component of this sink given their carbon storage potential relative to other land covers. If northern temperate forests are a significant carbon sink, then future management practices on these forests may have important implications for the global carbon cycle and potential changes in climate.

Broadly defined, northern temperate forests cover about 4.4 billion acres (1.8 billion ha), primarily in North America, Europe, and the Soviet Union (World Resources Institute, 1990). These forests contain most of the world's coniferous growing stock and supply the majority of softwood roundwood. About 17% of northern temperate forests (731 million acres or 296 million ha) are in the United States (Waddell *et al.*, 1989). Roughly two-thirds of U.S. forests are classified as tim-

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berland (forest land producing or capable of producing crops of industrial wood and not withdrawn from timber utilization), the bulk of which is held by private owners. Private timberlands are generally the most productive forest lands in the U.S. for growing timber, supplying the majority of stumpage for solid wood and pulp products (Waddell *et al.*, 1989).

The purpose of this study was to project carbon storage in U.S. private timberlands. Since private timberland acreage has been relatively stable and is expected to decline only slightly in the coming decades (Alig *et al.*, 1990), carbon storage in these lands will be determined mostly by forest management practices, in particular the timing and volume of harvests. Harvest rates will be influenced by numerous interrelated factors, including timber growth rates, the demand for wood products, and technological change. Although U.S. private timberlands account for only about 8% of all northern temperate forests, they may be broadly representative of some of these forests. Many northern temperate forests will be subject to the same market forces which will shape U.S. private timberland management in the future. To the extent that these forces have similar effects on the management of these forests, similar trends in carbon storage may be observed.

## Forest Carbon Budgets

Carbon fluxes in U.S. private timberlands are expected to be strongly influenced by timber harvests. To clarify these impacts, a simple model of carbon fluxes in a single timber stand is considered below. In Figure 1, the timber stand has an initial carbon inventory ($C_0$). After a harvest, the inventory declines to $T_1$ due to the conversion of carbon stored in the soil, forest floor, understory vegetation, and trees (Table I). Some of the soil and forest floor carbon is unaffected by the harvest ($F_1$) and a portion of the harvested tree carbon is sequestered in solid wood and pulp products ($P_1$). Over time, the decline in carbon stored in products (and landfills) is outweighed by increases in forest carbon due to understory and tree regeneration and growth. The carbon budget for the stand is balanced when the amount of forest carbon ($F'_1$) equals the initial inventory ($C_0$) minus the amount still fixed in wood products and landfills ($P'_1$).

Assuming the carbon budget is balanced after the first harvest rotation, the length of the second rotation must be increased to balance the budget a second time. In addition to replacing losses of forest carbon resulting from the second harvest ($C_0$ minus $T_2$), forest carbon growth must offset continuing declines in carbon sequestered in wood products from the first harvest ($P'_1$ minus $P''_1$). The carbon budget will be balanced after the second rotation when the forest carbon ($F'_2$) equals the initial inventory ($C_0$) minus the amount of carbon in wood products from the second harvest ($P'_2$) plus the decline in wood products from the first harvest ($P'_1$ minus $P''_1$). If forest carbon growth is the same during the first and second rotations, then clearly a longer second rotation will be required to balance the carbon budget.

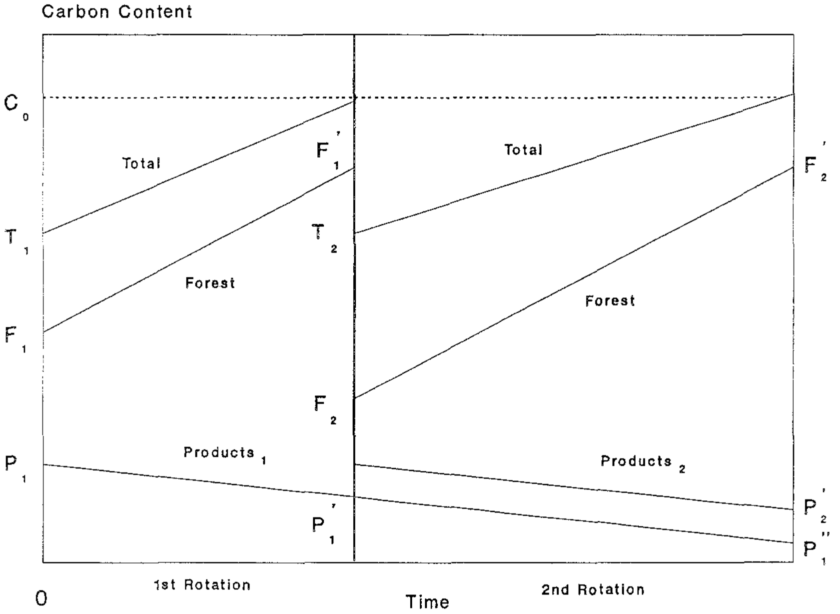

Fig. 1. Changes in the carbon inventory from harvesting a stand of timber.

TABLE I: Definitions of forest carbon components used in forest carbon budget model

| Forest component | Definition |
|---|---|
| Trees | All above- and below-ground 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). |
| Soil | All organic carbon in mineral horizons to a depth of one meter, excluding coarse tree roots. |
| Forest floor | All dead organic matter above the mineral soil horizons, including litter, humus, and other woody debris. |
| Understory vegetation | All live vegetation except that defined as live trees. |

Source: Birdsey (1991)

Several conclusions regarding the effects of forest management on carbon budgets can be drawn from this analysis. Timber harvesting causes an initial carbon deficit. If the forest is reharvested before the budget is balanced, the carbon deficit is increased. Conversely, carbon surpluses result when the forest carbon accumulates beyond the balanced budget inventory. If the budget is balanced initially, then over successive harvest rotations, shorter rotation lengths and higher timber removals rates than growth will result, all else equal, in carbon deficits. Provided declines in sequestered carbon from previous harvests are first offset, then longer rotations, greater sequestration in wood products and landfills, and higher forest growth will lead, all else equal, to budget surpluses.

## A Base-run Projection for U.S. Private Timberlands

The USDA Forest Service conducts periodic assessments of the nation's forest resources in response to Federal Resources Planning Act (RPA) directives. Recent forest inventories reveal an estimated 347 million acres (140 million ha) of private timberland in 1987, approximately one-half of the forest land in the United States (Waddell *et al.*, 1989). In 1987, the net annual growth of growing stock (merchantable portion of living commercial species) was 16.7 billion cubic feet. Removals (harvests and thinnings) of growing stock were 13.1 billion cubic feet, or about 78% of growth.

The U.S. Forest Sector Model, maintained by the Forest Service, is used to project changes in forest resources under the basic assumption of market equilibrium (demand equals supply) for wood products (Figure 2). The Timber Assessment Market Model (TAMM) (Adams and Haynes, 1980; Haynes and Adams, 1985) projects U.S. demand for wood products, including demand for stumpage from private timberlands. TAMM interacts with the Aggregate Timberland Assessment System (ATLAS) (Mills and Kincaid, 1991) to determine changes in the U.S. private timberland inventory. ATLAS incorporates assumptions about silvicultural treatments and harvesting methods (in this analysis, all harvests are clearcuts). Timber growth assumptions used in making projections are derived from Forest Service permanent plot inventories. Land use trends are projected with regional models (Alig *et al.*, 1990).

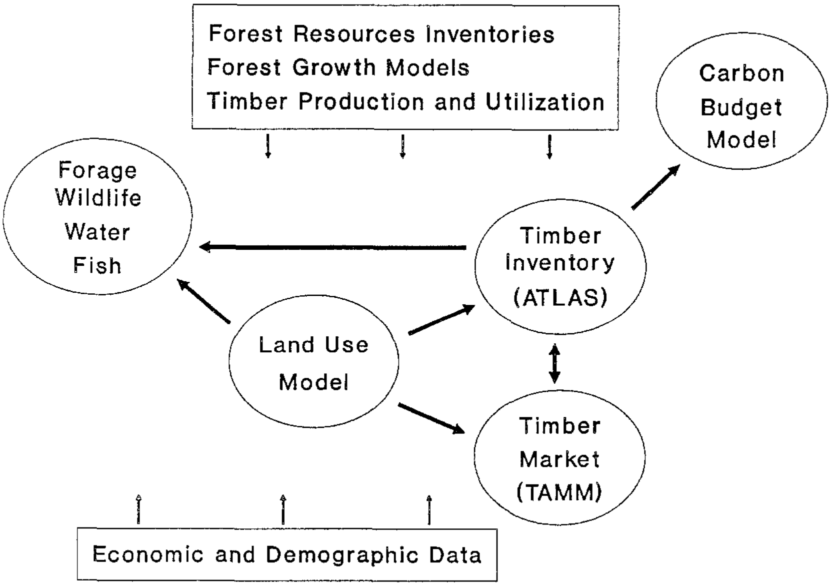

Fig. 2. The U.S. forest sector model.

The U.S. Forest Sector Model is used to develop a base-run projection reflecting current trends in forest resource use (Table II). The principal assumption in this scenario is that future increases in population and economic activity will increase the demand for wood products. Increasing demand results in higher real prices for wood products and increased removals from private timberlands. After 2020, private timberland removals are projected to exceed growth and consequently, the inventory declines from a peak in 2010. Higher prices for wood products are assumed to induce the adoption of more efficient processing technologies which extend timber supplies from private lands. The private timberland base is expected to decline by 19 million acres (8 million ha) by 2040 due in part to population-related demands for other land uses (for example, urbanization).

Management practices in the base-run scenario reflect the influence of higher demand for wood products. Rotation lengths tend to decrease over time since

TABLE II: Basic results of the U.S. forest sector model, base-run projections

| Result | | Projections | | | | |
|---|---|---|---|---|---|---|
| | 1987 | 2000 | 2010 | 2020 | 2030 | 2040 |
| | | Millions | | | | |
| U.S. population | 242 | 275 | 294 | 312 | 325 | 333 |
| | | Trillion 1982 dollars | | | | |
| Gross National Product | 3.7 | 5.4 | 7.0 | 9.2 | 12.0 | 15.6 |
| | | Billion cubic feet | | | | |
| Growing stock on private timberland | | | | | | |
| Area (million acres) | 347 | 342 | 338 | 334 | 331 | 329 |
| Inventory | 456 | 483 | 488 | 485 | 473 | 460 |
| Growth | | 207 | 169 | 175 | 179 | 183 |
| Removals | | 179 | 159 | 173 | 187 | 194 |
| | | 1982 = 100 | | | | |
| Lumber price indices | | | | | | |
| Softwood | 112 | 146 | 155 | 163 | 160 | 158 |
| Hardwood | 120 | 133 | 146 | 163 | 182 | 199 |
| | | 1982 $/Thousand board feet | | | | |
| Stumpage prices | | | | | | |
| South | 124 | 169 | 218 | 243 | 222 | 232 |
| Pacific coast | 114 | 160 | 212 | 240 | 249 | 245 |
| | | Billion board feet | | | | |
| Softwood lumber | | | | | | |
| Production | 34 | 39 | 40 | 44 | 47 | 49 |
| Imports | 14 | 11 | 12 | 13 | 11 | 10 |

Source: USDA Forest Service (1990).
Note: Growth and removals represent changes over the preceding ten-year period.

higher prices give landowners incentives to cut timber earlier. Landowners also respond to higher demand for wood products by increasing timber supplies through management practices. For example, on many forests landowners are assumed to use genetically-improved planting stock and intensify silvicultural treatments. As discussed below, these changes in management practices have implications for the forest carbon budget. These changes do not, however, reflect management strategies to mitigate or adapt to possible climatic changes. Nor does the base-run projection include prospective responses of forests to climate change. Complete results and assumptions of the base-run scenario are found in USDA Forest Service (1990).

## Estimating Carbon Storage in U.S. Private Timberlands

Base-run projections of growing stock volumes on U.S. private timberlands were converted to estimates of forest carbon. Growing stock inventories by age class and area were derived from the ATLAS model and grouped into 248 'management units', defined by region, owner, species, and site quality. The growing stock inventories were treated as 'snapshots' of the forest at particular times and converted to tree, soil, forest floor, and understory carbon. Thus, the model only simulated changes in carbon stored in the merchantable portion of trees. Carbon inventories for the soil, forest floor, and understory vegetation were then derived from the growing stock inventories using equations discussed below. Removals of growing stock for each management unit also were converted to estimates of harvested carbon.

Tree carbon was assumed to be a constant multiple of growing stock volume. Total tree volume was estimated from growing stock volume to account for additional volume in non-merchantable portions of the tree such as roots and branches (Birdsey, 1991). Tree volume was converted to carbon using separate factors to account for differences in wood density between regions and species (Birdsey, 1991). Changes in the tree carbon inventory result from tree growth and timber removals. Increases in the tree carbon inventory result from growth of growing stock. In the general model, tree carbon increases rapidly in early years but as tree productivity declines the rate of increase declines (Figure 3). Declines in the tree carbon inventory were estimated from growing stock removals. Following a harvest, the non-merchantable portion of the tree was assumed to be converted to emissions instantly. The disposition of the merchantable portion will be discussed in greater detail below.

Soil, forest floor, and understory carbon inventories were estimated using quadratic equations expressing carbon as a function of growing stock volume. Equations were derived from data on carbon storage in relatively undisturbed, second-growth stands (Birdsey, 1991). Separate equations were estimated to account for differences in carbon storage between regions, species, site quality, and prior land uses (forest, cropland, and pasture). In the general model, soil carbon

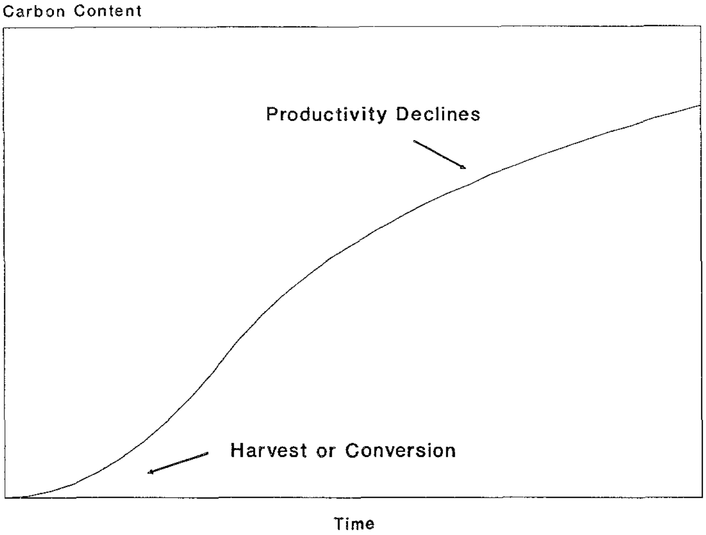

Fig. 3. General model of tree carbon inventory over time. Note: This curve represents the tree carbon inventory over time for an average stand. Differences in species, site quality, region, and prior land use account for differences in these curves (see text).

declines after a harvest due to heightened exposure to heat and moisture, then increases with tree growth, litterfall, and root turnover (Figure 4). The rate of increase in forest floor carbon was assumed to be constant and then taper off as tree productivity declines (Figure 5). Understory carbon increases rapidly after a

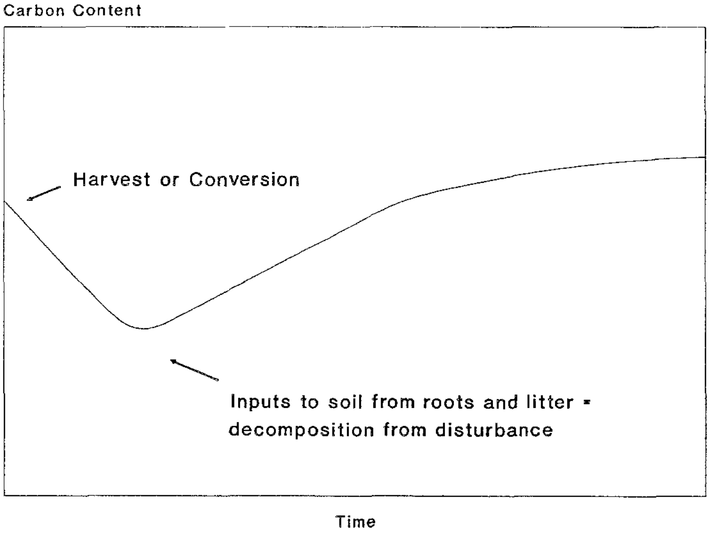

Fig. 4. General model of soil carbon inventory over time. Note: This curve represents the soil carbon inventory over time for an average stand. Differences in species, site quality, region, and prior land use account for differences in these curves (see text).

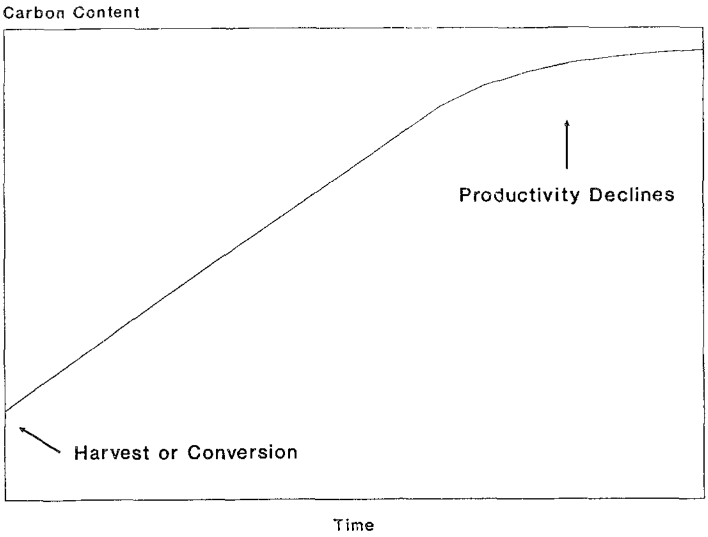

Fig. 5. General model of forest floor carbon inventory over time. Note: This curve represents the forest floor carbon inventory over time for an average stand. Differences in species, site quality, region, and prior land use account for differences in these curves (see text).

harvest, declines after trees are established, and increases when gaps appear in the canopy (Figure 6).

As mentioned, no attempt was made to account separately for fluxes of soil, forest floor, and understory carbon resulting from tree growth and removals. Only the net change, as reflected in changes in the growing stock inventory over time, was estimated. This method was augmented by modeling the direct effects of harvesting and replanting activities. For each management unit (management units can be loosely thought of as stands, but see above description), the model specifies that the amount of soil carbon immediately after a harvest is equal to the amount immediately before a harvest. After a harvest, the soil carbon inventory changes as depicted in Figure 4. This method insured that, for each management unit, the initial soil carbon inventory was consistent with the inventory prior to harvest, reflecting the fact that harvests cause only a portion of soil carbon to be converted to emissions. Conversely, all forest floor and understory carbon accumulated between harvests was assumed to be converted to emissions by harvesting and replanting activities. After a harvest, forest floor and understory inventories were returned to an initial value.

## Disposition of Growing Stock Removals

A model of harvested carbon flows (HARVCARB) (Row and Phelps, 1991) was used to track U.S. private timberland removals from harvest to final disposition. As mentioned above, growing stock removals were derived from the ATLAS model

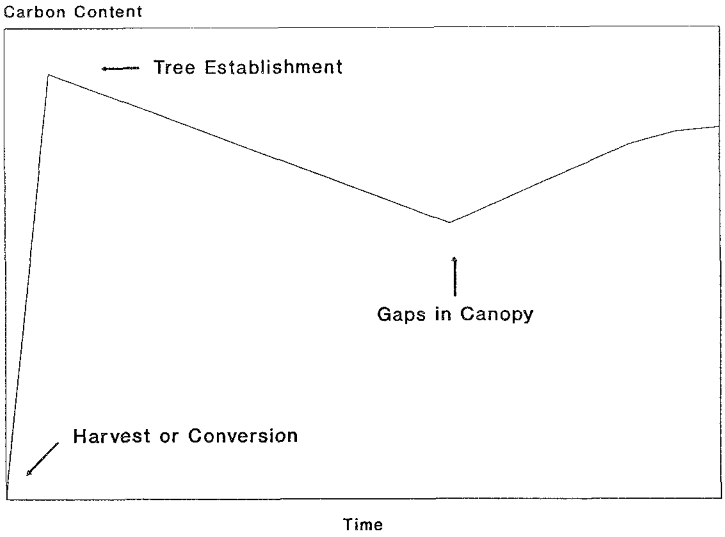

Fig. 6. General model of understory carbon inventory over time. Note: This curve represents the understory carbon inventory over time for an average stand. Differences in species, site quality, region, and prior land use account for differences in these curves (see text).

and converted to carbon using separate factors for regions and species (Birdsey, 1991). Growing stock removals were augmented to account for nongrowing stock removals (salvable dead trees, noncommercial species, etc.) using data in Waddell *et al.* (1989).

HARVCARB was used to trace removals through three transformation phases. In the first phase, logs are processed into primary products such as lumber, plywood, paper and paperboard. In the next, primary products are transformed into end-use products such as housing, packaging, and newsprint. The first two phases generate substantial amounts of byproducts, much of which are used in cogeneration. The third phase describes the disposal of end-use products, reflecting the length of time products remain in use and final disposition patterns. Products which are recycled or disposed in landfills are fixed as carbon, with allowance for landfill emissions. Products not recycled or disposed in landfills are burned with or without energy generation or left to decompose.

Disposition patterns for three broad regions (Figure 7) were calculated for different types of harvests (Table III). Harvest types reflect differences in the diameters of logs harvested and end-use patterns. Pulpwood harvests correspond to harvests of small diameter trees used to make paper. Since most paper products are short-lived, the percentage of carbon fixed in products declines sharply between the first and tenth year. In addition, in the first year a relatively large amount is converted to emissions through burning and decomposition, reflecting lower recovery rates (quantity of product produced per unit of input) for paper compared with solid wood products. Sawtimber harvests refer to harvests of larger diameter logs

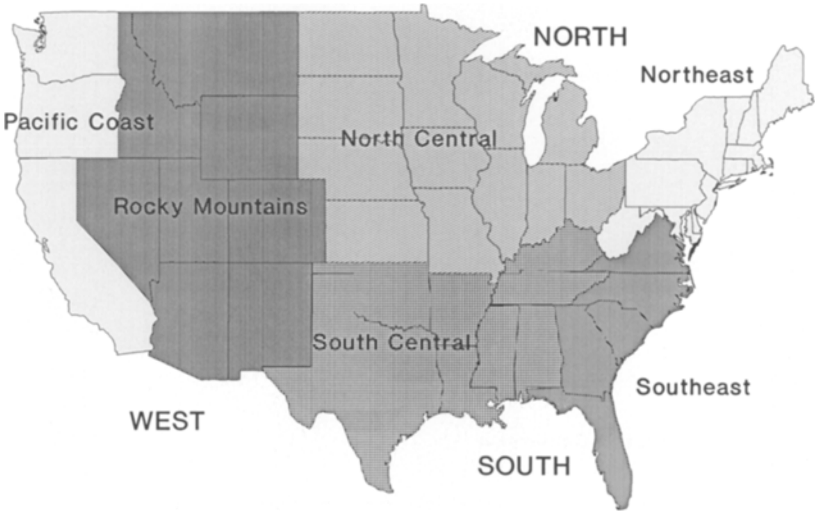

Fig. 7. Regions used in forest carbon budget model.

TABLE III: Disposition patterns of wood products by region and harvest types

| Use category | Years after harvest | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 |
| South | | | | | | |
| Softwood pulpwood | | | | | | |
| Products | 0.44 | 0.24 | 0.19 | 0.16 | 0.13 | 0.11 |
| Landfills | 0.00 | 0.13 | 0.15 | 0.16 | 0.17 | 0.16 |
| Energy | 0.35 | 0.36 | 0.37 | 0.37 | 0.37 | 0.37 |
| Emissions | 0.21 | 0.27 | 0.29 | 0.31 | 0.33 | 0.36 |
| Softwood sawtimber | | | | | | |
| Products | 0.57 | 0.38 | 0.32 | 0.27 | 0.22 | 0.19 |
| Landfills | 0.00 | 0.12 | 0.16 | 0.18 | 0.20 | 0.20 |
| Energy | 0.32 | 0.34 | 0.34 | 0.34 | 0.34 | 0.35 |
| Emissions | 0.11 | 0.16 | 0.18 | 0.21 | 0.24 | 0.26 |
| Hardwood pulpwood | | | | | | |
| Products | 0.43 | 0.16 | 0.13 | 0.11 | 0.09 | 0.07 |
| Landfills | 0.00 | 0.16 | 0.18 | 0.18 | 0.17 | 0.17 |
| Energy | 0.40 | 0.42 | 0.42 | 0.42 | 0.43 | 0.43 |
| Emissions | 0.17 | 0.26 | 0.27 | 0.29 | 0.31 | 0.33 |
| Hardwood sawtimber | | | | | | |
| Products | 0.56 | 0.33 | 0.25 | 0.21 | 0.16 | 0.14 |
| Landfills | 0.00 | 0.16 | 0.21 | 0.21 | 0.23 | 0.22 |
| Energy | 0.31 | 0.33 | 0.33 | 0.34 | 0.34 | 0.34 |
| Emissions | 0.13 | 0.18 | 0.21 | 0.24 | 0.27 | 0.30 |
| North | | | | | | |
| Softwood pulpwood | | | | | | |
| Products | 0.44 | 0.26 | 0.21 | 0.18 | 0.15 | 0.12 |
| Landfills | 0.00 | 0.12 | 0.14 | 0.15 | 0.16 | 0.16 |

TABLE III (*continued*)

| Use category | Years after harvest | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 |
| Energy | 0.31 | 0.32 | 0.33 | 0.33 | 0.33 | 0.34 |
| Emissions | 0.25 | 0.30 | 0.32 | 0.34 | 0.36 | 0.38 |
| Softwood sawtimber | | | | | | |
| Products | 0.55 | 0.37 | 0.30 | 0.26 | 0.21 | 0.18 |
| Landfills | 0.00 | 0.12 | 0.16 | 0.17 | 0.19 | 0.19 |
| Energy | 0.32 | 0.33 | 0.34 | 0.34 | 0.35 | 0.35 |
| Emissions | 0.13 | 0.18 | 0.20 | 0.23 | 0.25 | 0.28 |
| Hardwood pulpwood | | | | | | |
| Products | 0.36 | 0.14 | 0.11 | 0.09 | 0.07 | 0.06 |
| Landfills | 0.00 | 0.14 | 0.15 | 0.15 | 0.15 | 0.14 |
| Energy | 0.35 | 0.36 | 0.36 | 0.36 | 0.37 | 0.37 |
| Emissions | 0.29 | 0.36 | 0.38 | 0.40 | 0.41 | 0.43 |
| Hardwood sawtimber | | | | | | |
| Products | 0.52 | 0.30 | 0.23 | 0.19 | 0.15 | 0.12 |
| Landfills | 0.00 | 0.15 | 0.18 | 0.20 | 0.21 | 0.20 |
| Energy | 0.36 | 0.37 | 0.38 | 0.38 | 0.38 | 0.39 |
| Emissions | 0.12 | 0.18 | 0.21 | 0.23 | 0.26 | 0.29 |
| West | | | | | | |
| Softwood pulpwood | | | | | | |
| Products | 0.49 | 0.29 | 0.24 | 0.20 | 0.16 | 0.14 |
| Landfills | 0.00 | 0.13 | 0.16 | 0.17 | 0.18 | 0.18 |
| Energy | 0.35 | 0.36 | 0.36 | 0.37 | 0.37 | 0.37 |
| Emissions | 0.16 | 0.22 | 0.24 | 0.26 | 0.39 | 0.31 |
| Softwood sawtimber | | | | | | |
| Products | 0.63 | 0.46 | 0.39 | 0.33 | 0.27 | 0.23 |
| Landfills | 0.00 | 0.11 | 0.15 | 0.18 | 0.21 | 0.22 |
| Energy | 0.28 | 0.29 | 0.29 | 0.30 | 0.30 | 0.30 |
| Emissions | 0.09 | 0.14 | 0.17 | 0.19 | 0.22 | 0.25 |
| Softwood large sawtimber | | | | | | |
| Products | 0.58 | 0.42 | 0.36 | 0.30 | 0.25 | 0.21 |
| Landfills | 0.00 | 0.10 | 0.14 | 0.17 | 0.19 | 0.20 |
| Energy | 0.27 | 0.29 | 0.29 | 0.30 | 0.30 | 0.30 |
| Emissions | 0.15 | 0.19 | 0.21 | 0.23 | 0.26 | 0.29 |
| All hardwoods | | | | | | |
| Products | 0.50 | 0.24 | 0.17 | 0.14 | 0.12 | 0.10 |
| Landfills | 0.00 | 0.18 | 0.21 | 0.21 | 0.21 | 0.20 |
| Energy | 0.37 | 0.39 | 0.39 | 0.40 | 0.40 | 0.40 |
| Emissions | 0.13 | 0.19 | 0.23 | 0.25 | 0.27 | 0.30 |

Source: Disposition percentages are from runs of HARVCARB (Row and Phelps, 1991) done for this analysis.

Note: Entries reflect the end of the year percentage of merchantable growing stock removals in each category. Thus, for a softwood pulpwood harvest in the South, 44% of the carbon removed is in products at the end of the first year. At the end of ten years, 24% of the carbon removed is in products, etc.

used mostly for lumber and plywood. Lumber and plywood are generally long-lived and so a greater amount of sawtimber harvests remain fixed in wood products and landfills compared with pulpwood harvests. Large sawtimber harvests refer to old growth harvests in the West. Disposition patterns for old growth harvests are similar to sawtimber harvests except that less carbon is initially stored in products due to greater breakage during harvests and more defects.

## Results

Base-run results reveal that U.S. private timberlands stored over 20 billion metric tons of carbon in 1980 (Table IV). By 2040, this inventory is projected to increase to 22 billion metric tons. The tree carbon inventory increases to 2010, then declines to 2040 (which, by assumption, follows the same pattern as the growing stock inventory, Table II). Little change is shown in forest floor and understory carbon. This result reflects the base-run projection of a stable growing stock inventory (removals are about equal to growth) and the assumption that forest floor and understory carbon does not accumulate over harvest rotations. The largest in-

TABLE IV: Forest carbon inventory on U.S. private timberlands by region, base-run projections

| Component | | Projections | | | | | |
|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 |
| | | | | Million metric tons | | | |
| United States inventory | | | | | | | |
| Soil | 11745 | 12064 | 12401 | 12668 | 12904 | 13135 | 13174 |
| Floor | 1380 | 1438 | 1462 | 1467 | 1454 | 1427 | 1396 |
| Understory | 350 | 341 | 344 | 347 | 349 | 348 | 349 |
| Tree | 6832 | 7492 | 7691 | 7721 | 7584 | 7335 | 7064 |
| Total | 20308 | 21335 | 21899 | 22203 | 22290 | 22246 | 21984 |
| Total Regional inventories | | | | | | | |
| North | | | | | | | |
| East | 5707 | 6149 | 6527 | 6816 | 6964 | 7079 | 7072 |
| Central | 3511 | 3672 | 3841 | 3949 | 4006 | 4045 | 3985 |
| Total | 9218 | 9821 | 10368 | 10765 | 10970 | 11124 | 11057 |
| South | | | | | | | |
| East | 3866 | 3949 | 3934 | 3870 | 3732 | 3543 | 3338 |
| Central | 4508 | 4809 | 4827 | 4821 | 4861 | 4853 | 4871 |
| Total | 8374 | 8758 | 8761 | 8691 | 8593 | 8396 | 8209 |
| West | | | | | | | |
| Coast | 1790 | 1818 | 1829 | 1824 | 1826 | 1840 | 1845 |
| Rocky Mountain | 926 | 938 | 941 | 923 | 901 | 886 | 873 |
| Total | 2716 | 2756 | 2770 | 2747 | 2727 | 2726 | 2718 |

Note: Regional inventories are the sum of soil, forest floor, understory, and tree carbon.

creases are in soil carbon, which increases by 1.4 billion metric tons by 2040. After 2010, soil carbon increases at a decreasing rate due to greater harvesting rates and harvesting of stands before soil carbon has returned to the level at the previous harvest (see Figure 4).

The greatest increases in forest carbon are projected for the northern regions (Table IV). In these regions, non-industry owners have substantial holdings of timberland of limited commercial value which are often managed for purposes other than timber production. Growth is projected to be substantially greater than removals on these lands and growing stock and carbon inventories are expected to increase. In the South, forest carbon declines slightly, yet subregional changes are more pronounced. In the South Central, the forest carbon inventory increases primarily between 1980 and 1990 due to the build up of inventories on non-industry hardwood lands. After 1990, removals are expected to match growth and future increases in forest carbon result from soil carbon accumulation. Declining forest carbon in the Southeast is attributable to high removals rates relative to growth and declines in timberland area. Forest carbon is stable in the West, reflecting projections of stable growing stock inventories and timberland area.

Projections indicate that between 1980 and 2040, 9.9 billion metric tons of carbon will be removed from U.S. private timberlands (the sum of the absolute value of all U.S. carbon fluxes in Table V). About 2.7 and 1.4 billion metric tons are stored in wood products and landfills, respectively. Approximately 3.6 billion metric tons are burned for energy and 2.2 billion metric tons are burned without energy generation or emitted through decomposition. Although removals increase over time, net additions to the products category decline due to flows from the products category to the other disposition categories, particularly landfills and emissions. The amount of removals burned for energy increases primarily because removals increase.

In Table V, removals burned for energy are considered a negative flux even though wood is most likely substituted for fossil fuels. In theory, after trees are harvested and burned for energy, there is no change in atmospheric carbon if trees are replanted and grown in their place. In our model, the forest carbon inventory (Table IV) reflects carbon stored in replanted trees. Thus, the forest carbon increment is a positive flux and wood energy is a negative flux.

Combining the fluxes of forest carbon and removals yields a carbon budget for U.S. private timberlands (Figure 8). The analysis covers only the change in carbon associated with U.S. private timberland management between 1980 and 2040. Thus, carbon harvested prior to 1980 is not recorded, although some is undoubtedly added to landfills and emissions after 1980. In Figure 8, positive additions to the fixed carbon stock (i.e., carbon stored in forests, products, and landfills) are indicated by boxes above zero (after 2020, additions to the forest carbon inventory are negative, indicating removals exceed growth). Negative changes in the fixed carbon stock (i.e., emissions, including emissions from energy generation) are represented by boxes below zero. The net change in the fixed carbon stock is found

TABLE V: Carbon removals fluxes resulting from U.S. private timberland management, base-run projections

| Component | Projections | | | | | |
|---|---|---|---|---|---|---|
| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 |
| | Million metric tons | | | | | |
| United States removals fluxes | | | | | | |
| Products | 617 | 490 | 450 | 411 | 387 | 345 |
| Landfills | 0 | 163 | 234 | 286 | 332 | 354 |
| Energy | −405 | −506 | −586 | −653 | −704 | −742 |
| Emissions | −160 | −261 | −344 | −424 | −485 | −548 |
| Net storage | 52 | −113 | −246 | −380 | −470 | −591 |
| Regional net storage | | | | | | |
| North | | | | | | |
| East | 8 | −15 | −30 | −44 | −64 | −84 |
| Central | 0 | −22 | −36 | −51 | −68 | −83 |
| Total | 8 | −37 | −66 | −95 | −132 | −167 |
| South | | | | | | |
| East | 6 | −45 | −87 | −121 | −154 | −196 |
| Central | 3 | −48 | −100 | −157 | −161 | −192 |
| Total | 9 | −93 | −187 | −278 | −315 | −388 |
| West | | | | | | |
| Coast | 30 | 15 | 5 | −5 | −19 | −29 |
| Rocky Mountain | 5 | 2 | 2 | −1 | −4 | −6 |
| Total | 35 | 17 | 7 | −6 | −23 | −35 |

Note: Positive values represent net additions to the fixed carbon stock and negative values represent net emissions of carbon over the preceding ten-year period. Removals burned for energy are treated as emissions in calculating net storage (see text).

by summing the positive and negative quantities. For the entire base-run projection, the net change is −0.07 billion metric tons. Regional carbon budgets are found by combining data in Tables IV and V in a similar manner. In all regions, positive carbon removals fluxes give way to negative fluxes as the amount of carbon sequestered in products declines. In the North, negative removals fluxes are offset by positive forest fluxes, resulting in a carbon budget surplus (net storage). In the South, negative removals and forest fluxes result in a carbon deficit (net emissions), particularly in the Southeast. The carbon budget is in rough balance in the West.

## Conclusions

The central conclusion drawn from this analysis is that if current trends in U.S. private timberland management continue, the effectiveness of these lands as a carbon sink may be limited. While carbon budget surpluses are expected in near decades, increasing deficits are projected in the future as harvests increase to meet higher demand for wood products. In the next several decades, forest growth and additions to wood products and landfills offset deficits in forest carbon from har-

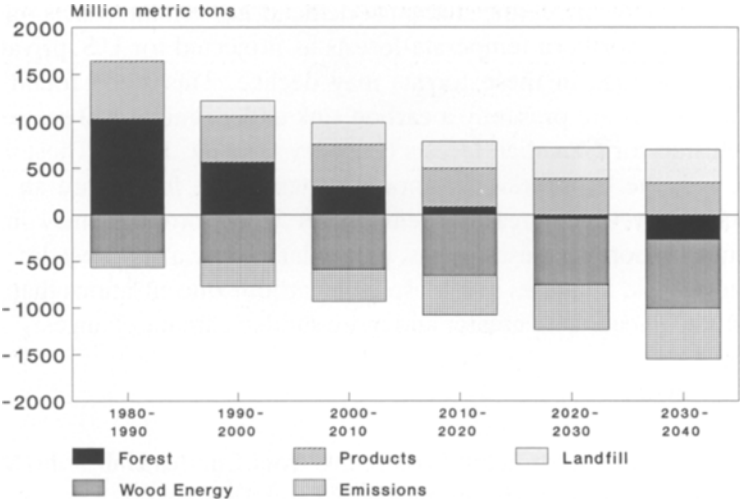

Fig. 8. Carbon fluxes resulting from management of U.S. private timberlands, base-run projections. Note: Additions to the fixed carbon stock (positive fluxes) are indicated by boxes above zero. Negative fluxes (emissions) are represented by boxes below zero. The net change is found by summing the positive and negative quantities.

vesting. After 2020, removals rates are expected to exceed growth and forest carbon fluxes are negative. Forest growth does not keep pace with carbon deficits due to harvesting and declines in carbon in wood products and landfills from previous harvests. While the carbon budget is in rough balance between 1980 and 2040, forest carbon fluxes (additions to trees, soils, etc.) would need to be sharply increased after 2040 to maintain the balance since carbon stored in products and landfills will continue to decline.

The results of this analysis may have important implications for carbon storage in other northern temperate forests. If population and economic activity increase worldwide on a scale projected for the United States, the demand for stumpage from these lands would almost certainly increase. Clearly, not all northern temperate forests would be affected in the same way. Many of these forests are preserved or uneconomical for timber production. For example, 500 million acres (202 million ha) of Canadian forests are classified as unproductive (Forestry Canada, 1991). Much of the (former) Soviet Union's 1900 million acres (769 million ha) of forest is east of the Ural Mountains where timber production is limited by inaccessibility, low timber volumes per acre, and severe climate (ECE/FAO, 1989; USDA Forest Service, 1990). Yet a significant portion of northern temperate forests are productive (600 million acres or 243 million ha in Canada and 328 million acres or 133 million ha in Europe) and would likely be influenced by rising stumpage demand (Forestry Canada, 1991; ECE/FAO, 1986). In addition, forests which are presently unproductive might offer economic timber opportunities under higher demand conditions.

To the extent that increasing stumpage demand has similar effects on the management of other northern temperate forests as projected for U.S. private timberlands, carbon storage in these forests may decline. This study found that U.S. private timberlands are presently a carbon sink and a similar analysis reached the same conclusion for Canadian forests (Forestry Canada, 1991). These results are consistent with the hypothesis that northern temperate forests are an important carbon sink. However, increasing demand for wood products may limit future carbon sequestration by these forests, particularly after a few decades. This may result in more rapid increases in atmospheric carbon concentrations than presently forecast, possibly leading to greater and more sudden climatic changes.

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