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Forest Carbon Management in the United States: 1600–2100

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ABSTRACT

This paper reviews the effects of past forest management on carbon stocks in the United States, and the challenges for managing forest carbon resources in the 21st century. Forests in the United States were in approximate carbon balance with the atmosphere from 1600–1800. Utilization and land clearing caused a large pulse of forest carbon emissions during the 19th century, followed by regrowth and net forest carbon sequestration in the 20th century. Recent data and knowledge of the general behavior of forests after disturbance suggest that the rate of forest carbon sequestration is declining. A goal of an additional 100 to 200 Tg C/yr of forest carbon sequestration is achievable, but would require investment in inventory and monitoring, development of technology and practices, and assistance for land managers.

Clearing of forests for agriculture, forest management, and use of wood has a significant effect on terrestrial carbon stocks in the United States (Birdsey and Heath, 1995). Timber extraction and deforestation during the settlement and initial development of the nation's infrastructure from about 1600–1900 caused declines in forest area and tree stocking, followed by recovery and intensified management of the forest land during the 20th century (MacCleery, 1992). Now there are new challenges for managing forest carbon resources in the 21st century (Schultze et al., 2000). The 21st century is already characterized as a period of increasing attention to global stewardship, during which development and application of forest management technology can stabilize the roles of forests and wood products as sinks for atmospheric carbon dioxide (CO_2) and as sources of renewable energy and materials that help reduce demand for fossil fuels.

Forests in the United States currently sequester about 200 Tg C/yr from the atmosphere (Heath and Smith, 2004), an amount equivalent to about 10% of U.S. emissions of CO_2 from burning fossil fuels. By engaging in various forestry activities, it may be possible to sequester additional carbon in forests. Forestry opportunities for helping manage the atmospheric concentration of CO_2 include many different kinds of activities that can either increase sequestration, reduce emissions, or both (Birdsey et al., 2000). Of particular interest are activities in which improved carbon management is compatible with other goals such as restoration of degraded forests or timber production. Some entities have concluded that increased forest carbon sequestration can offset emissions from burning of fossil fuels at lower cost than reducing emissions, as demonstrated by tree-planting projects already undertaken by electric utilities (Hopkin, 2004).

This paper reviews the effects of past forest management on carbon stocks in the United States, and the challenges for managing forest carbon resources in the 21st century. We develop some new estimates of changes in forest carbon stocks before 1952, merge these estimates with contemporary estimates and projections, and explore some of the technological and social challenges to increasing the role of U.S. forests in removing CO_2 from the atmosphere.

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MATERIALS AND METHODS

Estimated changes in carbon stocks are based on historical and projected forest inventory data from the USDA Forest Service. The inventory approach accounts for all factors that affect forests, both natural and anthropogenic, because it is based primarily on periodic measurements of selected forest parameters that are related to ecosystem carbon. For example, there is a strong relationship between forest volume and biomass (Smith et al., 2003). We accounted for carbon in forest ecosystem pools (except soil) and in wood products, including the proportion of discarded wood products that does not decompose in contemporary landfills. We used the "stock change" calculation method, where the inventory at time 1 minus the inventory at time 2, divided by the time interval, equals average annual net change in carbon stocks.

Estimates of carbon in forest ecosystems for 1935 and earlier are based on a reconstruction of the U.S. inventory of sawtimber from a variety of historical references compiled by Reynolds and Pierson (1941). (The term sawtimber is a classification of inventory composed of live trees containing sawlogs, and meeting minimum specifications for size and freedom from defect.) Table 1 is a reproduction of these inventory estimates and the causes of changes in the stock of sawtimber. To convert estimates of the volume of sawtimber to mass of carbon, we used the ratio of sawtimber volume in 1953 (USDA Forest Service, 1958) to carbon mass in 1953 (Heath and Smith, 2004), which is 2 056 847 million board feet (7158 million cubic meters) divided by 16 613 Tg C for a factor of 123.8. The same calculation for 1997, 3 232 530 million board feet (11 249 million cubic meters) divided by 24 292 Tg C, yields a factor of 133.1, which is similar to the value for 1953. This similarity indicates the strong correlation between the quantity of large logs and the average carbon stock on forest land.

Estimates of carbon in forest ecosystems (excluding soil) for 1953 through 2002 are based on much more detailed inventory data for 1987 and later, observations from intensive ecosystem studies, and application of statistical models to convert inventory estimates to carbon estimates (Heath and Smith, 2004; USDA, 2004). The statistical models were applied to inventory summary data for the period 1953–1977.

To estimate carbon in harvested wood before 1935 (labeled "commodity cut" in Table 1), we used the factor 8.137 to

Table 1. Drain on the sawtimber resource of the United States, 1630–1930, in billion board feet (million cubic meters).†

	Commodity cut				Other losses					Stock change		
Decade	Fuelwood	Lumber	Other products‡	Total cut	Farm clearing	Fire	Other disturbance§	Wood waste¶	Total loss	Total drain	Net growth	Sawtimber stock
	billion board feet (million cubic meters)											
1630–1639	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	30 (104)	148 (515)	0 (0)	178 (619)	178 (619)	183 (637)	7625 (26535)
1640–1649	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	30 (104)	148 (515)	0 (0)	178 (619)	178 (619)	183 (637)	7630 (26552)
1650–1659	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	31 (108)	148 (515)	0 (0)	179 (623)	180 (626)	185 (644)	7635 (26570)
1660–1669	1 (3)	0 (0)	0 (0)	1 (3)	0 (0)	31 (108)	148 (515)	0 (0)	179 (623)	180 (626)	185 (644)	7640 (26587)
1670–1679	1 (3)	0 (0)	1 (3)	2 (7)	1 (3)	31 (108)	148 (515)	0 (0)	180 (626)	182 (633)	185 (644)	7645 (26605)
1680–1689	1 (3)	0 (0)	1 (3)	2 (7)	3 (10)	31 (108)	148 (515)	0 (0)	182 (633)	184 (640)	186 (647)	7648 (26615)
1690–1699	1 (3)	0 (0)	1 (3)	2 (7)	6 (21)	31 (108)	148 (515)	0 (0)	185 (644)	187 (651)	187 (651)	7650 (26622)
1700–1709	2 (7)	0 (0)	2 (7)	4 (14)	9 (31)	31 (108)	150 (522)	0 (0)	190 (661)	194 (675)	194 (675)	7650 (26622)
1710–1719	4 (14)	0 (0)	2 (7)	6 (21)	13 (45)	31 (108)	155 (539)	0 (0)	199 (693)	205 (713)	203 (706)	7650 (26622)
1720–1729	7 (24)	0 (0)	2 (7)	9 (31)	18 (63)	31 (108)	160 (557)	0 (0)	209 (727)	218 (759)	215 (748)	7648 (26615)
1730–1739	9 (31)	0 (0)	3 (10)	12 (42)	22 (77)	32 (111)	165 (574)	0 (0)	219 (762)	231 (804)	226 (786)	7645 (26605)
1740–1749	13 (45)	0 (0)	3 (10)	16 (56)	27 (94)	34 (118)	170 (592)	0 (0)	231 (804)	247 (860)	237 (825)	7640 (26587)
1750–1759	19 (66)	0 (0)	3 (10)	22 (77)	38 (132)	36 (125)	175 (609)	0 (0)	249 (867)	271 (943)	251 (873)	7630 (26552)
1760–1769	24 (84)	0 (0)	4 (14)	28 (97)	48 (167)	38 (132)	180 (626)	0 (0)	266 (926)	294 (1023)	269 (936)	7610 (26483)
1770–1779	31 (108)	1 (3)	4 (14)	36 (125)	63 (219)	41 (143)	184 (640)	0 (0)	288 (1002)	324 (1128)	294 (1023)	7585 (26393)
1780–1789	39 (136)	1 (3)	5 (17)	45 (157)	90 (313)	47 (164)	184 (640)	0 (0)	321 (1117)	366 (1274)	321 (1117)	7555 (26291)
1790–1799	50 (174)	2 (7)	5 (17)	57 (198)	114 (397)	56 (195)	183 (637)	1 (3)	354 (1232)	411 (1430)	351 (1221)	7510 (26135)
1800–1809	67 (233)	4 (14)	6 (21)	77 (268)	130 (452)	67 (233)	181 (630)	1 (3)	379 (1319)	456 (1587)	376 (1308)	7450 (25926)
1810–1819	89 (310)	5 (17)	8 (28)	102 (355)	149 (519)	80 (278)	178 (619)	1 (3)	408 (1420)	510 (1775)	400 (1392)	7370 (25648)
1820–1829	120 (418)	7 (24)	11 (38)	138 (480)	174 (606)	90 (313)	175 (609)	1 (3)	440 (1531)	578 (2011)	422 (1469)	7260 (25265)
1830–1839	162 (564)	12 (42)	15 (52)	189 (658)	191 (665)	102 (355)	171 (595)	1 (3)	465 (1618)	654 (2276)	434 (1510)	7104 (24722)
1840–1849	216 (752)	36 (125)	20 (70)	272 (947)	202 (703)	113 (393)	167 (581)	5 (17)	487 (1695)	759 (2641)	459 (1597)	6884 (23956)
1850–1859	281 (978)	69 (240)	30 (104)	380 (1322)	228 (793)	120 (418)	161 (560)	9 (31)	518 (1803)	898 (3125)	476 (1656)	6584 (22912)
1860–1869	321 (1117)	108 (376)	47 (164)	476 (1656)	220 (766)	121 (421)	161 (560)	14 (49)	516 (1796)	992 (3452)	483 (1681)	6162 (21444)
1870–1879	324 (1128)	160 (557)	69 (240)	553 (1924)	172 (599)	117 (407)	159 (553)	21 (73)	469 (1632)	1022 (3557)	461 (1604)	5653 (19672)
1880–1889	293 (1020)	232 (807)	140 (487)	665 (2314)	110 (383)	104 (362)	154 (536)	30 (104)	398 (1385)	1063 (3699)	409 (1423)	5092 (17720)
1890–1899	236 (821)	321 (1117)	170 (592)	727 (2530)	50 (174)	84 (292)	146 (508)	40 (139)	320 (1114)	1047 (3644)	329 (1145)	4438 (15444)
1900–1909	177 (616)	413 (1437)	220 (766)	810 (2819)	19 (66)	57 (198)	125 (435)	49 (171)	250 (870)	1060 (3689)	230 (800)	3720 (12946)
1910–1919	130 (452)	409 (1423)	200 (696)	739 (2572)	3 (10)	35 (122)	91 (317)	48 (167)	177 (616)	916 (3188)	240 (835)	2826 (9834)
1920–1929	83 (289)	370 (1288)	136 (473)	589 (2050)	0 (0)	16 (56)	40 (139)	45 (157)	101 (351)	690 (2401)	301 (1047)	2215 (7708)

† Original data from Reynolds and Pierson (1941) are in billion board feet. The original units (with conversion to million cubic meters in parentheses) are shown here because the methods presented in this paper are dependent on starting with units of board feet.
‡ Use of round and hewn materials for houses, ships, and bridges.
§ Includes fire, insects, disease, windfall.
¶ Sawtimber from harvest operations that could not be salvaged.

convert harvested sawtimber volume in board feet to cubic volume of growing stock (Smith et al., 2004). Then we used the ratio of volume of growing stock to mass of carbon in 1953, which is 31.1 (USDA Forest Service, 1958; Heath and Smith, 2004). These two factors multiplied together equal 253.1. Then we used proportions from Row and Phelps (1996) as shown in Birdsey (1996) to estimate the amount of carbon remaining in harvested wood products for each decade following a harvest. We selected the proportions for harvest of softwood sawtimber in the Pacific Northwest as representative of the utilization of large sawtimber typically harvested during the 19th century. Beginning at time of harvest through 100 yr, these proportions are: 0.501, 0.371, 0.331, 0.299, 0.264, 0.241, 0.221, 0.197, 0.178, 0.165, and 0.156. These proportions were applied to the estimated harvest of lumber and roundwood shown in Table 1. The calculated amounts of carbon remaining in each decade from each harvest estimate were summed to obtain an estimate of the total carbon stock in harvested wood products from the earliest time period through 1935, after which we used estimates from Heath and Skog (2004). The Heath and Skog approach is similar, but involves different sets of proportions to account for regional differences in utilization, and includes the proportion of discarded wood products that remains in contemporary landfills.

The projected trend in forest ecosystem carbon through 2040 was based on macroeconomic models of land use and the forest sector, and a carbon budget model as described in Heath and Birdsey (1993). The projected trend was extrapolated to 2100 by assuming that ecosystem productivity, natural disturbance, and harvesting continue at rates similar to those projected through 2040. We also assumed that carbon sequestered in wood products and landfills in the projection period continues at the contemporary rate of about 60 Tg C/yr (Heath and Skog, 2004).

The alternate projection is based on an analysis of the potential for increasing carbon sequestration in forests (Birdsey et al., 2000). We assumed implementation of a forest carbon management program that would linearly increase annual sequestration by 100 Tg C above the baseline by the end of the projection period.

Our approach is consistently based on inventory data for the whole time period, yet there is increasing uncertainty backward through time because of changing definitions and inventory methods, a reduction in available data, and unavailable documentation about past methods. Some of the key temporal changes in inventory methodology involve changing standards for defining forest land and volume of sawtimber. An additional source of uncertainty involves our application of constant factors (e.g., the ratio of carbon mass to sawtimber volume) over long periods of time when the distribution of trees by size classes is changing. We did not attempt to estimate changes in soil carbon even though these changes are likely to be significant. It is highly likely that changes in soil carbon are positively correlated with changes in forest ecosystem carbon, but at a lesser magnitude (Lal et al., 1998; Post and Kwon, 2000). We did not attempt to quantify the magnitude of these uncertainties, but the reader should keep in mind that recent estimates are more certain than historical estimates. According to Smith and Heath (2000), current estimates of carbon changes for large areas based on inventory data can be within 10% of the true value 80% of the time.

EXTRACTION AND DEFORESTATION: 1600–1900

The period from 1600–1800 was characterized by a slow expansion of settlement. Beginning about 1800, the development of the basic infrastructure of the country took place, with forests and wood products playing a pivotal role. Human impacts on forests of the 19th century were so pervasive that the effects are still noticeable on nearly every acre of today's forest land (Fedkiw, 1989).

Economists of the early 20th century characterized the 19th century by studying the various causes of the drain on the original sawtimber resource that was present in 1630 (Reynolds and Pierson, 1941). Table 1 summarizes the timing and magnitude of sawtimber removed for commodity use and lost to various other causes. Fuelwood use, the main energy source for the industrial revolution in the United States, peaked around 1875. Wood harvested for lumber increased to more than 400 billion board feet (1400 million cubic meters) per decade just after 1900, before declining. Land clearing for agriculture increased steadily from about 1700 until 1860, then declined.

Taken together, the various drains on the sawtimber resource caused net emissions from U.S. forest land to reach nearly 800 Tg C/yr just after 1900 (Fig. 1). This estimate is significantly larger in magnitude and the timing is slightly different than previously reported by Houghton et al. (1999). To put this estimate in perspective, and considering that emissions from soil are not included, it is comparable to recent emissions from global land-use changes which are estimated to be between 500 and 2300 Tg C/yr (Houghton, 2003). Carbon emissions from U.S. forest land were partially offset by temporary sequestration in lumber and structural material, at a rate of about 200 Tg C/yr for a period just before 1900 (Fig. 1). As the sawtimber removal rate declined, emissions from burned or decaying wood products exceeded the rate of input to the wood products carbon pool, resulting in a period of net emissions from the wood products pool after 1900.

CONTINUED HARVEST, REGROWTH, AND MANAGEMENT: 1900–2000

Forest dynamics in the 20th century were strongly influenced by harvest of most of the remaining original

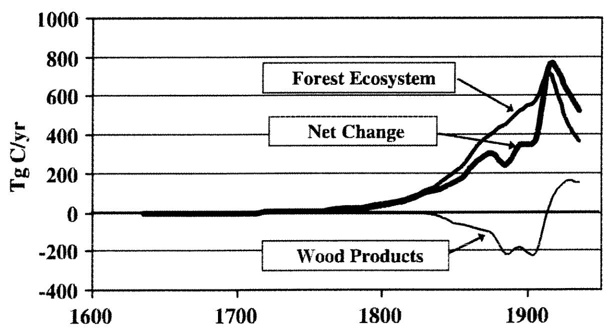

Fig. 1. Estimated net carbon emissions and sequestration calculated from changes in the sawtimber resource, 1650–1930 (Table 1). Estimated carbon changes in the forest ecosystem are based on changes in carbon stocks. Estimated carbon changes in wood products are based on quantity of sawed lumber. Net change is the sum of estimated carbon changes in the forest ecosystem and wood products. Estimation methods are described in the text.

sawtimber resource, by regrowth of forests on areas harvested in the 19th century, and by the emergence of science-based intensive forest management (Birdsey and Lewis, 2003). The timing and relative influence of these factors varied by region of the United States.

In the South during the first half of the 20th century, the uncontrolled use of fire to reduce tree stocking and provide forage for livestock was replaced by a policy of fire suppression (Larson, 1960). This allowed restocking by southern pines and hardwoods, which continued through the end of the century (Fig. 2). Southern forests in the second half of the 20th century were also transformed by clearing of bottomland hardwoods for crops and by establishment of pine plantations on many timber harvest sites and marginal agricultural lands (Smith et al., 2004). Some of the plantations were managed intensively for wood production using agronomic methods to support rapid growth in the South's forest products industry.

In the North, forests were allowed to grow again on cutover timberland and on marginal cropland that reverted back to forest (MacCleery, 1992). Intensive industrial management of forests occurred mainly in the northern areas of New England and the Lake States and was generally much less intensive than in the South.

In the West, much of the remaining old-growth forest area was harvested. Investments in intensive silviculture for wood production were focused primarily on Douglas-fir plantations on the west side of the Cascades in Oregon and Washington. Fire suppression was common throughout the West and allowed significant stand structural changes to occur (Gallant et al., 2003). For example, an area of conifer-dominated forest land in the Northern Rockies shows nearly complete dominance of mature stand classes by the end of the 20th century (Fig. 3).

The carbon budget of the U.S. forest sector for the latter half of the 20th century is a reflection of these varied influences in different regions (Fig. 4). The rate of carbon sequestration in forest ecosystems increased from 1953–1986, then declined from 1986 to the present rate of about 140 Tg C/yr (Heath and Smith, 2004). This is a significant change from an increasing to a decreasing rate of carbon sequestration. The amount of carbon sequestered in wood products has increased to a steady

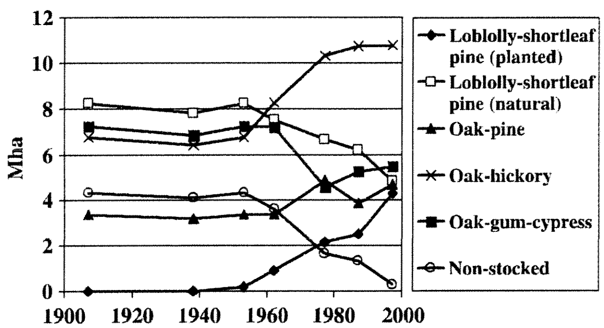

Fig. 2. Selected forest type changes in the southeastern United States, 1906–1997. Data from periodic compilations of forest inventory statistics as described in Birdsey and Lewis (2003).

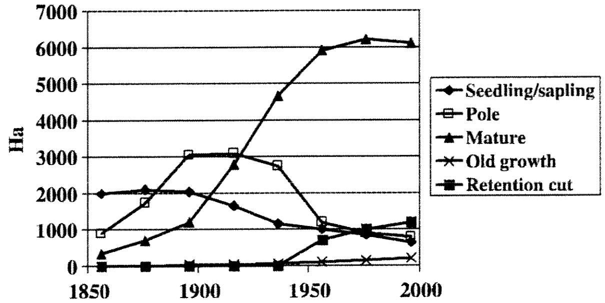

Fig. 3. Forest structure changes in an area of the Northern Rockies, 1850–2000 (adapted from Gallant et al., 2003).

rate of about 60 Tg C/yr (Heath and Skog, 2004) so that the total sequestration in U.S. forests is currently about 200 Tg C/yr. This estimate for the forest sector does not include some potentially large sources or sinks of forest carbon: forest soils, reserved forest land, and other forest land. We hypothesize that these pools are net sinks for carbon at present, but we do not have sufficient inventory data to quantify and test the hypothesis.

When viewed over a longer historical period, and considering the factors that have shaped forests of the 20th century, it is very likely that the strong 20th century regrowth, a response to the heavy drain on the forests of the 19th century, is coming to an end. The net forest sector carbon budget for the period 1630–2000 illustrates the relative steady state of forests from 1630–1800, the peaking of emissions at about 800 Tg C/yr around 1900, the large swing to net sequestration of 250 Tg C/yr around 1985, and the emerging downturn in sequestration rate (Fig. 5). There are two reasons why the peak net emissions of the 19th century are higher in magnitude than the peak net sequestration in the 20th century. First, the clearing of forests and intense utilization of the sawtimber resource happened more rapidly than forests were able to regrow. Second, some of the land that was cleared for agriculture remains in agriculture use, so the forest land base of the 20th century is smaller than that of the 19th century.

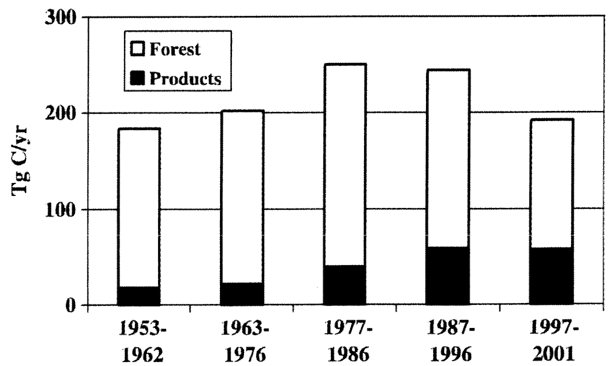

Fig. 4. Carbon sequestration on United States timberland and in wood products, 1953–2001. Excludes soil carbon, carbon on reserved forest land, and carbon on low productivity forest land. Estimates from Heath and Smith (2004), Heath and Skog (2004), and USDA (2004).

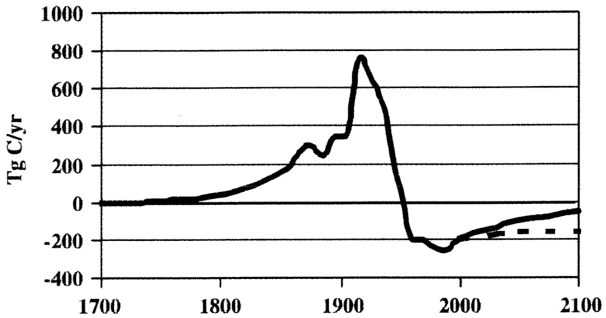

Fig. 5. Carbon emissions in the United States from drain on the sawtimber stand, and sequestration from regrowth, 1630–2000. Projections from 2000–2100 show a continuation of current trends (solid line) and a possible alternate trend (dashed line) that reflects implementation of policies to increase carbon sequestration by the forest sector.

GLOBAL STEWARDSHIP: 2000–2100

The 21st century begins with a heightened awareness of the changing composition of the atmosphere and the role of forests in removing atmospheric CO_2 (Goodale et al., 2002; Janssens et al., 2003). There has been a 30% increase in the atmospheric concentration of CO_2 since 1880, to a current level of about 375 ppm according to the Department of Energy, Carbon Dioxide Information Analysis Center. Under a "business as usual" scenario of global economic growth continuing as currently projected, and without controls on emissions, the concentration of CO_2 in the atmosphere is expected to rise to 700 ppm or more (Intergovernmental Panel on Climate Change, 2001). Stabilizing atmospheric CO_2 at about 500 ppm is often suggested as a goal in international climate policy studies. It is clear that achieving this goal would require application of a wide range of technologies, including forestry (Caldiera et al., 2004; Pacala and Socolow, 2004). The deployment rate of new technology must increase over time to eventually stabilize the atmospheric CO_2 concentration.

The prospective role of forestry in helping to stabilize atmospheric CO_2 depends on harvesting and disturbance rates, expectations of future forest productivity, and the ability to deploy technology and forest practices to increase the retention of sequestered CO_2. The U.S. timber harvest is expected to continue growing through 2050 (Haynes, 2003), and therefore the associated carbon sequestration in wood products (about 60 Tg C/yr) will help maintain the U.S. forest sector as a net carbon sink. Important questions are how to maintain forest ecosystems as carbon sinks over an indefinite period of time, and how to optimize the production of forest biofuels and biomaterials that help reduce demand for fossil energy.

The forest sector includes a variety of activities that can contribute to increasing carbon sequestration, including: afforestation, mine land reclamation, forest restoration, agroforestry, forest management, biomass energy, forest preservation, wood products management, and urban forestry (Birdsey et al., 2000). Taken together, this group of forestry activities could potentially increase carbon sequestration by 100 to 200 Tg C/yr, more than enough to offset projected declines in the sequestration rate by the forest sector of the United States. Implementing these actions will require development of new forestry technology; improvements in measuring, monitoring, and verifying the exchange of CO_2 between forests and the atmosphere; and transfer of the new technology to land managers. The remainder of this paper explores emerging forest management policies, the ecological basis for increasing carbon sequestration by forests, some potential new technology, and some of the socioeconomic issues.

GREENHOUSE GAS POLICIES AND APPROACHES TO MANAGEMENT

The U.S. national plan for reducing greenhouse gases involves research to develop new technology, voluntary participation by the private sector, and targeted incentives (Abraham, 2004). A key part of the U.S. plan is a revision of the guidelines for reporting greenhouse gas reductions and sequestration. In 2002, the President directed the Secretaries of Energy and Agriculture to revise the guidelines that were originally authorized in the 1992 Energy Policy Act, Section 1605(b) (http://www.pi.energy.gov/enhancingGHGregistry/index.html; verified 14 Feb. 2006). The guidelines describe how to estimate and report accomplishments to the national greenhouse gas registry. Participation in the program is voluntary, and helps entities document actions that lead to real greenhouse gas reductions and sequestration. The new rules and guidelines take into account emerging domestic and international approaches to managing greenhouse gases and crediting actions.

Actions to manage greenhouse gases are emerging at many levels of public and private organizations. The main international approach to manage greenhouse gases under the United Nations Framework Convention on Climate Change is the Kyoto Protocol. Now ratified, the protocol includes several mechanisms: national reduction targets, recognition of international assistance projects, and emissions trading (Christiansen, 2004). In the United States, the Environmental Protection Agency and the Department of Energy have programs to encourage reductions in emissions or increases in sequestration by the private sector and by state and local governments (United States Department of Energy, 2005). The U.S. approach involves voluntary participation with incentives, and an emerging private market known as the Chicago Climate Exchange. Several states and some regions have greenhouse gas action plans and registries in various stages of implementation (Dernbach, 2000). Market approaches are under development in the United States, the European Union, and elsewhere (Totten, 1999). The European approach is a "cap and trade" system modeled after the successful scheme used in the United States for reducing sulfur dioxide emissions (Christiansen, 2004). Whether these approaches are successful for managing greenhouse gases or not remains to be determined, as the scope of the problem is significantly more complex than anything previously attempted.

FOREST ECOSYSTEMS, PRACTICES, AND TECHNOLOGY

Disturbance is characteristic of U.S. forests. Each decade, disturbances affect up to half of U.S. forest land (Birdsey and Lewis, 2003). Many kinds of disturbances are included in this estimate (Fig. 6). Some, such as air pollution and weather damage, are not included.

Understanding how carbon stocks change after disturbance is critical for managing carbon in forest ecosystems (Pregitzer and Euskirchen, 2004). Net carbon accumulation depends on time since disturbance, with the rates of change in the different carbon pools varying by forest biome (Fig. 7). Some generalizations emerge from these complex global patterns. Total ecosystem carbon increases with time since disturbance, although some individual carbon pools such as woody debris may decline for a period of time after harvest. The rate of carbon sequestration, as indicated by either net primary productivity (NPP) or net ecosystem productivity (NEP), increases after disturbance to a variable point in time, and then declines as forests mature. Microbial respiration is a key mechanism that regulates net ecosystem productivity. The global analysis strongly suggests that as a general rule, microbial respiration declines with age (Pregitzer and Euskirchen, 2004). In other words, peak ecosystem respiration occurs early in stand development, not late in succession during mature or old-growth stages. This means there may be opportunities to manage respiration following disturbance, for example, by minimizing respiration of soil C through management practices, utilizing harvest residue (slash) in ways that decrease the flux of C back to the atmosphere, or accelerating net primary productivity through intensive management practices or genetics to offset the pulse of microbial respiration following harvest.

Forest management technologies that may reduce CO_2 emissions from forests or increase productivity include: nutrient management, residue management and utilization, thinning and better utilization of products from thinning, low-impact harvesting, optimizing rotation length, species or genotype selection, and forest biotechnology (Stanturf et al., 2003; Stainback and Alavalapati, 2005). Because of the high diversity of forest ecosystems, there is not a single best suite of practices that can be recommended. Practices must be specific to site characteristics and the environment. At the landscape scale, stands representing all stages in the forest life cycle should operate as a functional system that maintains an overall carbon balance among the different ecosystem carbon pools (Harmon, 2001; Jarvis et al., 2005). Another critical consideration is that carbon sequestration is not likely to be the main goal of land ownership, so increasing the rate of net ecosystem productivity or maximizing carbon stocks must be considered in the context of a wider set of ownership goals.

RESEARCH NEEDS

Research, development, and application is needed to facilitate the implementation of forest carbon management for the purpose of stabilizing carbon sequestration in U.S. forests. These needs involve a series of topics and disciplines—a provisional list is shown in Table 2.

A better understanding of socioeconomic issues is critical because there is a large difference between the biological, economic, and social opportunities for increasing forest carbon sequestration, and because management of forests must complement other landowner objectives such as timber production or habitat restoration. Carbon accounting and measurement can be

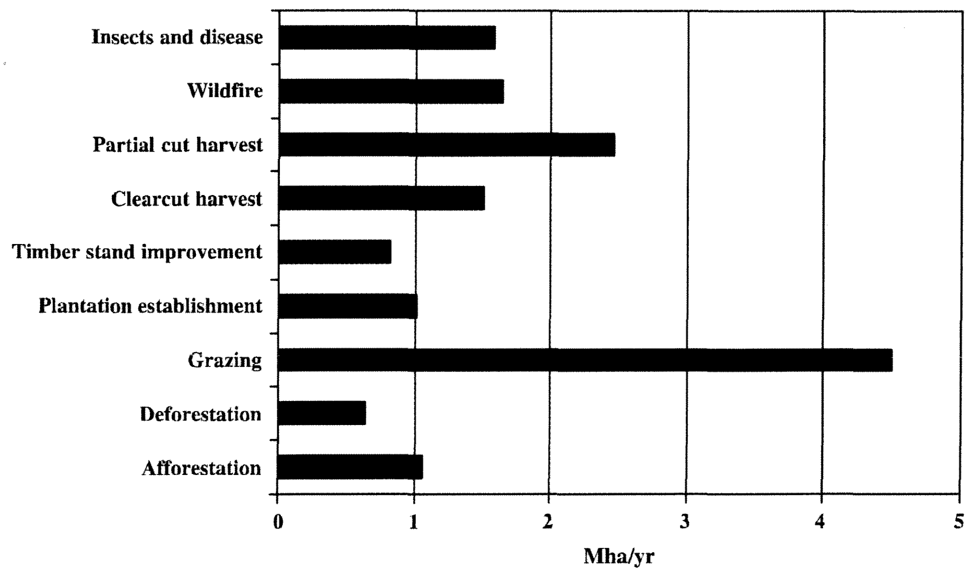

Fig. 6. Disturbances affecting U.S. forests, 1990s. Estimates from Birdsey and Lewis (2003).

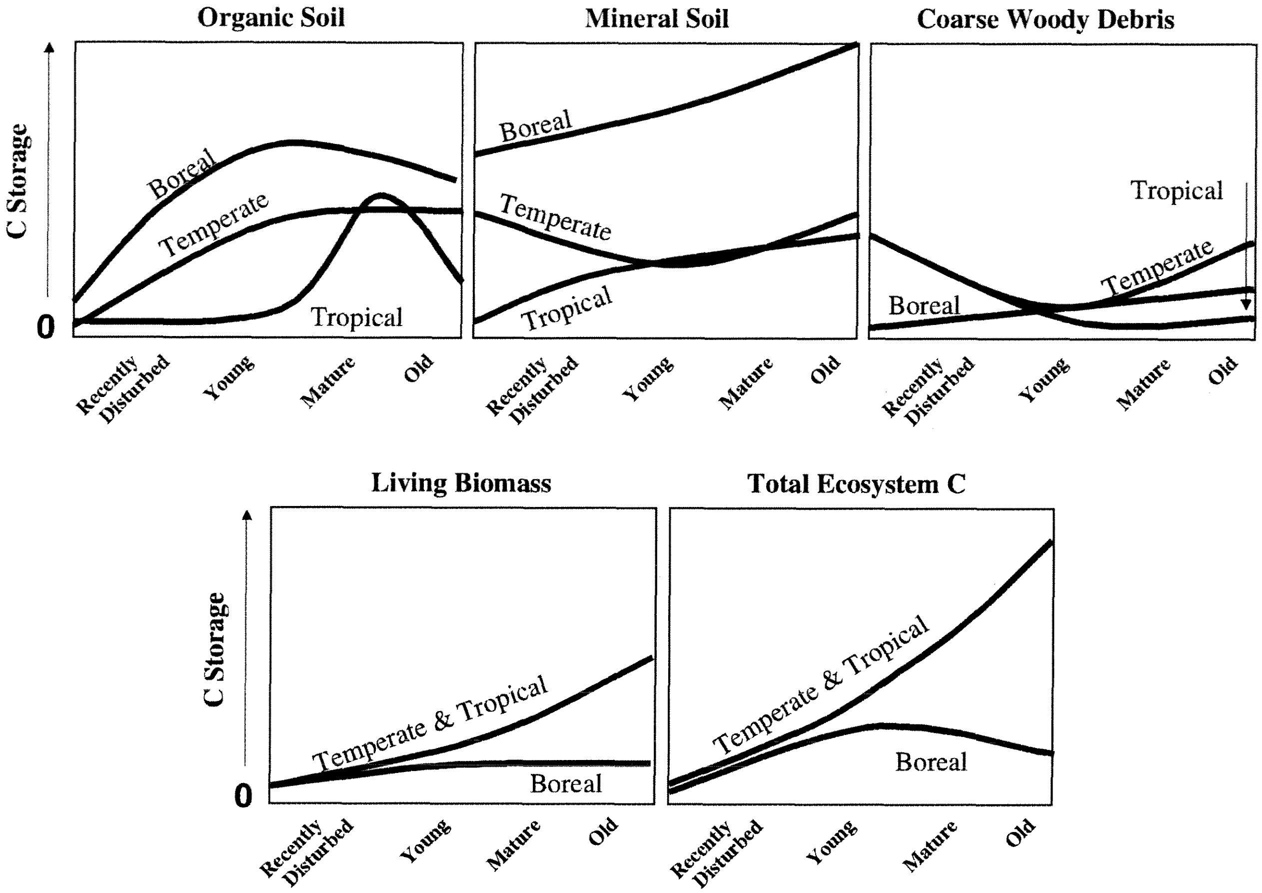

Fig. 7. How carbon stocks change after disturbance (adapted from Pregitzer and Euskirchen, 2004).

Table 2. Some examples of research needed to improve practices and application of forest carbon management.

Socioeconomic issues
Quantifying the magnitude of the forestry opportunity
Relative benefits of sequestration vs. emissions reduction
Integrating carbon management with other objectives
Land-use policies and drivers of land-use change
Forest carbon accounting and measurement issues
Life cycle analysis including fossil fuel emissions associated with management, use, and substitution effects
Additionality, leakage, and avoided emissions
Reducing cost of measurement and monitoring
Carbon management technology
Reduce emissions from forests (respiration of coarse woody debris and soil C)
Utilization of logging residues
Low-impact harvesting
Reduce emissions from operations and manufacturing
Efficiency in harvesting technology and biomass transportation
Efficiency in manufacturing operations
Mechanistic studies of C fluxes along chronosequences after various disturbances
Well-designed field experiments to develop practices for maximizing net ecosystem productivity (NEP) following harvest
Improve efficiencies of carbon management and manufacturing technologies
Technology transfer
Decision support tools
Demonstration projects

expensive, so some new work is needed to develop credible accounting systems and estimation techniques that are commensurate with the value to forestry entities of tracking and reporting on their activities. The monitoring cost is potentially large since forest ecosystems are characterized by multiple carbon pools, with some relatively easy to measure and monitor, such as tree boles, and others much more difficult, such as forest soils. Perhaps the most critical need is to develop effective forest management practices that can increase carbon sequestration without compromising productivity of other goods and services of forests. Past silvicultural research has focused on timber production without complete accounting for effects on the forest carbon cycle, so existing experiments and analyses are inadequate for informing land managers about best management practices for carbon. Finally, there is a need to develop and disseminate information about forest carbon management opportunities, practices, and accounting methods to a very large and diverse population of land managers and forest resource agencies and organizations. This requires new education and technology transfer materials, including decision support systems that can facilitate access to research results.

CARBON MANAGEMENT QUESTIONS AND CONCERNS

Although the role of forests in helping to regulate atmospheric CO_2 is not questioned, the deliberate use of forests as part of a greenhouse gas management strategy raises some questions and concerns (Körner, 2003; Scholes and Noble, 2001; Intergovernmental Panel on Climate Change, 2000). Carbon stored in forests can be unexpectedly released back to the atmosphere, for example because of a natural disturbance such as wildfire. Should an entity claiming a forest carbon credit be debited for unexpected natural release of stored carbon? Also, complete accounting for human-induced changes in all forest carbon and wood product pools may be difficult, and some accounting and measurement issues remain unresolved. For example, changes in forest soil carbon are difficult to measure, but are likely to be slow relative to live biomass or woody debris. Can changes in forest soil carbon be ignored in most circumstances? Where and when are substantial changes in soil carbon likely to occur?

The potential rate of participation in voluntary programs to manage forest carbon is not well known. Participation is likely to be determined by factors such as the trading price of carbon dioxide, transaction costs, acceptance of forest carbon credits as equally tradeable with credits from emissions reduction, and the accuracy with which additional forest carbon sequestration can be estimated and reported. In addition, a technical support system will be needed to provide land managers with the knowledge and tools necessary to make competent decisions about how to manage specific forest systems to reduce greenhouse gases.

CONCLUSIONS

Forests in the United States were in approximate carbon balance with the atmosphere from 1600–1800. Utilization and land clearing caused a large pulse of forest carbon emissions to build during the 19th century, followed by regrowth and net forest carbon sequestration in the 20th century. Recent data and knowledge of the general behavior of forests after disturbance suggest that the rate of forest carbon sequestration is declining. Some effort will be required to stabilize forest carbon sequestration at a rate that is higher than projected. A goal of an additional 100 to 200 Tg C/yr of forest carbon sequestration is achievable, but would require investment in inventory and monitoring, development of technology and practices, and deployment of decision-support systems.

Forest carbon management raises some interesting questions for the 21st century. Forest resource sustainability is often discussed as a way to ensure the continued production of a variety of forest goods and services. Is carbon management compatible with forest resource sustainability? How does forest carbon management enhance or detract from other ecosystem services such as water and biodiversity? These are important questions for consideration by the various actors in the forest carbon management scheme: federal, state, and local governments; forest industries; other private landowners; and a variety of non-governmental organizations.

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