Carbon Sequestration in Forests as a National Policy Issue

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Abstract.—The United States' 1993 Climate Change Action Plan called upon the forestry sector to sequester an additional 10 million metric tons/yr by the year 2000. Forests are currently sequestering carbon and may provide opportunities to mitigate fossil fuel emissions in the near-term until fossil fuel emissions can be reduced. Using the analysis of carbon budgets based on forest inventories, we analyze the impact of forest management activities on carbon storage at the state and national level.

PROBLEM

Human activities have changed and are continuing to change the concentration and distribution of trace gases and aerosols in the atmosphere, and the amount, type, and distribution of vegetation on the Earth's surface. The cumulative influence of these activities on natural processes is cause for global concern. Atmospheric chemistry has been altered noticeably by the release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide (IPCC 1995). When the atmospheric concentration of these gases increases, the result is an increase in the amount of solar and terrestrial radiation absorbed by the atmosphere. Thus, these gases essentially slow the release of surface generated heat from the Earth's atmosphere into space. The amount of warming is a function of the concentration of these greenhouse gases in the atmosphere and the ability of these gases to absorb solar radiation (radiative properties of the gases).

Atmospheric carbon dioxide concentration has increased from a pre-industrial 280 ppmv to 358 ppmv in 1994 (IPCC 1995). This increase is the result of fossil fuel emissions from industrial and domestic activities, and land-use conversions. Methane concentrations have gone from 700 ppbv in pre-industrial times to 1720 ppbv in 1994 as a result of the production and use of fossil fuel, and anthropogenic activities such as livestock production. Nitrous oxide concentrations have gone from 275 ppbv pre-industrial to 312 ppbv in 1994. The main sources are from agriculture and industrial processes. Carbon compounds containing flourine, chlorine, bromine, and iodine, known as halocarbons, act as greenhouse gases. Additionally, these gases react to thin the ozone layer which shields the Earth from harmful solar radiation. The emissions of halocarbons are expected to fall as a result of the Montreal Protocol international negotiations which were convened to address the loss of the ozone layer. Scientists generally agree that climate has changed over the last century and that a discernible human influence is seen in the basis for this change. The global mean surface air temperature has increased between 0.3 and 0.6 degrees C since the late nineteenth century (IPCC 1995).

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If the rate at which carbon dioxide is added to the atmosphere continued at the 1994 levels, for at least two centuries; the atmospheric concentration of carbon dioxide would reach 500 ppmv by the end of the twenty-first century. Predicting the future level of atmospheric carbon dioxide and its resulting impact on climate rests on assumptions about the future emissions of carbon dioxide, other greenhouse gases, and aerosol precursors, and the longevity of these emissions in the atmosphere. Using demographic, economic, and policy factors to establish different future scenarios, the IPCC (1995) projected emissions with the resulting carbon dioxide concentrations. The concentration of carbon dioxide by 2100 in all of the scenarios increases from 35 percent to 170 percent above 1990 levels. General scientific consensus is that, under a mid-range emission scenario and the effects of aerosols, the global mean temperature will increase by about 2 degrees C by 2100. Alternative emission scenarios result in temperature increases from 1 to 3.5 degrees C by 2100 (IPCC 1995). Stabilizing the concentrations of greenhouse gases would require large decreases in emissions. A number of carbon cycle models suggest the stabilization of atmospheric carbon dioxide concentrations at 450, 650, or 1000 ppmv could be achieved only if global anthropogenic carbon dioxide emissions drop to 1990 levels by, respectively, approximately 40, 140, or 240 years from now, and drop substantially below 1990 levels subsequently (IPCC 1995).

POLICY CONTEXT

Because of the possible dire consequences of climate change, nations are examining ways to control greenhouse gas emissions in the face of economic and population growth pressures. The most recent document describing U. S. policy and preferred actions concerning global climate change is The Climate Change Action Plan (CCAP) (Clinton and Gore 1993) and Technical Supplement (U.S. Dept of Energy 1994). This plan was written in response to the Framework Convention on Climate Change (FCCC), an agreement (with no international binding obligations) signed by the United States and over 50 other countries at the United Nations Conference on Environment and Development ("Earth Summit") in Rio de Janeiro, Brazil in June, 1992. The objective of the FCCC is to stabilize "greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (Article 2, FCCC)" (Clinton and Gore 1993).

The United States Climate Change Action Plan describes actions which would help meet the FCCC objective by reducing greenhouse gas emissions to 1990 levels by the year 2000. Strategies in the United States focus on reducing the emissions in energy-related sectors of the economy such as transportation and manufacturing and in forestry, on increasing the amount of carbon taken up and stored by natural systems. The forestry sector is currently sequestering more carbon than it emits, and is considered an area to provide opportunities to mitigate fossil fuel emissions in the near-term until ways to reduce fossil fuel emissions can be developed. Generally, activities that increase biomass on a site, such as tree planting, increase carbon sequestration, and activities that decrease biomass such as prescribed burning release carbon to the atmosphere.

For the purposes of comparison, all of the greenhouse gases are converted to a common unit, metric tons of carbon equivalent, by conversion factors based on radiative forcing. The 1990 U.S. greenhouse gas emissions were 1,462 million metric tons of carbon equivalent (MMTCE) assuming forests were storing 130 MMTCE. By 2000, U.S. greenhouse gas emissions are projected to be 1,568 MMTCE assuming a forest sink of 137 MMTCE. Actions by the year 2000 must reduce expected U.S. emissions by an estimated 108 MMTCE.

A number of actions are outlined for emission reductions in efficiency of energy use, energy supply actions, methane recovery and reduction strategies, and control strategies for halocarbons and nitrous oxide gas. Preferred actions in the building and transportation sectors include strategies to increase energy efficiency in residential and commercial buildings, reduce growing demand for vehicle travel, and increase the efficiency of generating and distributing electricity. In the CCAP, the forestry sector is called upon to sequester an additional 10 MMTCE (to 147 MMTCE) by the year 2000 by accelerating tree planting in nonindustrial private forests, encouraging forest management evaluation in nonindustrial private forests, and expanding programs to increase the recycling of wood fiber.

Using the carbon budget inventory approach, we examine the magnitude of some silvicultural activities in sequestering carbon at the scale of an individual state and at the national level.

CARBON BUDGET METHODS

A carbon budget (sometimes called carbon balance) shows the inventory of carbon in carbon pools and the balance of exchange between the pools. Pools represent the measurable compartments of carbon within the ecosystem. The rate of exchange between pools and between the pools and the atmosphere is called carbon flux. Budgets typically are based on inventory or field research data. Two approaches have been used to compute a budget for an ecosystem or forest stand. One approach computes carbon budgets for ecosystems in physiological terms, including photosynthesis, respiration, and allocation (which refers to the relative amount of carbon stored in specific plant structures) using daily or monthly time steps (McGuire and Joyce 1995; VEMAP members 1995). Generally, the models producing these budgets are called process models, as they describe the processes underlying the system under study. The models are quite useful for investigating certain aspects of carbon budgets such as how the effects of elevated carbon dioxide and altered temperature and precipitation will affect ecosystem function and thereby carbon storage (Melillo et al. 1995). However, these models generally focus on pristine conditions rather than the existing vegetation inventoried in forest inventories and managed through silvicultural activities.

The second approach, the focus of this paper, uses commonly collected forest inventory data, linked to forest tree growth and yield functions and converted to tree carbon using conversion factors (Heath and Birdsey 1993). Carbon in other ecosystem components, such as litter layer, is represented by empirical equations based on site-specific information from ecological studies. This approach may be applied at the stand, forest, state, or regional level, and maybe used to develop carbon estimates over stand age.

An example stand-level carbon budget showing carbon over stand age is given in Figure 1. This budget was calculated for average Douglas-fir stands in the northern Rocky Mountains using average regional inventory data (see Woudenberg and Farrenkopf 1995). The stand was naturally regenerated following a clearcut. At that time, the carbon in trees is very low and over time, gradually increases to be greater than the carbon in the soil.

Using the inventory approach, we can represent the storage of carbon in forests as:

$$C_t = T_t + FF_t + U_t + S_t, \text{ with } T_t = V_t{*}CF$$

where C_t = total carbon in the forest, T_t = the amount of carbon in trees, aboveground and belowground, FF_t = carbon in the forest floor, U_t = the amount of carbon in the understory, S_t = the amount of soil carbon in the forest, and V_t = volume of trees, all at time *t*. CF is the conversion factor which converts volume in trees to carbon. Sometimes two conversion factors are needed: one to convert merchantable volumes to total tree biomass, and a second to convert total tree biomass to carbon. The tree component includes 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). Forest floor is all dead organic matter above the mineral soil horizons, including litter, humus, and other woody debris. Understory vegetation includes all live vegetation except that defined as live trees. The soil carbon includes all organic carbon in mineral horizons to a depth of 1 meter, excluding coarse tree roots. Common units for reporting carbon in vegetation biomass are million metric tons (MMT=teragrams=10^{12} grams), and billion metric tons (petagrams=10^{15} grams).

Carbon flux can be calculated as:

$$F_p = C_t - C_{t-1}$$

with F_p = carbon flux for period *p*. Carbon flux is expressed on an annual basis by dividing F_p by length of period. Fluxes could also be examined for specific tree-related inventory components, such as growth, or mortality.

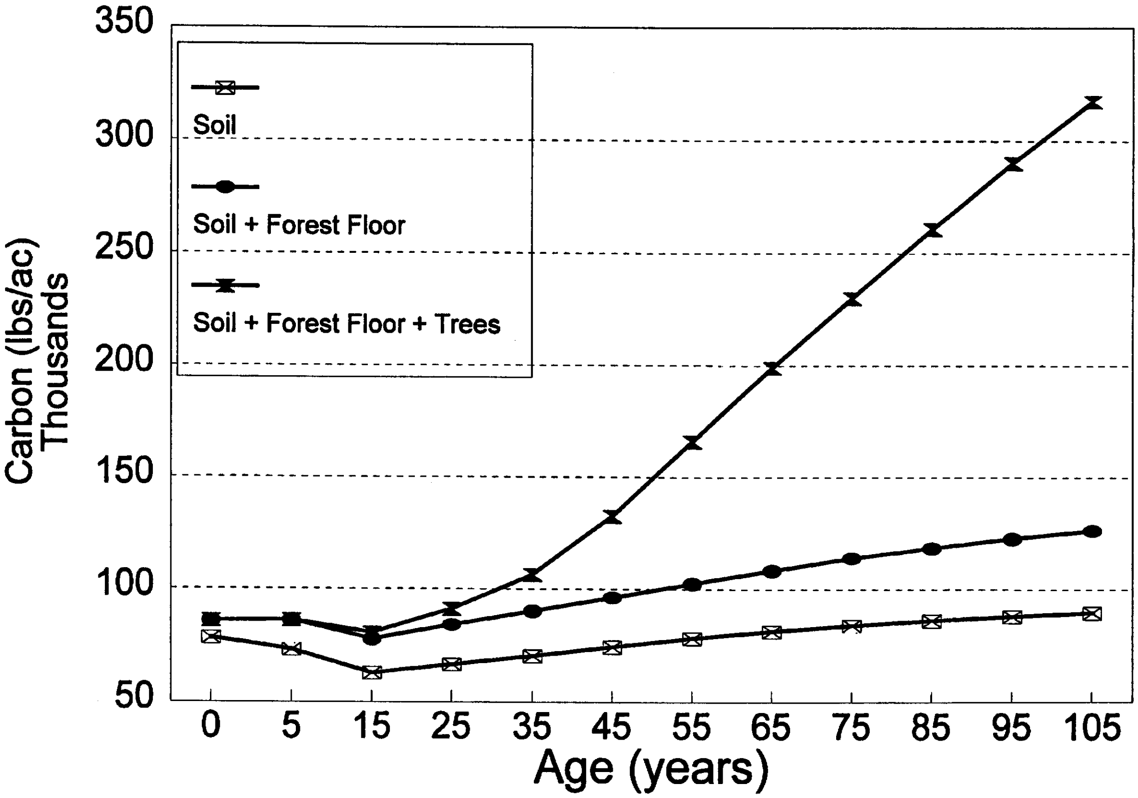

Figure 1.—Carbon changes over time for average Douglas-fir stands in the northern Rocky Mountains.

ESTIMATING CARBON ON TIMBERLANDS: IDAHO CASE STUDY

Carbon inventory

Idaho has 21.8 million acres of forestland. Within this acreage, 14.5 million acres feature forests defined as timberlands with tree growth greater than 20 cu ft/ac/yr and that are available for harvest (Birdsey 1992). This acreage is spread across public (11.2 million acres) and private (3.3 million acres) ownership. We estimate carbon inventory for the state, followed by an analysis of how various events such as fire or harvests contribute to carbon flux at the State level.

Birdsey (1992) computed the carbon stored at the State level from inventory data available for Idaho. Using the following equation:

$$C_t = T_t + FF_t + U_t + S_t,$$

$$1,466,560 = 603,299 + 215,100 + 10,659 + 637,502$$

Units are in 1,000 metric tons. The 1.47 billion metric tons of carbon stored in the Idaho forests represents about 4 percent of the carbon in conterminous U.S. forests. In the Idaho forests, about 41 percent of the stored carbon is in trees, 43 percent is in soi!, 15 percent is in the forest floor and 1 percent is in understory vegetation.

Carbon flux and Components

Carbon flux in aboveground tree biomass can be calculated using appropriate conversion factors and standing inventories at two points in time. Merchantable volume is reported by forest type by State in reports such as Powell et al. (1993). The understory and forest floor components are small relative to the carbon stored in trees and assumed not to contribute to large changes in carbon flux from forests. Little is known about belowground tree carbon component especially in its response to disturbance, and this component was not included in the following analyses.

Because softwoods are approximately 98 percent of the volume in Idaho, only softwood conversion factors were used. An average conversion factor was calculated by weighting the average carbon by forest type by the amount of land area in forest types. For aboveground merchantable volume conversion to carbon, the conversion factor is 5.6829 kg C/cu ft. To convert to total above-ground carbon, merchantable cu ft volume must be multiplied by 10.7861 kg C/cu ft to account for branches, leaves, and bark.

The net volume of growing stock on timberland in Idaho was an estimated 33,001 million cubic feet in 1992 (Powell et al. 1993), and 32,600 m cu ft in 1987 (Waddell et al. 1989). Annual carbon flux is then (401,000 cu ft * 10.7861 kg C/ cu ft)/5 years = 0.8 MMT/yr. National forest inventory estimates were not updated over this period so this increase represents volume increases only on private timberlands in Idaho, and as such, is a conservative estimate of the volume change in this time period.

Components of inventory, such as carbon in growth and removals, may be calculated in a similar way. The annual growth in 1991 is reported as 728,705 cu ft/yr, removals 333,015 cu ft/yr, and mortality is 182,614 cu ft/yr (Powell et al. 1993). Growth and mortality are average annual estimates calculated from periodic inventories, and removals are based on timber products output surveys and State harvesting reports. The privately-owned timberlands in Idaho were surveyed in 1981 and 1991; the dates of inventories on other ownerships vary. Net annual growth is reported as the increment of net volume of trees at the beginning of the specific year surviving to its end plus the net volume of trees reaching the minimum size class during the year. Because this volume estimate does not include branches, bark on, or leaves, growth is multiplied by 10.7861 kg C/cu ft to produce carbon growth increment. Removals are the net volume of trees removed from the inventory during a specified year by harvesting, or cultural operations such as timber stand improvement. Removals are converted from cu ft to kg C by multiplying by 5.5829 kg C/cu ft. The amount of carbon going into the logging debris pool is the difference between total carbon in removals and merchantable carbon removals. On timberlands, mortality is reported as the volume of sound wood in trees that died from natural causes during a specified year. Because this estimate should include branches, bark, or leaves, carbon in annual mortality is computed by multiplying annual mortality in cu ft by 10.7861 kg C/cu ft.

Table 1.—Estimated annual C flux by forest change or disturbance for Idaho.[a]

Type of change	C flux (MMT/yr)
Net Growth	7.8
Removals	-1.9
Logging debris	-1.7
Mortality	-2.0[b]
Wildfire	-2.6[c]
Probable land use	-0.2[d]

[a]See text for interpretation. Net growth is equivalent to total carbon flux between inventories.
[b]Assumes all carbon is lost from tree when mortality occurs.
[c]Assumes wildfire burns 58,343 hectares on average, and releases 44.8 MT/ha. (Assumes fires consume 30 percent of carbon in trees, all forest floor, and down and dead debris; 68.3 MT/ha in trees and 24.36 MT/ha in the forest floor).
[d]Assumes loss of 4,858 ha/yr (12,000 ac/yr) from timberland, with 46.3 MT/ha/yr released.

Inventory estimates do not report losses to prescribed fires or wildfires explicitly. Wildfires burned 106,164 ha (262,241 acres) annually on average in the period 1984-1990 on 15.7 million ha (38.8 million acres) of both forested and nonforested lands in Idaho (U.S. Department of Agriculture, Forest Service 1992). Assuming the number of acres of forested land burned in proportion to the ratio of forested land to nonforested land burned, on average wildfires burned 58,343 ha (144,116 acres) on forestland annually over this period. Average carbon in Idaho in trees on forestland is 68.3 MT/ha (Birdsey 1992).

Land use changes can alter the amount of carbon stored on timberlands. We assume a loss of 4,858 ha/yr (12,000 ac/yr) (Powell et al. 1993) from timberlands with 46.33 MT C/ha/yr released. This land is being used primarily for homes, roads, vacation or second homes, and pasture or crop agriculture (Ralph Alig pers. comm.).

Annual carbon flux for various forest activities or changes are listed in Table 1. A positive estimate indicates that carbon is removed from the atmosphere and sequestered in the forest; a negative estimate indicates that carbon is released into the atmosphere from the forest. Note that net growth is equal to the carbon increment between two successive inventories. In this case, an additional 7.8 MMT/yr is being sequestered. Potentially, if there were no removals, mortality, wildfires or land use changes, the annual carbon flux for Idaho would be 16.2 MMT/yr. The magnitudes of carbon flux from the activities in this State are quite large compared to 10 MMT/yr, the amount of carbon the 1993 Climate Change Action Plan requested from the U. S. forest sector. With magnitudes like these, proposed changes in activities that result in a 1 MMT/yr difference at the State level could be considered noticeable at the national level. Based on estimates used here, activity changes that would affect carbon sequestration by 1 MMT are: 92,712,000 cu ft growth or mortality (in other words, increasing or decreasing growth by 92,712,000 cu ft would increase or decrease carbon sequestration by 1 MMT), 104,747,000 cu ft removals (includes above-ground logging debris carbon flux), change in wildfire of 22,300 ha (55,100 ac), and a change in land use of 21,584 ha (53,313 ac).

Activities altering the carbon in the forest floor could also be of a magnitude to be considered noticeable. An average hectare of forestland in Idaho contains 26.7 metric tons of carbon in the litter layer (Birdsey 1992). Based on estimates from Brown and See (1981), about 19.7 metric tons/ha downed dead fuel would accumulate in mature forests, primarily in absence of harvesting and thinning. Activity changes that would release 1 MMT of carbon include removing the forest floor layer on 41,050 ha (101,400 ac) or removing dead, down woody fuels in mature forests on 50,800 ha (125,381 ac).

CARBON BUDGET AT THE NATIONAL LEVEL: UNITED STATES CASE STUDY

The state level analysis did not consider the role that economics would play in these timber management decisions or how climate change would affect the storage of carbon and carbon flux. The role that economics might have on these timber management decisions can be addressed by placing the carbon calculations in the context of the national timber policy models used by the Forest Service. Climate scenarios and ecological models can be used to bring into these timber policy analyses the potential effect of climate change.

Table 2.—Carbon flux from aboveground forest component for private timberlands in the United States for the baseline scenario and two alternative carbon sequestration scenarios: tree planting and increased recycling. Positive flux values indicate a storage of carbon. The flux values in parentheses indicate negative fluxes or the release of carbon into the atmosphere.

Year/Period	Base Run	Planting M/R	Recycling
	---------- *Million metric tons* ----------		
Storage:			
1990	7,838	7,838	7,838
2000	8,266	8,218	8,288
2010	8,554	8,498	8,674
2020	8,610	8,631	8,843
2030	8,516	8,547	8,836
2040	8,303	8,354	8,698
	----- *Million metric tons per year* -----		
Flux:			
1990-2000	43	38	45
2000-2010	29	28	39
2010-2020	6	13	17
2020-2030	(9)	(8)	(6)
2030-2040	(21)	(19)	(14)

Birdsey (1992) estimated carbon storage and flux for all forest land classes and all 50 States using the national compilations of forest inventory statistics (Cost et al. 1990; Powell et al. 1993; Waddell et al. 1989) supplemented with information from ecosystem studies. Biomass carbon is a function of inventory volume calculated from ratios and conversion factors based on the high correlation between volume and biomass (Cost et al. 1990). Carbon in the soil and the litter is estimated with models that relate organic matter to temperature, precipitation, and age class, using data from ecosystem studies compiled by various authors. The periodic inventories conducted in the United States allow the computation of carbon flux over time.

Approximately 54.6 billion metric tons of organic carbon are found within the forest ecosystems of the United States (Birdsey and Heath 1995), representing 5 percent of the world's forests (Dixon et al. 1994). Most of the forest carbon is found in the soil component. Trees, including the roots, account for 29 percent of all forest ecosystem carbon (Birdsey and Heath 1995). Fifty percent of this represents growing stock live tree section, another 30 percent is in other live solid wood above the ground, 17 percent is in the roots, 6 percent is in standing dead trees, and 3 percent is in the foliage. The proportion of carbon in the different components varies by region and reflects the temperature and precipitation of each region. Larger amounts of soil carbon are found in cooler and wetter regions. For example, over 75 percent of the total carbon in Alaska is in the soil. The Southeast and South Central States have carbon evenly split between the belowground and aboveground components.

Carbon budgets were projected into the future using the FORCARB model (Plantinga and Birdsey 1993), linked to a forest sector modeling system (see Birdsey and Heath 1995). Together these incorporate the demand for wood products and its impact on harvesting and other management decisions on carbon storage by timber management type by regions in the United States. Carbon is accounted for in biomass, soil, and the litter layer including coarse woody debris. Carbon is also computed for wood removed during the harvest by four disposition categories: wood-in-use, landfills, wood burned for energy, and emissions. FORCARB uses estimates of forest inventory, growth, and removals for age class distributions within each timber producing region in the United States, from the ATLAS inventory model (Mills and Kincaid 1991), so the estimation of carbon storage for each projection period is a straightforward application of the carbon accounting model. Carbon flux is estimated as the average annual change between successive inventory projection periods.

A base scenario is constructed with assumptions about the economic future, such as per capita income, population growth, and energy prices. This base scenario assumes that climate will be unchanged from the historic patterns. For this analysis, only private timberland is considered, and only carbon in trees is presented here (Table 2). Under the base scenario, forests release more carbon than is stored in the aboveground tree biomass by the end of the 50 year projection period.

Two policy activities to sequester carbon in forests under the historical climate were analyzed using FORCARB. The planting scenario assumes a federally funded program to plant about 6 million acres of loblolly pine over the next decade in Oklahoma and Texas. The recycling scenario assumes a future in which the use of recycled fiber in paper and board production rises to 39 percent of total fiber furnished by 2040 (Haynes et al. 1995).

The recycling scenario sequesters more carbon in the aboveground portion of U.S. forests than the tree planting scenario, but this scenario does not reflect the entire carbon sequestration effects. In the tree planting scenario, more trees mean more wood is available for harvest at lower prices. The greater the harvests, the more carbon stored in

Table 3.—Cumulative disposition of carbon removed from private timberland in the baseline scenario.

Year	In Use	Landfill	Energy	Emitted	Total
			Million metric tons		
2000	744	0	488	191	1,424
2010	1,264	199	1,060	490	3,015
2020	1,706	468	1,690	873	4,738
2030	2,119	778	2,358	1,304	6,558
2040	2,502	1,119	3,064	1,794	8,479

wood products, or burned for energy. Recycling, on the other hand, tends to lead to lower harvests and less wood goes into the wood product stream. This phenomenon shows in the results in a comparison of the cumulative disposition of carbon removed from private timberland for the policy scenarios. By 2040, the cumulative total of carbon removed in the base scenario is 8,479 MMT (see Table 3), but the total removed in the recycling scenario is only 8,203 MMT, and the total removed in the tree planting scenario is 8,601 MMT.

These two scenarios do not include the belowground component in the future projection. About two-thirds of the historical positive flux of carbon in U.S. forests is in the soil component (Birdsey and Heath 1995). Our understanding of the soil carbon dynamics limits this and other analyses (U.S. EPA 1994).

The IPCC/OECD (1994) report recommends that countries not include the carbon stored in wood products in the carbon accounting analyses at the country level. These analyses have followed this procedure. However, nearly 30 percent of the wood harvested remains in use, in the base scenario, by 2040 (Table 3). In addition, large amounts are used by energy and less than 21 percent is emitted from the harvesting process. This suggests that these policy analysis estimates of carbon sequestration may be low.

Finally, these projections assume the historical climate. To examine the impact of potential changes in climate on carbon storage, three climate scenarios were imposed upon a forest productivity model. Changes in forest productivity were then imposed on the linked timber inventory-FORCARB modeling system (Joyce et al. 1995). The scenarios reflect productivity changes attributable to climate change. For this analysis, only timberland is considered, and only carbon in trees is presented. Projected carbon changes on private timberland from climate change over the 1990 to 2040 period are shown, along with the recycling and planting scenarios, in Figure 2. Under the historical climate, the projections for carbon storage on timberland show a decline of 21 MMT per year on timberland by 2040. Under the minimum change climate scenario, forests also release more carbon than they store in the aboveground component. Under the moderate climate change and the maximum change scenario, forests accumulate carbon. This increase under the moderate and maximum change scenarios represents only the increase in tree carbon because estimates of possible changes in other forest ecosystem components were not projected.

These scenarios suggest that management activities and climate change can have an impact on the amount of carbon stored on forest lands and that alternative forest activities could affect the carbon stored through 2040.

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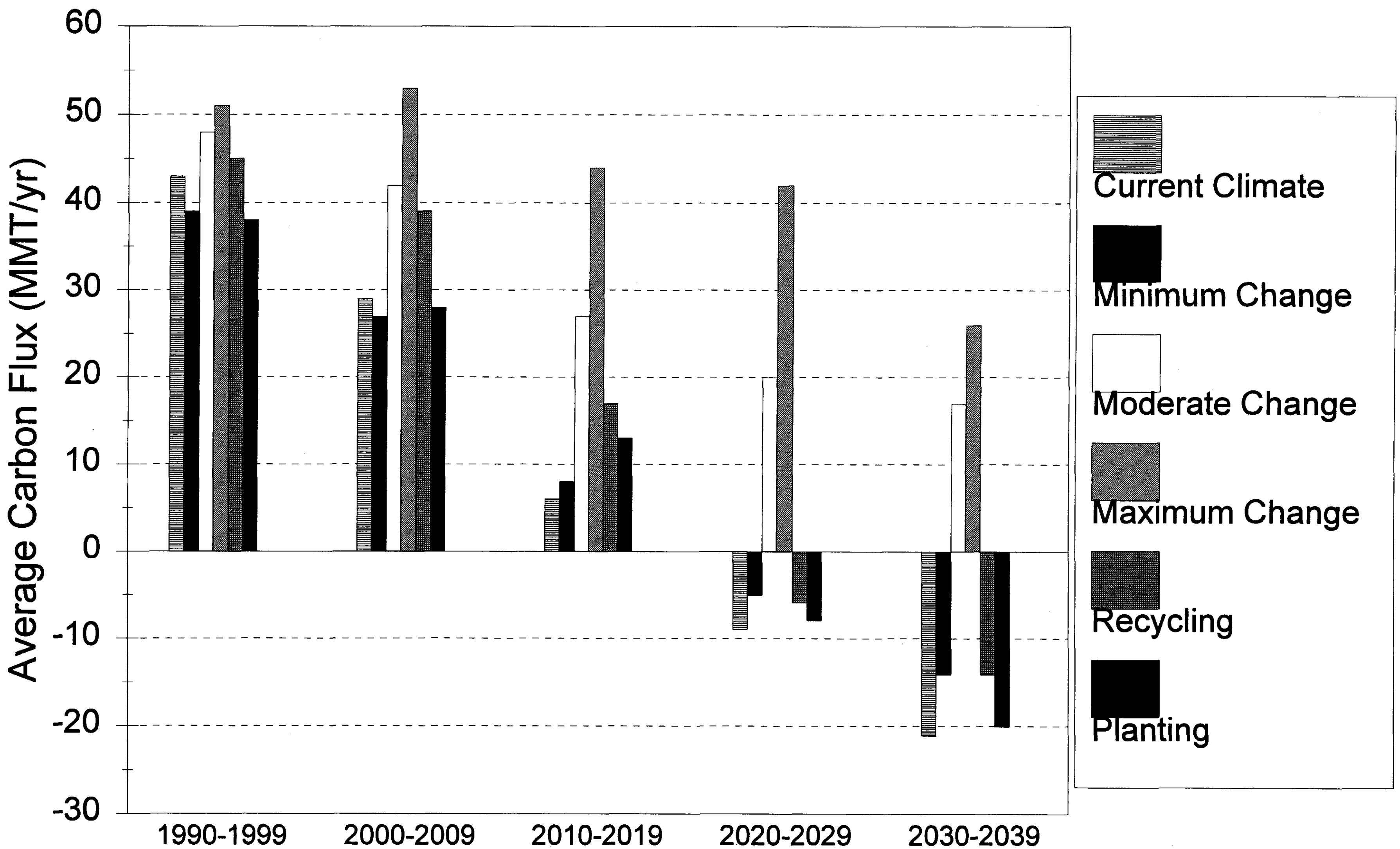

Figure 2.—Carbon flux for baseline, two alternative carbon sequestration scenarios, and three climate change scenarios.

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