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Carbon Sequestration in Forests

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Summary

Widespread concern about global climate change has led to agreements to reduce emissions of carbon dioxide (CO_2) and, under certain circumstances, to count additional carbon absorbed in soils and vegetation as part of the emissions reductions. Congress may consider options to increase the carbon stored (sequestered) in forests as it debates this and related issues.

Forests are a significant part of the global carbon cycle. Plants use sunlight to convert CO_2, water, and nutrients into sugars and carbohydrates, which accumulate in leaves, twigs, stems, and roots. Plants also respire, releasing CO_2. Plants eventually die, releasing their stored carbon to the atmosphere quickly or to the soil where it decomposes slowly and increases soil carbon levels. However, little information exists on the processes and diverse rates of soil carbon change.

How to account for changes in forest carbon has been contentious. Land use changes—especially afforestation and deforestation—can have major impacts on carbon storage. Foresters often cut some vegetation to enhance growth of desired trees. Enhanced growth stores more carbon, but the cut vegetation releases CO_2; the net effect depends on many factors, such as prior and subsequent growth rates and the quantity and disposal of cut vegetation. Rising atmospheric CO_2 may stimulate tree growth, but limited availability of other nutrients may constrain that growth.

In this context, timber harvesting is an especially controversial forestry practice. Some argue that the carbon released by cutting exceeds the carbon stored in wood products and in tree growth by new forests. Others counter that old-growth forests store little or no additional carbon, and that new forest growth and efficient wood use can increase net carbon storage. The impacts probably vary widely, and depend on many factors, including soil impacts, treatment of residual forest biomass, proportion of carbon removed from the site, and duration and disposal of the products. To date, the quantitative relationships between these factors and net carbon storage have not been established.

Some observers are concerned that “leakage” will undermine any U.S. efforts to sequester carbon by protecting domestic forests. By leakage, they mean that wood supply might shift to other countries, exacerbating global climate change and causing other environmental problems, or that wood products might be replaced by other products that use more energy to manufacture (thus releasing more CO_2). Others counter that the “leakage” arguments ignore the enormous disparity in ecological systems and product preferences, and discount possible technological solutions.

Several federal government programs affect forestry practices and thus carbon sequestration. Activities in federal forests affect carbon storage and release; timber harvesting is the most controversial such activity. Federal programs also provide technical and financial help for managing and protecting private forests, and tax provisions affect private forest management. Various federal programs can also affect the extent of forested area, by supporting development (which may cause deforestation) or encouraging tree planting in open areas, such as pastures.

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Global climate change is a widespread and growing concern that has led to extensive international discussions and negotiations.[1] Responses to this concern have focused on reducing emissions of greenhouse gases, especially carbon dioxide, and on measuring carbon absorbed by and stored in forests, soils, and oceans. One option for slowing the rise of greenhouse gas concentrations in the atmosphere, and thus possible climate change, is to increase the amount of carbon removed by and stored in forests. As Congress debates climate change and options for addressing the issue, ideas for increasing carbon sequestration in forests are likely to be discussed.

This report examines basic questions concerning carbon sequestration in forests. The first section provides a brief background on congressional interest in forest carbon sequestration. The second describes the basic carbon cycle in forests, with an overview of how carbon cycling and storage vary among different types of forests. The third section then addresses how forest carbon is considered in the global climate change debate. The section begins with an overview of accounting for forest carbon, then discusses the carbon consequences of forest management practices, the effects of changes in land use, and "leakage." The section then concludes with a summary of existing federal programs that could affect forest carbon sequestration.[2]

Background: Congressional Interest in Carbon Sequestration

The widespread and growing concern over global climate change has led to extensive international negotiations. In 1992, at the Earth Summit in Rio de Janeiro, the United Nations Framework Convention on Climate Change (which included voluntary pledges to reduce greenhouse gas emissions) was opened for signature. President George H. W. Bush signed this treaty, which was then ratified by the U.S. Senate.

Subsequent negotiations led to the 1997 Kyoto Protocol, under which the developed nations agreed to specified reductions in their emissions of greenhouse gases. President Clinton signed the Kyoto Protocol, but did not submit it to the Senate for ratification. Early in 2001, the George W. Bush Administration decided to reject the Kyoto Protocol, and withdrew from active participation in negotiations on the issues that remain to be resolved.[3] Although enough other parties have ratified the Protocol to bring it into force, the lack of U.S. involvement means that the United States will not participate in the emissions trading or other elements of the Kyoto Protocol activities that might relate to carbon sequestration.

The most voluminous greenhouse gas produced by humans is carbon dioxide (CO_2). In calculating overall carbon emissions, the Protocol allows certain removals of carbon by a nation's forests and soils—"carbon sinks"—to be counted and deducted from emissions. Thus, one option

[1] This report does not address underlying questions of whether global warming is occurring or of the possible human role. See CRS Report RL33849, *Climate Change: Science and Policy Implications*, by Jane A. Leggett.

[2] This report does not address the impacts of climate change on forests, although this is also an important scientific issue. For a discussion of these impacts, see the series of articles in "A Special Section on Climate Change and Forest Ecosystems," *Bioscience*, v. 51, no. 9 (Sept. 2001): 720-779.

[3] SeeCRS Report RL33826, *Climate Change: The Kyoto Protocol, Bali "Action Plan," and International Actions*, by Susan R. Fletcher and Larry Parker.

for mitigating greenhouse gas emissions—and thus possible climate change—is to increase the amount of carbon stored in forests.

Carbon sequestration, and the extent to which it can be counted as a reduction in a nation's carbon emissions, have been the focus of substantial controversy in international negotiations to finalize the operational rules of the Kyoto Protocol. The United States, with its extensive forests, argued that the carbon absorbed by them should be allowed to offset emissions, with no quantitative limit to the amounts that can be counted in this way. The European Union argued strongly in negotiations prior to 2001 that there should be fairly strict limits on how much carbon absorbed by "sinks" such as forests could be counted against emissions. In final negotiations during 2001 on rules to implement the Kyoto Protocol, after the United States had withdrawn from the negotiations, a compromise was reached that allows significant credit for carbon sinks (removals and storage of carbon). The Members of Congress attending these negotiations prior to 2001 followed this debate with interest, and were aware of the potential impacts of the various possible results of the negotiations. In particular, if emissions trading were to begin under the Kyoto Protocol, forest owners and managers in countries that were parties to the treaty might be able to receive credits and participate in the trading regime.

Administration and congressional interest in carbon sequestration continues, but U.S. participation in the Kyoto process is moot at this time. It is not clear whether a domestic forest carbon program might be established, although options have been discussed in legislative proposals. Protecting forests in developing countries, which might earn credits under the Kyoto Protocol, is already supported under the Tropical Forest Conservation Act (P.L. 105-214; 22 U.S.C. §§2341, et seq.).[4]

Mitigating climate change by enhancing forest carbon sequestration may be a relatively low-cost option and would likely yield other environmental benefits. However, forest carbon sequestration faces challenges: measuring the *additional* carbon stored (over and above what would occur naturally); monitoring and verifying the results; and preventing leakage. Numerous issues regarding the carbon cycle in forests, monitoring the levels and changes in forest carbon, and the scientific uncertainties about the relationships among forests, carbon, and climate change are likely to be the subject of ongoing federal research efforts, with funding and oversight by the Congress.

Carbon Cycling in Forests

Photosynthesis is the chemical process by which plants use sunlight to convert nutrients into sugars and carbohydrates. Carbon dioxide (CO_2) is one of the nutrients essential to building the organic chemicals that comprise leaves, roots, and stems. All parts of a plant—the stem, limbs and leaves, and roots—contain carbon, but the proportion in each part varies enormously, depending on the plant species and the individual specimen's age and growth pattern. Nonetheless, as more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering (storing) it in plant tissue (vegetation) above and below ground.

[4] See CRS Report RL31286, *Debt-for-Nature Initiatives and the Tropical Forest Conservation Act: Status and Implementation*, by Pervaze A. Sheikh.

Plants also respire, using oxygen to maintain life and emitting CO_2 in the process. At times (e.g., at night and during winter seasons in non-tropical climates), living, growing forests are net emitters of CO_2, although they are generally net carbon sinks over the life of the forest.

When vegetation dies, carbon is released to the atmosphere. This can occur quickly, as in a fire,[5] or slowly, as fallen trees, leaves, and other detritus decompose. For herbaceous plants, the above-ground biomass dies annually and begins to decompose right away, but for woody plants, some of the above-ground biomass continues to store carbon until the plant dies and decomposes. This is the essence of the carbon cycle in forests—net carbon accumulation (sequestration) with vegetative growth, and release of carbon when the vegetation dies. Thus, the amount of carbon sequestered in a forest is constantly changing with growth, death, and decomposition of vegetation.

In addition to being sequestered in vegetation, carbon is also sequestered in forest soils. Carbon is the organic content of the soil, generally in the partially decomposed vegetation (humus) both on the surface and in the upper soil layers, in the organisms that decompose vegetation (decomposers), and in the fine roots.[6] The amount of carbon in soils varies widely, depending on the environment and the history of the site. Soil carbon accumulates as dead vegetation is added to the surface and decomposers respond. Carbon is also "injected" into the soil as roots grow (root biomass increases). Soil carbon is also slowly released to the atmosphere as the vegetation decomposes. Scientific understanding of the rates of soil carbon accumulation and decomposition is currently not sufficient for predicting changes in the amount of carbon sequestered in forest soils.

The Forest Cycle

Forests generally go through cycles of growth and death, sequestering and releasing carbon. Some forests begin on spacious sites, with little or no existing vegetation, that may have been cleared by a natural disaster (most commonly wildfire) or by human activities (e.g., for agriculture). Other forests are relatively continuous, with natural clearings typically limited to the area occupied by one or a few large trees killed by lightning, disease, and such. Regardless of the size or origin of a clearing, most forests begin from essentially bare land, with some carbon stored in the soil (how much depends on the environment and history of the site, especially the last clearing process).

As trees and other woody plants become established, carbon stored on the site increases as woody biomass increases and as annual vegetation (e.g., tree leaves and herbaceous plants) typically grows faster than it decomposes. Productivity for commercially usable wood generally follows an S-shaped curve, with the volume growing at an increasing rate for many years, to a point known to foresters as the culmination of mean annual increment (generally taking 20 to 100 years or more, depending on the fertility of the site and the tree species), and then growing at a decreasing rate for many more years. In theory, forests can eventually become "over-mature," where the loss of commercial volume through tree mortality equals or exceeds the additional growth on the

[5] Fire is a self-sustaining chemical process that breaks organic chemicals down into minerals, water, and CO_2.

[6] Roots less than 2 millimeters in diameter are generally considered to be part of the soil, not part of the plant that grew them.

remaining trees. However, one study has shown that some old-growth ("over-mature") forests continue to accumulate carbon in their soils.[7]

The relationship between commercially usable wood produced and carbon sequestered varies substantially in three ways. First, the proportion of carbon in a tree's commercial wood (compared to the noncommercial biomass in bark, limbs, roots, and leaves or needles) varies among species; some (e.g., pines and other conifers) have a greater proportion of their total carbon in commercial wood.[8] Second, the proportion of carbon in a tree's commercial wood undoubtedly changes over time; while a temporal graph of carbon storage is probably also S-shaped (as for commercial wood productivity), the changes in timing and rates of increase (that cause the characteristic S shape) almost certainly differ. Finally, a significant portion of the vegetative carbon sequestered in a forest is in other plants—noncommercial species of trees, shrubs, grasses, and other herbaceous plants. The amount of carbon stored in this other (noncommercial) growth varies widely among forests. Thus, although many research studies assume a fixed relationship between commercial wood inventories and the amount of carbon stored,[9] the traditional measures of commercial wood production might not be very accurate for estimating carbon sequestration in forests.

Eventually, trees die. They may be cut down, burned in a wildfire, blown over or snapped off in a wind or ice storm, or killed by insects or diseases. Death can happen to a single tree in a forest, creating a small opening, or to all or most trees in an area. How quickly the carbon is released to the atmosphere depends on the cause of tree death, on whether it is harvested for use, and on various environmental factors. As noted above, fires quickly break down biomass and release an enormous amount of CO_2 into the atmosphere. Natural death and decay may require several weeks to several decades to completely decompose the biomass (depending on site conditions), putting some carbon into the soil and some directly into the atmosphere. Timber harvesting can store some vegetative carbon for very long periods in solid wood products with long-term uses (e.g., construction lumber in houses), while tree tops and limbs and noncommercial species are left to decay or to be burned. These possibilities are discussed in more depth below, under "Forestry Events and Management Activities."

[7] Guoyi Zhou, Shugyang Liu, Zhian Li, Deqiang Zhang, Xuli Tang, Chuanyan Zhou, Junhua Yan, and Jianming Mo, "Old-Growth Forests Can Accumulate Carbon in Soils," *Science*, v. 314 (Dec. 1, 2006): 1417. (Hereafter referred to as Zhou et al., "Soil Carbon in Old-Growth Forests.")

[8] This is one reason why these species are preferred for timber plantations—a greater proportion of total biomass production goes into commercial wood, and is not "wasted" on noncommercial biomass.

[9] One study—Paul Schroeder, "Can Intensive Management Increase Carbon Storage in Forests?" *Environmental Management*, v. 15, no. 4 (1991): 475-481—assumed a "biomass expansion factor" of 1.6; that is, it assumed that total biomass was 60% greater than (1.6 times) the commercial wood biomass. (Hereafter referred to as Schroeder, "Intensive Management for Carbon Storage.") Another study—Jack K. Winjum, Sandra Brown, and Bernhard Schlamadinger, "Forest Harvests and Wood Products: Sources and Sinks of Atmospheric Carbon Dioxide," *Forest Science*, v. 44, no. 2 (1998): 272-284—assumed biomass expansion factors of 1.3 for conifer forests and 2.0 for non-conifer forests. A third study—Robert J. Moulton and Kenneth R. Richards, *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States*, Gen. Tech. Rept. WO-58 (Washington, DC: USDA Forest Service, Dec. 1990)—used biomass expansion factors ranging from less than 2.0 to more than 8.0 just for different forests within the United States.

Forest Types

Carbon sequestration and release vary substantially by forest. Nonetheless, some generalizations are possible, because of the relative similarity of forests in specific "biomes"[10]—tropical, temperate, and boreal forests. **Table 1** shows average carbon levels sequestered in vegetation and soils for several major biomes, and the weighted average for all biomes.[11]

Table 1. Average Carbon Stocks for Various Biomes

(in tons per acre)

Biome	Plants	Soil	Total
Tropical forests	54	55	109
Temperate forests	25	43	68
Boreal forests	29	153	182
Tundra	3	57	60
Croplands	1	36	37
Tropical savannas	13	52	65
Temp. grasslands	3	105	108
Desert/semidesert	1	19	20
Wetlands	19	287	306
Weighted Average	***14***	***59***	***73***

Source: Adapted from Intergovernmental Panel on Climate Change, "Table 1: Global carbon stocks in vegetation and carbon pools down to a depth of 1 m [meter]," *Summary for Policymakers: Land Use, Land-Use Change, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change*, at http://www.ipcc.ch/pub/srlulucf-e.pdf, p. 4.

Tropical Forests

Tropical forests are generally defined by their location—between the Tropic of Cancer and the Tropic of Capricorn (23° north and south of the Equator, respectively). Some tropical forests are relatively dry, open woodlands, but many receive heavy rains and are called moist or humid tropical forests; these are the classic rainforests, or "jungles." Tropical forests contain an enormous diversity of "hardwood" tree species,[12] and are difficult to categorize into "forest types," because of this breadth of species diversity.

[10] A "biome" is defined as a "[r]egional land-based ecosystem type ... characterized by consistent plant forms and ... found over a large climatic area." Examples include tropical rainforests, tundra, temperate grasslands, deserts, etc. From *The Dictionary of Ecology and Environmental Science,* Henry W. Art, ed. (New York, NY: Henry Holt & Co., 1993), p. 65.

[11] Data on carbon stocks presented in this section are CRS calculations from data in Intergovernmental Panel on Climate Change, "Table 1: Global carbon stocks in vegetation and carbon pools down to a depth of 1 m [meter]," *Summary for Policymakers: Land Use, Land-Use Change, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change,* at http://www.ipcc.ch/pub/srlulucf-e.pdf, Dec. 27, 2001. (The report is hereafter referred to as IPCC, *Special Report*.)

[12] "Hardwoods" is a term commonly used for trees in the phylum Anthophyta (angiosperms, or flowering plants), because the dominant hardwood tree species of temperate climates (oaks and maples) are harder (more dense) than the (continued...)

Moist tropical forests are important for carbon sequestration, because they typically have high carbon contents—averaging nearly 110 tons per acre. (See **Table 1**.) About half of the carbon in moist tropical forests is contained in the vegetation, a higher percentage and a much higher quantity than in any other biome. The remaining carbon is in tropical forest soils; tropical forest soils have only modest carbon levels (compared with other biomes), because the dead biomass rapidly decomposes in the warm, humid conditions and the minerals rapidly leach out of tropical forest soils.

Temperate Forests

Temperate forests typically occur in the mid-latitudes—generally to about 50° north and south of the Equator (a little farther north in Europe, because of the continental warming from the Gulf Stream). There are a large variety of temperate forests, including hardwood types (e.g., oak-hickory and maple-beech-birch), softwood types (e.g., southern pine, Douglas-fir, and lodgepole pine), and a few mixed types (e.g., oak-pine). However, within each forest type, and overall, temperate forests have much lower tree species diversity than tropical forests.

Temperate forests generally contain less carbon than tropical forests, averaging nearly 70 tons per acre. More than one-third of the carbon is stored in the vegetation, and nearly two-thirds in the soil. The higher proportion (but lower level) in the temperate forest soils (compared to tropical forest soils) is because of slower decomposition rates. Many of these forests are managed to produce commercial wood products, and the management practices used in temperate forests can thus have a significant impact on carbon sequestration.

Boreal Forests

Boreal forests generally occur north of temperate forests, mostly in Alaska, Canada, Scandinavia, and Russia. (The only boreal forests in the Southern Hemisphere are on mountaintops in New Zealand and high in the Andes Mountains of South America.) Boreal forests are dominated by conifers—mostly spruce, fir, and larch, with scattered birch and aspen stands.

Boreal forests generally contain more carbon than temperate or tropical forests, averaging more than 180 tons per acre. Less than one-sixth of boreal forest carbon is in vegetation. The rest, 84%, is in boreal forest soils—about three times the amount in temperate and tropical forests, and far higher than any other biome except wetlands.[13] Carbon accumulates to high levels in boreal forest soils because of the very slow decomposition rates, owing to short summers and the high acidity of conifer forest soils, both of which inhibit decomposition. The high boreal forest soil carbon

(...continued)

major "softwood" species (pines, firs, and spruces), trees of the order Coniferales (conifers). However, some "hardwood" species (e.g., aspen and poplar) are much softer (less dense) than many "softwoods." In temperate areas, most hardwoods are also deciduous (losing all their leaves annually), while most conifers are evergreen (retaining their needles for more than one year), leading to common use of "deciduous" and "evergreen" as synonyms for angiosperms and conifers. However, certain conifers (notably larches) are deciduous, while many hardwoods in subtropical climates and most in tropical climates are evergreen. For this report, "hardwood" is used to indicate angiosperms, while "softwood" (or conifer) is used for coniferous species.

[13] Soil carbon levels in wetlands are nearly double the level in boreal forests, because the frequent standing water prevents aerobic decomposition, and anaerobic (without oxygen) decomposition processes are much slower than aerobic processes.

level is important for carbon cycling, because many believe that management activities that disturb boreal forest soils can increase their release of carbon.

Measuring and Altering Forest Carbon Levels

Aside from the questions of whether climate change is occurring and whether human activities are the cause, the role of forestry and land use in mitigating climate change has been quite controversial. The disputes are largely the result of the scientific uncertainties in measuring changing carbon levels in forests, changing land uses, and changing demand for products. This section summarizes forest carbon accounting concerns, possible consequences of changes in land use and of forest management events and practices, "leakage," and existing federal programs related to these concerns.

Forest Carbon Accounting

Different countries have various views on how to count carbon sequestered or released from forests. In general, countries with extensive and expanding forests (e.g., Russia, Canada, Brazil, and the United States) prefer a full accounting, while countries with less forestland (e.g., many European countries) are concerned about the potential to overstate the carbon benefits of forestry management practices and land use changes that enhance carbon sequestration. Countries with net deforestation rates are also concerned about counting forest sequestration, because it could effectively increase their net emission rated under international agreements.

Article 3.3 of the Kyoto Protocol allows counting the carbon effects (both sequestration and release) of afforestation, reforestation, deforestation, and other forestry and land use changes that have occurred since 1990, if the change in carbon stock is verified. Verification requires a system for estimating the carbon effects—because a census of carbon changes on every forested acre is infeasible—and for reporting the carbon effects.

For countries with carbon commitments (rather than for projects), the surest, easiest system for verifying the change in carbon levels is to measure the change in the levels from the beginning to the end of the relevant time period—1990 (the baseline) and 2008-2012 (the Kyoto Protocol commitment period); however, this is a very slow and expensive approach.[14] A variety of models can be used for estimating carbon level changes. The two basic approaches are:

- a "land-based" approach, which begins by identifying the acceptable activities for sequestering carbon and estimating the carbon consequences of those activities, and then monitors the *lands* to determine the extent to which those activities occur; and
- an "activity-based" approach, which also begins by identifying the acceptable activities for sequestering carbon and estimating the carbon consequences of

[14] Richard Birdsey, Ralph Alig, and Darius Adams, "Chapter 8. Mitigation Activities in the Forest Sector to Reduce Emissions and Enhance Sinks of Greenhouse Gases," *The Impact of Climate Change on America's Forests: A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment* (Linda A. Joyce and Richard Birdsey, tech. eds.), Gen. Tech. Rept. RMRS-GTR-59 (Fort Collins, CO: USDA Forest Service, 2000), p. 116. (Hereafter referred to as Birdsey et al., "Forest Mitigation.")

> those activities, and then monitors the *activities* to determine the extent to which those activities occur.[15]

The approach taken affects the intensity and spatial scale of the monitoring required, and different models impose different requirements for data, boundary conditions, carbon stocks, and more. However, the Intergovernmental Panel on Climate Change contends that, regardless of the approach and model:[16]

> A well-designed carbon accounting system would provide transparent, consistent, comparable, complete, verifiable, and efficient recording and reporting of changes in carbon stocks and/or changes in greenhouse gas emissions by sources and removals by sinks from applicable land use, land-use change, and forestry activities and projects under relevant Articles of the Kyoto Protocol.

There are significant difficulties in achieving such a "well-designed carbon accounting system." Some observers have noted that the "language, terminology, and accounting methods contained in the [Kyoto Protocol] are somewhat vague and can be interpreted in different ways."[17] In addition, there are scientific uncertainties in measuring the 1990 baseline carbon stocks, the lands treated, the carbon impacts of various treatments, and the question of "leakage," as discussed in the following sections.

Land Use Changes

Over time, forests can grow on lands that were in other uses (e.g., croplands), and vice versa. Deforestation is the conversion of forests to pasture, cropland, urban areas, or other landscapes that have few or no trees. Afforestation is planting trees on lands that have not grown trees in recent years, such as abandoned cropland.

Not all land use changes have comparable carbon consequences. Tropical deforestation, if a pasture replaces the forest, could substantially reduce carbon sequestration, since tropical savannahs store less than half as much carbon on average as tropical forests.[18] In contrast, in temperate zones, carbon sequestration might actually *increase* if native grassland replaces forest, since temperate grasslands store 50% more carbon on average than do temperate forests; but, if the temperate deforestation is for crop production, less carbon would be sequestered, since croplands store only half as much carbon on average as temperate forests.[19] The actual impacts—both the quantity and the timing or duration of the change—probably depend on the actual practices employed on the various sites. Other changes may be less obvious. Converting a "working forest" (i.e., one that is managed to produce timber and other values) to a rural residential subdivision would likely reduce forest cover and perhaps undergrowth (thus releasing some vegetative carbon), but the rest of the vegetation would likely continue to grow, and thus may continue to sequester carbon for longer in the subdivision than in a working forest (depending on the nature and duration of the wood products derived from the working forest).

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[15] IPCC, *Special Report*, "4. Carbon Accounting."

[16] IPCC, *Special Report*, paragraph 31.

[17] Birdsey et al., "Forest Mitigation," p. 112

[18] CRS calculations from data in IPCC, *Special Report*, table 1, p. 4.

[19] CRS calculations from data in IPCC, *Special Report*, table 1, p. 4.

Thus, it may not be possible to draw simple conclusions about the carbon consequences of land use changes, especially in temperate zones.

According to the *1997 National Resources Inventory,* more than 25 million acres of private forestland in the United States were converted to other uses between 1982 and 1997.[20] Of these, nearly 12 million acres were developed for other uses, while 4 million acres were converted to pasture and nearly 4 million acres were either inundated by water (deforested) or transferred to federal ownership (and probably remained forested). During the same period, nearly 26 million acres were converted to private forestland—a net increase of nearly a million acres of private forestland. Of these, more than half (nearly 14 million acres) were previously pastureland, and more than 5 million acres were cropland.

The conversion of forestland to other uses is dominated by development. The rate of development reflects economic growth, interest rates, and development incentives—stronger growth, lower interest rates, greater incentives stimulate more development (and more conversion of forestland), while slower growth or recession, higher interest rates, or weaker incentives may retard development. While federal monetary, fiscal, and tax policies clearly affect development rates, their impact on forestland conversion is likely less of a consideration than the goal of trying to provide stable economic growth for the U.S. economy. The conversion of pasture and cropland to forests is also affected by the general economy, but is also likely to be directly affected by existing federal programs, such as the forestry assistance programs and other agricultural conservation programs (discussed below).

Forestry Events and Management Activities

As discussed above, forests cycle carbon, accumulating carbon from the atmosphere during some periods in the forest cycle and releasing carbon to the atmosphere at other times. When forest practices alter the vegetation on a site, they alter this ebb and flow of carbon storage and release by changing biomass levels, vegetative growth patterns, and soil structure and composition. There have been debates in the literature, and at least one congressional hearing, about the carbon impacts of various forest management practices.[21] This section examines the implications of various forestry practices and events for carbon sequestration. First, however, it examines generic considerations of what happens to the carbon in cut vegetation and in soils from forestry practices.

Vegetation and Soil Carbon

A wide array of practices are used in managing forests. Most involve altering the vegetation, and thus the carbon cycle, on the site. Before discussing specific practices, it is important to examine

[20] USDA Natural Resources Conservation Service and Iowa State University Statistical Laboratory, *Summary Report: 1997 National Resources Inventory* (Washington, DC: Dec. 1999), p. 35.

[21] U.S. House, Committee on Resources, Subcommittee on Forest and Forest Health, *H.Con.Res. 151, Expressing the Sense of the Congress that the United States Should Manage Its Public Domain National Forests to Maximize the Reduction of Carbon Dioxide in the Atmosphere Among Many Other Objectives and that the United States Should Serve as an Example and as a World Leader in Actively Managing Its Public Domain National Forests in a Manner that Substantially Reduces the Amount of Carbon Added to the Atmosphere* (Washington, DC: U.S. Govt. Print. Off., 1998), Serial No. 105-61.

what happens to vegetation that is cut but not removed from the forest and what happens to the soil carbon, as these factors apply to most, if not all, forest management practices.

What Happens to the Cut Vegetation?

Most forest practices involve cutting some of the existing vegetation on a site—to harvest commercial wood, to focus growth on fewer trees, to reduce competition among plants, etc. What happens to the cut vegetation is critical for assessing carbon sequestration. When commercial harvests are involved, some of the biomass is removed from the site and turned into products. (The carbon consequences of removed vegetation are discussed below.) How much biomass (and carbon) is removed has not been broadly quantified; various studies report that 50% to 80% of tree carbon (excluding forest soil carbon) is removed in commercial timber harvest operations.[22] Others have stated that "wood products formed only a modest fraction of the total" carbon stored by a forest.[23] This is consistent with a newer report showing wood products (and landfills) accounting for a little more than 6% of forest-related carbon stocks.[24] The proportion of carbon and biomass removed from any particular site varies widely, and depends on the species involved, the density of the stand (which affects both tree form and undergrowth vegetation), the diversity of tree species and tree sizes in the stand, and various environmental factors (e.g., the site's climate and soil fertility)

Much biomass (and carbon) remains on the site; for some forest practices, such as precommercial thinning (described below), all the cut biomass remains on the site. The remaining biomass—coarse roots, limbs, leaves or needles, and other unusable woody material, often called "slash" in timber harvesting—begins to deteriorate, and to release carbon. How fast the carbon is released depends on whether and how the biomass is treated. Slash treatments include rolling, chopping, and crushing, all of which are designed to compact the biomass and accelerate its deterioration, which typically takes several weeks to several years, depending primarily on the climate. Burning is also common, and leads to deterioration (and release of some of the carbon to the atmosphere) in minutes or hours, rather than weeks, months, or years. Many research studies presume that the carbon from slash is released within a year of the harvest; others presume that it is quickly absorbed by new growth resulting from the treatment. Data on the extent of various slash treatments and on the carbon impacts of the various treatments are sparse.

[22] See Mark E. Harmon, William K. Ferrell, and Jerry F. Franklin, "Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests," *Science*, v. 247 (Feb. 9, 1990): 699-702 (hereafter referred to as Harmon, et al., "Conversion of Old Growth Forests"); Robert C. Musselman and Douglas G. Fox, "A Review of the Role of Temperate Forests in the Global CO_2 Balance," *Journal of the Air and Waste Management Association*, v. 41, no. 6 (June 1991): 798-807 (hereafter referred to as Musselman and Fox, "Role of Temperate Forests"); and Andrew J. Plantinga, Thomas Mauldin, and Douglas J. Miller, "An Econometric Analysis of the Costs of Sequestering Carbon in Forests," *American Journal of Agricultural Economics*, v. 81, no. 4 (Nov. 1, 1999).

[23] Roderick C. Dewar and Melvin G. R. Cannell, "Carbon Sequestration in the Trees, Products and Soils of Forest Plantations: An Analysis Using UK Examples," *Tree Physiology*, v. 11 (1992): 49-71. Summary at http://heronpublishing.com/tree/summaries/volume11/a11-49.html.

[24] R. A. Birdsey and G. M. Lewis, *Carbon in U.S. Forests and Wood Products, 1987-1997: State-by-State Estimates*, Gen. Tech. Rept. NE-310 (Newton Square, PA: USDA Forest Service, Northeast Research Station and U.S. Environmental Protection Agency, 2002).

What Happens to Forest Soil Carbon?

Relatively little literature on forests and carbon addresses the mechanisms by which carbon is accumulated in and released by forest soils. One source noted "the large uncertainty in estimates of change in soil carbon."[25] Dead vegetation is broken down by decomposers—primarily invertebrate animals and fungi. Decomposition releases carbon to the atmosphere and incorporates carbon as organic matter (humus) in the soil. The dead carbon in the soil (i.e., not the decomposers or fine plant roots, which comprise the living carbon in the soil) slowly continues to decompose, changing from organic to inorganic forms; the inorganic forms eventually (1) dissolve in percolating rainwater and leach through the soil into groundwater and surface waters; (2) oxidize and get released directly to the atmosphere; or (3) are absorbed by new vegetation. The rates at which carbon from dead vegetation returns to the atmosphere likely depend on a variety of factors, such as the nature of the vegetation, the composition of the soil, and the humidity levels, all of which affect the type and quantity of decomposers on a site.

Activities that disturb soils almost certainly decrease soil carbon levels. Some studies presume a loss of soil carbon following a soil-disturbing activity, such as timber harvesting.[26] Others note the loss without quantifying it.[27] In general, disturbing soils accelerates decomposition rates, by increasing exposure of soil carbon to air, thus accelerating oxidation. Activities that disturb soils also kill living soil carbon—invertebrate animals, fungi, and fine roots—which then begin to decompose. Thus, forestry activities that disturb soils, particularly activities to remove the cut vegetation (such as commercial timber harvesting), will also likely reduce soil carbon levels. Forestry activities that do not disturb soils, such as fertilization and prescribed burning, probably have much less effect on soil carbon, although they affect the forest carbon balance in other ways (as discussed below).

Forest Events—Wildfires[28]

Fires in forests and grasslands are common events that significantly affect the carbon cycle. As noted above, fire is a self-sustaining chemical process that quickly mineralizes organic matter; in minutes, fires convert organic matter into its components—minerals, water vapor, and CO_2. Wildfires are a very significant source of atmospheric CO_2, and the need to control wildfire to reduce CO_2 emissions, as well as for safety reasons, has been discussed. Furthermore, the likelihood, extent, and/or frequency of wildfires may be exacerbated by expected climate change.

Wildfire is a natural phenomenon, although efforts are made to manage wildfires. One study estimated that in pre-industrial America (200-500 years ago), wildfires burned nearly 10 times as many acres and as much biomass as in recent years.[29] Especially in temperate ecosystems, with dry biomass and lightning, wildfires are inevitable.

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[25] R. A. Houghton, J. L. Hackler, and K. T. Lawrence, "The U.S. Carbon Budget: Contributions from Land-Use Change," *Science*, v. 285 (July 23, 1999): 577.

[26] Musselman and Fox, "Role of Temperate Forests," p. 803.

[27] Harmon, et al., "Conversion of Old-Growth Forests."

[28] For background information, seeCRS Report RL30755, *Forest Fire/Wildfire Protection*, by Ross W. Gorte.

[29] Bill Leenhouts, "Assessment of Biomass Burning in the Conterminous United States," *Conservation Biology* [online], v. 2, no. 1 (1998); available at http://www.consecol.org/vol2/iss1/art1.

Some have proposed wildfire protection by reducing biomass levels in forests. Several of the forestry practices discussed below are intended at least partly to reduce wildfire risks by reducing biomass levels—wildfire fuels. The presumption is that lower fuel loads will lead to fewer and less intense fires that are easier (and less costly) to control. Numerous on-the-ground anecdotes support this presumption. However, little empirical research documents this presumption. One study found that "scant information exists on fuel treatment efficacy for reducing wildfire severity."[30] A summary of wildfire research reported that prescribed burning generally reduced fire severity, that mechanical fuel reduction did not consistently reduce fire severity, and that little research has examined the potential impacts of mechanical fuel reduction with prescribed burning or of commercial logging.[31] The possibility of removing some noncommercial biomass from the forest and using it to produce energy is also being considered, and is discussed below.

One study found that fires in boreal forests may actually cool the atmosphere, despite their large CO_2 releases.[32] The researchers found that loss of dark-colored conifers increased snow cover and that subsequent regrowth was of light-colored birch and aspen. The result was significantly greater *albedo* (light reflectivity), which led to greater cooling than the CO_2 release led to warming. The extent to which this conclusion can be extended is unclear, and of course, boreal forest fires may have other undesirable effects.

Forestry Practices

In general, forestry practices are used for four basic goals or purposes: to establish trees on a site; to reduce vegetative competition; to improve tree growth in other ways; and to harvest the commercially usable wood. In the climate change negotiations, credit for carbon sequestered by forests was intended to be allowed only for *additional* carbon sequestered because of changes in forestry practices.

Stand Establishment

One basic objective of forestry is getting trees to start growing. On sites that have recently had trees on them, but are now cleared (because of timber harvesting or natural disaster), the practice is called reforestation. Tree planting on sites that have not recently had trees on them, such as pastures, is called *afforestation*. In addition, *interplanting* (planting additional trees) is used on sites that have fewer trees than are considered desirable.

Reforestation can use natural or artificial methods. Natural regeneration relies on tree seeds from surrounding forest stands. Artificial regeneration includes planting seeds, or more commonly seedlings from nurseries, on the site. Advantages of natural regeneration include lower cost and greater stand diversity (both of tree species and of the genetic diversity of the dominant tree

[30] Philip N. Omi and Erik J. Martinson, *Effects of Fuels Treatment on Wildfire Severity: Final Report*, submitted to the Joint Fire Science Program Governing Board (Ft. Collins, CO: Colorado State Univ., Western Forest Fire Research Center, Mar. 25, 2002), p. I.

[31] Henry Carey and Martha Schumann, *Modifying WildFire Behavior—The Effectiveness of Fuel Treatments: The Status of Our Knowledge*, Southwest Region Working Paper 2 (Santa Fe, NM: National Community Forestry Center, April 2003).

[32] J. T. Randerson, H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R., Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, and C. S. Zender, "The Impact of Boreal Forest Fire on Climate Warming," *Science*, v. 314 (Nov. 17, 2006): 1130-1132.

species), which generally increases forest resilience and resistance to pests and pathogens. Advantages of artificial regeneration include greater dominance of commercially desirable tree species, greater control over the number of trees established, and more rapid establishment of trees, all of which increase growth of the desired trees. Artificial regeneration may be necessary for afforestation, since surrounding tree seed sources might be inadequate or nonexistent. Artificial regeneration likely provides more commercial wood growth faster, and may sequester more carbon faster, than natural regeneration.

Establishing stands of trees will generally sequester more carbon than leaving the sites without forest cover. Savannas and other non-forest biomes store much less carbon in their vegetation, and *may* reach a plateau or stable carbon stock in their soils in only a few years. In contrast, forests continue to sequester additional carbon in vegetation and roots as it grows for many years—usually at least decades, and even centuries in some ecosystems. (Note, however, from **Table 1**, that temperate grasslands have greater average carbon stocks than temperate forests, generally because perennial grasses increase soil carbon more than forests.) Thus, reforestation and especially afforestation, regardless of whether by natural or artificial regeneration, generally provide continuing additional carbon sequestration for an extended period.

Reducing Competition

Another basic forestry practice is to encourage growth of the commercially desired trees by killing other vegetation that competes with the trees for space, light, and nutrients. This practice is called *release* when the competing vegetation is as tall as or taller than the desired trees, or when it is of a different species (e.g., palmetto growing under southern pine trees). Release can be done chemically (with herbicides) or mechanically (with machines or tools) to kill the unwanted vegetation.

Thinning is the forestry practice of removing some of the desired tree species (as well as the undesired tree species) when the competition for space, light, and nutrients reduces the growth rate of the commercial timber volume. Precommercial thinning occurs when the trees are too small to have any commercial value (generally less than 5.5 inches in diameter), while commercial thinning is the practice of selling the trees to be removed.

Thinning and release are often proposed as forest management practices to increase forest carbon sequestration. Some models estimate total carbon on a site as a fixed relationship to commercial wood volume on a site. Since thinning and release increase commercial timber growth, these models would similarly project thinning and release to increase carbon sequestration.

Others, however, observe that the purpose of thinning and release is often to concentrate the same amount of growth on fewer stems.[33] One study examined the potential of thinning and release to increase carbon storage.[34] This study found that thinning only increased total carbon storage in dense, young stands where severe competition significantly reduced growth rates; in other cases, the practice was "redistributing stand growth to a smaller number of larger trees," with little overall change in carbon storage. The author also noted that thinning may increase the loss of soil carbon, by reducing canopy cover and disturbing the surface and thus accelerating decomposition rates. In contrast, release in a southern pine ecosystem was found to increase total carbon storage

[33] See David M. Smith, *The Practice of Silviculture*, 7th ed. (New York, NY: John Wiley & Sons, Inc., 1962), p. 29.

[34] Schroeder, "Intensive Management for Carbon Storage."

over the life of the stand, and to promote soil carbon storage. Thus, forestry practices that reduce vegetative competition apparently increase carbon sequestration in some circumstances, but not in others, limiting generalizations about their potential for increasing carbon sequestration.

Other Growth Improvement

Other forestry practices are also intended to increase tree growth rates. Pruning removes the lowest branches of a commercial tree, which may stimulate some upward growth, but generally emphasizes wood value (growing clear wood, without knots) rather than growth. It is not used much, because it has been found to be unprofitable in most situations.

Fertilizing forest stands is another practice to increase tree growth. Applying fertilizers to forests can significantly increase growth rates, if the nutrient being applied (nitrogen, potassium, phosphorus, etc.) is in short supply in the forest soil. Furthermore, fertilization is likely to stimulate all vegetative growth, not just tree growth. This is borne out in research on the impact of forestry practices on carbon sequestration.[35] An important question, whose answer is not apparent from the research, is whether the accelerated growth rate from fertilization persists for a long time (i.e., whether the growth rate remains higher for an extended period), whether it produces a short-term increase for which the pre-fertilizer rate is sustained for a long time (i.e., whether the pre-fertilization growth rate is maintained after the short-term increase); or whether other factors limit long-term growth rates (i.e., whether growth rates after the short-term increase are less than the pre-fertilization growth rates, because other nutrients are overdrawn by the fertilizer-stimulated growth).

Some have suggested that greater atmospheric CO_2 levels could fertilize forests, stimulating tree growth. A number of studies artificially increased CO_2 levels in tree plantations, and found that growth rates did increase;[36] others, however, question whether the increased growth rate can be sustained.[37] At the broader scale, in at least some areas, other nutrients (especially nitrogen) are likely to limit the ability of forests to expand growth with more CO_2 available.

Another forestry practice, which is becoming more widely used, is prescribed burning—intentionally setting fires in certain forest areas under specified weather and fuel conditions.[38] Prescribed burning typically produces many forest benefits, including less competing vegetation (akin to release or thinning), lower fuel loads that may contribute to catastrophic wildfires, and a

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[35] Schroeder, "Intensive Management for Carbon Storage."

[36] See, for example, E. H. DeLucia, D. J. Moore, and R. J. Norby, "Contrasting Responses of Forest Ecosystems to Rising Atmospheric CO_2: Implications for the Global C [Carbon] Cycle," *Global Biogeochemical Cycles*, v. 19 (July 19, 2005).

[37] Adrien C. Finzi, David J.P. Moore, Evan H. DeLucia, John Lichter, Kirsten S. Hofmockel, Robert B. Jackson, Hyun-Seok Kim, Roser Matamala, Heather R. McCarthy, Ram Oren, Jeffrey S. Pippen, and William H. Schlesinger, "Progressive Nitrogen Limitation of Ecosystem Processes Under Elevated CO_2 in a Warm-Temperature Forest," *Ecology*, v. 87, no. 1 (Jan. 2006): 15-25.

[38] Prescribed burning is typically only used in ecosystems adapted to relatively frequent surface fires (5- to 35-year intervals between fires), which burn the grasses, needles, twigs, and undergrowth while allowing most of the trees to survive. Such *frequent-fire* ecosystems occur primarily in temperate zones, especially where lightning occurs with little or no rainfall. However, not all temperate forest ecosystems have adapted to relatively frequent surface fires. Some, such as lodgepole pine, jack pine, and aspen, are adapted to regenerate naturally following periodic "crown" fires, where many or most of the trees are killed. In such ecosystems, prescribed burning would poorly simulate natural ecological patterns.

flush of nutrients (since fire reduces biomass to its mineral components). However, prescribed fires also present a risk, since they occasionally escape from the prescribed areas and can cause damage; they also generate substantial amounts of carbon dioxide (one of the mineral components of biomass) and other air pollution. In the short term, prescribed fires clearly increase atmospheric carbon levels. To the extent that prescribed burning reduces catastrophic wildfires, this practice may be shifting one source of carbon emissions (wildfire) to another (prescribed fire); however, to date, no quantitative relationship has been established between prescribed burning and the extent and severity of wildfires. In addition, at least for dead biomass on a site, prescribed burning merely concentrates into a few minutes or hours the carbon release that occurs over a few weeks to a few years in other forms of biomass decomposition. Thus, it is not clear how much of the carbon release from prescribed burning is in addition to the carbon release that might otherwise occur from forests.

Timber Harvesting

For wood that has been removed from the forest, the rate of carbon release depends on what is done with the wood. For *sawtimber* (logs of at least 11.5 inches in diameter), about half is converted into solid wood products (primarily lumber and plywood); another 10% is bark, and the remaining 40% is sawdust and wood scrap.[39] Lumber and plywood have differing usable lives, depending on the use of the wood, and ranging from less than 10 years for shipping pallets to 100 years or more for residential construction.[40] Clearly, some wood—from broken pallets, furniture, concrete forms, etc.—is disposed in landfills (and probably sequesters carbon there) and some is burned, but the majority of carbon in solid wood products remains sequestered in those products for decades. Most (more than 95%) of the bark and sawdust are either used as pulp to make paper or burned to produce energy (thus substituting for timber used in papermaking or for fossil fuels); less than 5% of waste wood from sawmills ends up in landfills.

For *pulpwood* (logs or bolts less than 11.5 inches in diameter and usually less than 8 feet in length) and waste from sawtimber processing, virtually all the wood fiber (the cellulose and hemi-cellulose) is used in paper products. The spent pulping liquors (the chemicals that dissolve the lignin, the "glue" which holds cellulose in a rigid structure) are generally used to produce energy.[41] Any waste paper in the production facility is generally recycled into pulp. Other than in energy production (which substitutes for fossil fuels), there is little paper waste that returns carbon directly to the atmosphere. In contrast to solid wood products, which may sequester carbon for decades, most paper products have relatively brief duration, releasing their carbon to the atmosphere relatively quickly—in less than a year for many paper products, and in less than 10 years for most paper products.[42] However, paper can also be recycled—dissolved, cleaned, and made into new paper products. Increasing the recycling of *post-consumer waste* paper (the paper

[39] Harmon, et al., "Conversion of Old-Growth Forests."

[40] Kenneth E. Skog and Geraldine A. Nicholson, "Carbon Sequestration in Wood and Paper Products," in *The Impact of Climate Change on America's Forests: A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment* (Linda A. Joyce and Richard Birdsey, tech. eds.), Gen. Tech. Rept. RMRS-GTR-59 (Fort Collins, CO: USDA Forest Service, 2000), pp. 79-88. (Hereafter referred to as Skog and Nicholson, "Carbon Sequestration in Products.")

[41] CRS could find no source that identifies the proportion of carbon from wood pulp converted into paper products.

[42] Skog and Nicholson, "Carbon Sequestration in Products." However, use of biomass waste to generate heat and/or electricity can substitute for fossil fuel use, thereby avoiding other CO_2 emissions.

thrown away by consumers and most likely to end up in landfills) can reduce the carbon released by paper production and use.

The carbon impacts of commercial timber harvesting have been debated extensively, but with little resolution. Some have calculated that harvesting timber from an "over-mature" forest can sequester substantial additional carbon, because (a) the forest is currently sequestering little additional carbon (the amount stored is large, but annual addition from tree growth is small or even negative), (b) the timber can continue to store carbon for decades in long-term solid wood products, and (c) the newly established stand can sequester large amounts of carbon through its vigorous growth.[43] Others have calculated that the carbon released by harvesting operations substantially exceeds the additional carbon sequestered by new forest stands.[44] One source has stated that timber harvesting (in a heavy thinning or selection harvest) reduces carbon storage, "because the growth of residual trees is less rapid than the decomposition of the detritus and harvested wood products."[45] Another study has shown that some old-growth forests continue to accumulate carbon in their soils.[46] All of these conclusions may be valid in certain circumstances; the consequences probably depend on a variety of factors, such as which products are manufactured, how those products are used, how much carbon is left on the site, and what happens to it. There are, of course, other considerations associated with discussions of harvesting old-growth forests.

In addition, reduced impact logging (RIL) has been developed primarily to reduce the damage that timber harvesting can do to soils and to residual trees. It is becoming more widely discussed, especially for tropical forest harvests, but descriptions of RIL are generally either lacking in details or highly site-specific with limited general applicability. This is probably because the practices that will reduce logging damages depend on a variety of site conditions, such as soil type and water content, tree species diversity, etc. Nonetheless, as RIL becomes more widely practiced, it seems likely that logging damages (including carbon release) will decline.

Wood Energy

Using wood residues for energy production has occurred for many years at wood production facilities. The old "teepee" burners for disposing of wood waste are all defunct, and as noted above, the wood waste not used for paper production is already being used to produce energy to operate lumber and plywood mills. Even 30 years ago, less than 4% of the woody biomass removed from forests ended up as unused wood residues.[47]

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[43] See John Perez-Garcia, Chadwick D. Oliver, and Bruce R. Lippke, "How Forests Can Help Reduce Carbon Dioxide Emissions to the Atmosphere," (July 7, 1997) in U.S. House, Committee on Resources, Subcommittee on Forest and Forest Health, *Hearing on H.Con.Res. 151*, Sept. 18, 1997 (Washington, DC: U.S. Govt. Print. Off., 1998), Serial No. 105-61, pp. 46-68. (Hereafter cited as Perez-Garcia et al., "How Forests Reduce Carbon Dioxide Emissions.")

[44] Harmon, et al., "Conversion of Old-Growth Forests"; and Peter M. Vitousek, "Can Planted Forests Counteract Increasing Atmospheric Carbon Dioxide?" *Journal of Environmental Quality*, v. 20 (April-June 1991): 348-354.

[45] Byung Bae Park, *Effects of Silvicultural Treatments on Carbon Storage in Northern Hardwood Forests*, available at http://www.esf.edu/resorg/rooseveltwildlife/Research/Silv/Silv.htm.

[46] Zhou, et al., "Soil Carbon in Old-Growth Forests."

[47] U.S. Congress, Office of Technology Assessment, *Wood Use: U.S. Competitiveness and Technology, Volume II—Technical Report*, OTA-M-224 (Washington, DC: Nov. 1984), p. 18. (Hereafter cited as OTA, *Wood Use*.)

Wood can be used to produce energy either by burning it directly, modifying it to produce more consistent burning characteristics (e.g., by pulverizing it and compressing it into pellets), or by digesting it to produce liquid fuel (methanol or ethanol). The biomass remaining from ethanol production is also burnable, and can be used to power the ethanol production instead of using fossil fuels. Many have noted that abnormally high biomass levels are exacerbating risks of forest fires, and have proposed removing much of that biomass to protect forests and communities located near forests. Such woody forest residues could be used to produce energy.

Using wood for energy has some significant drawbacks. Although wood could replace some fossil fuels, it still produces CO_2 (and water vapor and some other by-products) when burned. Wood residues in the forest—from timber harvesting, thinning, or other forestry practices—are widely dispersed; haul distances (and thus costs) may limit the scale of wood energy production facilities. More important, perhaps, is that wood residues are highly variable in size, ranging from tree tops (4 inches or more in diameter) to twigs. Thus, collecting residues is a very labor-intensive activity. The cost to collect and transport forest residues to a wood energy facility can be a major hindrance to using woody forest residues for energy production.

Leakage

Changes in land use practices to sequester carbon in the United States can also have more subtle impacts on carbon storage globally. Domestic practices to store carbon by reducing the amount of timber harvested can have an effect commonly called *leakage*—by shifting land uses geographically (e.g., more tropical forest harvests to offset less temperate forest harvests) or by shifting demand to other products that require more carbon to produce (e.g., steel or aluminum studs to replace wood studs in homebuilding).

Land Use Leakage

The primary concern, expressed in numerous articles, is that forest protection and logging restrictions in the United States will lead to more timber harvesting and associated environmental damage elsewhere—especially in tropical forests—to satisfy U.S. demand for wood products.[48] This leakage is undesirable, it is argued, because U.S. forest management protects the environment more than comparable activities in other countries. These critics assert that U.S. federal and state environmental laws are stricter and more rigorously enforced than other nations' environmental laws for protecting air and water quality, maintaining animal habitats, and preserving rare plants and animals. The result is less forest destruction and greater soil protection, both of which would lead to less carbon release following timber harvesting. In addition, most states (and federal law for federal lands) require reforestation following timber harvests (except for planned conversions to other uses), so deforestation is less common in the United States.

[48] See, e.g., Con H. Schallau and Alberto Goetzl, "Effects of Constraining US Timber Supplies: Repercussions Are National and Global," *Journal of Forestry*, v. 90, no. 7 (July 1992): 22-27; Roger A. Sedjo, A. Clark Wiseman, David J. Brooks, and Kenneth S. Lyon, *Global Forest Products Trade: The Consequences of Domestic Forest Land-Use Policy*, Discussion Paper 94-13 (Washington, DC: Resources for the Future, Feb. 1994); and John M. Perez-Garcia, "Global Economic and Land Use Consequences of North American Timberland Withdrawals," *Journal of Forestry*, v. 93, no. 7 (July 1995): 34-38.

Other reasons are also given for why leakage is undesirable.[49] One is that harvesting in tropical forests typically results in more waste. Tropical forest harvests typically focus on the most valuable species, leaving most of the trees, many of which are damaged; temperate forests have less diversity of plant species, which can lead to greater efficiency in biomass utilization, and thus less biomass waste to return carbon to the atmosphere. Also, temperate forests have less carbon per acre, on average, to release when timber is harvested than do tropical forests. In addition, others note, "[t]imber extraction is often the first step towards opening up the tropical forest and clearing the land for agricultural production. What is more, in many developing countries, property law establishes deforestation as a prerequisite of formal claim over the land for those settling in forested areas."[50] Tropical timber harvests can thus lead to permanent deforestation.

These rationales are supported by substantial anecdotal evidence, but others counter that such assertions have limited empirical foundation. Concerns generally focus on the potential impacts on tropical forests, but the preferred timber species for U.S. consumption are softwoods, not the hardwoods found in the tropics. It is not clear how much tropical timber would substitute for domestic softwood timber.[51] Imports from tree plantations in Chile and New Zealand and from virgin forests in eastern Russia seem more likely, but the environmental effects probably differ substantially from the presumed impacts of leakage to tropical forests.[52] One economist also has pointed out the difficulties in making international comparisons of environmental choices, because of the monumental biological and social differences between the United States and other countries, especially those with tropical forests.[53]

Product Demand Leakage

Another concern often noted is that domestic forest protection to sequester carbon could shift demand to substitute products whose production requires more energy, and thus releases more carbon.[54] Most lumber and plywood are used in construction—new residences, home remodeling, and non-residential buildings.[55] Substitute products include steel and aluminum for studs, joists, and sheathing, and concrete and masonry for walls and flooring. The recent reports expressing concerns about product demand leakage usually cite studies from the 1970s and early 1980s comparing the energy used to produce wood products and their substitutes—notably, studies by

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[49] See Ed Barbier, "The Environmental Effects of Trade in the Forestry Sector," *The Environmental Effects of Trade* (Paris, France: Organisation for Economic Co-operation and Development [OECD], 1994), pp. 55-101.

[50] Ibid., p. 67.

[51] Research on Japanese timber consumption (which is more diverse than U.S. timber consumption) showed limited substitution between well-known and lesser-known species from tropical forests. See Jeffrey R. Vincent, Alamgir K. Gandapur, and David J. Brooks, "Species Substitution and Tropical Log Imports by Japan," *Forest Science*, v. 36, no. 3 (Sept. 1990): 657-664. However, as tropical log supplies have dwindled, substitutability among tropical species might have risen in Japan.

[52] See David J. Brooks, "Federal Timber Supply Reductions in the Pacific Northwest: International Environmental Effects," *Journal of Forestry*, v. 93, no. 7 (July 1995): 29-33.

[53] David J. Brooks, *U.S. Forests in a Global Context*, Gen. Tech. Rept. RM-228 (Fort Collins, CO: USDA Forest Service, July 1993).

[54] See, e.g., Perez-Garcia et al., "How Forests Reduce Carbon Dioxide Emissions," and R. Neil Sampson, "Forest and Wood Products Role in Carbon Sequestration," in U.S. House, Committee on Resources, Subcommittee on Forest and Forest Health, *Hearing on H.Con.Res. 151*, Sept. 18, 1997 (Washington, DC: U.S. Govt. Print. Off., 1998), Serial No. 105-61, pp.34-45.

[55] Western Wood Products Association, *1999 Statistical Yearbook of the Western Lumber Industry* (Portland, OR), p. 32.

the Committee on Renewable Resources for Industrial Materials (CORRIM) of the National Academy of Sciences and by the Office of Technology Assessment of the U.S. Congress.[56] While energy use is not a perfect predictor of carbon release and production technologies have undoubtedly changed substantially in the intervening decades, these studies indicate that wood production requires only about a quarter of the energy needed for concrete and masonry production, and less than 5% of the energy needed for steel or aluminum produced for residential construction. A newer report, depicting average CO2 emissions, showed somewhat different results, with wood framing, covering, and windows releasing about 30% as much CO_2 as steel and aluminum and about 10% as much CO_2 as concrete and masonry.[57]

Other economists point out that supply substitution is not the only feasible response to changing domestic timber supplies—that demand could be influenced through price changes (although timber is highly price-inelastic), through development of less energy-intensive/carbon-producing non-wood substitutes, and through government policy (e.g., by altering locally-established building codes).[58]

Federal Government Programs

Various federal programs could be used to encourage forestry practices to increase carbon sequestration. One approach is to implement more carbon-sequestering forestry practices on federal lands. Another is to provide technical and financial assistance for forest management practices to private landowners. A third is "tax expenditures" (tax incentives) to encourage carbon-sequestering forestry practices by private landowners.

Federal Forests[59]

The federal government owns about 650 million acres of land in the United States—about 29% of the total U.S. land area.[60] Although this includes hundreds of buildings around the country, the vast majority (99.6%) is considered rural—national parks and monuments, national wildlife refuges, national forests, public lands, military bases, etc. The majority of the federal lands are in Alaska (39%) and the 11 coterminous western states (another 54%).

The Forest Service estimates that the federal government administers about 118 million acres of forest land—defined as lands available for timber harvesting and capable of growing at least 20

[56] National Academy of Sciences, Committee on Renewable Resources for Industrial Materials, *Renewable Resources for Industrial Materials* (Washington, DC: 1976), 266 p.; National Academy of Sciences, Committee on Renewable Resources for Industrial Materials, "Wood and Fiber: Special CORRIM Panel II Report," *Journal of the Society of Wood Science and Technology*, v. 8, no. 1 (spring 1976): 1-72; and OTA, *Wood Use*.

[57] Cooperative Research Centre for Greenhouse Accounting (CRC), *Counting Carbon: Wood Products*, at http://www.greenhouse.crc.org.au/counting_carbon/wood.cfm. The CRC has ceased operations, but its materials are still being made available by Australian National University.

[58] David J. Brooks, "International Dimensions of U.S. Forestry," *Agriculture Outlook '93 Conference* (Washington, DC: U.S. Dept. of Agriculture, Dec. 2, 1992), pp. 19-33.

[59] For a description of federal lands and the agencies that administer them, see CRS Report RL32393, *Federal Land Management Agencies: Background on Land and Resources Management*.

[60] U.S. General Services Administration, *Federal Real Property Profile As of September 30, 2004* (Washington, DC: June 2000), pp. 18—19.

cubic feet of industrial wood per acre annually.[61] Additional federal lands undoubtedly meet the growth standard, but are not included because timber harvesting is precluded by statute (e.g., national parks and wilderness areas) or by administrative decision (e.g., national monuments and inventoried roadless areas). Other federal lands have trees and accumulate wood fiber, but not rapidly enough to meet the growth standard (e.g., Bureau of Land Management lands in central Alaska). Clearly, forestry practices can and do occur on federal forest lands, affecting both the sequestering and the releasing of carbon, as discussed above. In addition, forestry practices to sequester additional carbon (e.g., planting trees) can occur on sites that would not generally be considered "working" forests (e.g., national parks and military bases). Finally, much of the debate over the carbon consequences of timber harvesting—whether replacing old-growth forests with new, vigorous stands yields new release or net storage of carbon—has focused on federal forests, because most of the remaining old-growth forests occur on federal lands.

Federal Assistance for State and Private Forestry

The federal government has numerous programs that provide technical and financial assistance for forest management of nonfederal (mostly state and private) forest lands, though none explicitly includes carbon sequestration as a purpose.[62] Many programs provide assistance for forestry practices, especially planting trees and improving tree growth. Some (e.g., the Forest Stewardship Program) provide technical assistance. Others (e.g., the Forest Land Enhancement Program) provide financial assistance (usually a share of the activity's cost).[63] One program (Urban and Community Forestry) provides both technical and financial help. All are at least coordinated with, if not funded and operated through, state forestry agencies. It should be recognized, however, that most of these programs are restricted to moderately or highly productive private forest lands.

The federal government also has programs to assist in protecting nonfederal forests. One focuses on identifying and controlling insect and disease infestations, run by the Forest Service, in cooperation with the states. Another emphasizes preventing and controlling catastrophic wildfires, through assistance (money, equipment, and technical help) to states and to rural volunteer fire departments. A third forest protection program, the Forest Legacy, provides federal funding for the federal government or for states to purchase title or easements on forestlands that might be converted to other uses (e.g., agriculture or housing).

Finally, the Forest Service is also authorized to provide technical forestry assistance to other countries. This international forestry program includes information about carbon sequestration as well as about forestry practices that yield other economic and social benefits.

Federal Tax Expenditures

"Tax expenditures" are specific tax incentives established to encourage or allow certain activities. Three federal tax expenditures apply to forestry practices. One is special treatment of

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[61] From http://ncrs2.fs.fed.us/4801/fiadb/rpa_tabler/Draft_RPA_2002_Forest_Resource_Tables.pdf on Mar. 7, 2007.

[62] See CRS Report RL31065, *Forestry Assistance Programs*, by Ross W. Gorte.

[63] FLEP was enacted with mandatory appropriations totaling $100 million for FY2003-FY2007, but $40 million was borrowed for firefighting, nearly $10 million was repaid, and then the remaining funds (more than $20 million) were cancelled by Congress in the FY2005 Interior Appropriations Act.

reforestation expenses: a tax credit and accelerated amortization of annual reforestation expenses.[64] Private landowners are allowed to take a tax credit for 10% of their annual reforestation costs, up to $1,000 credit per year, and to amortize their reforestation costs, up to $10,000 per year, over an 84-month period. With reforestation costs averaging about $250 per acre (generally higher in the West and lower in the South), this provision would apply to about 40 acres of reforestation annually—not significant to major corporate forestland owners (who may own more than a million acres of forestland), but substantial for many of the non-industrial private landowners who own nearly half of the forestland in the United States.

The second special provision allows the expensing of multi-period timber growing costs; that is, annual management expenses can be deducted from other current income, rather than capitalized and deducted from timber income from the managed stands. As with the accelerated amortization for reforestation, this reduces the current income tax liability for the private landowners—a significant benefit for all private forestland owners. It also simplifies their bookkeeping for tax purposes—a significant benefit for the non-industrial landowners with modest forestland holdings and only occasional timber income.

Finally, timber income is allowed to be treated as a capital gain, if the private landowner has owned the trees for more than a year and does not retain an economic interest in the trees after the sale. (This latter provision essentially precludes certain timber sale practices commonly used by the federal government.) Currently, this provision benefits private forestland owners, because capital gains tax rates are significantly lower than regular income tax rates.

These three tax expenditures affect carbon-sequestering forestry practices in several ways. The reforestation tax credit and accelerated depreciation and the expensing of multi-period timber growing costs effectively reduce the landowners' costs of these forestry practices, which can induce additional forestry practices and thus may add to carbon sequestration. Capital gains treatment of timber income likely encourages timber harvesting, but as discussed above, the carbon consequences of timber harvesting are disputed.

Federal Programs Affecting Land Use

Many federal programs, in addition to the programs discussed above, can affect the rate of deforestation and afforestation in the United States. Development on forest land, often called "urban sprawl," is affected by a wide variety of federal programs, such as transportation and other infrastructure assistance programs and various tax expenditures. The U.S. General Accounting Office (now the Government Accountability Office) examined these programs, finding that federal impacts are pervasive, but that changing federal policies might not have major impacts.[65] The only federal program directly targeted on reducing the development of forest land is the Forest Legacy (described above), which funds federal and state acquisition of title or easements for forestland threatened with development (i.e., conversion to non-forest uses).

[64] Other reforestation expenses must be capitalized, and carried on the books to be deducted against timber income when the reforested stand is harvested, 20-100 years or more later.

[65] U.S. General Accounting Office (now Government Accountability Office), *Community Development: Extent of Federal Influence on "Urban Sprawl" Is Unclear*, GAO/RCED-99-87 (Washington, DC: April 1999).

Numerous agricultural conservation programs affect the conversion of forests to and from pasture and cropland.[66] Most notable is the USDA's Conservation Reserve Program (CRP). The CRP pays farmers who own environmentally sensitive and highly erodible cropland, under multi-year contracts, to protect those lands; planting trees is a common method for protecting these croplands, and the CRP is the largest federal tree planting program that has ever existed, even though its primary purpose is to protect soils. Other USDA programs that might include funding for afforestation include the Environmental Quality Enhancement Program (EQIP), the Farmland Protection Program, and the Wildlife Habitat Incentives Program.

Accounting for Forest Carbon Sequestration

Section 1605(b) of the Energy Policy Act of 1992 (P.L. 102-486) established a purely voluntary system to collect information from entities that emit greenhouse gases, including information on how they are reducing emissions or sequestering carbon by "any measures, including fuel switching, forest management practices, tree planting," and more. The Energy Information Agency established guidelines for data reporting and self-certification. While most of the emissions reductions reported in the §1605(b) program are related to energy efficiency or conservation, some are forestry projects—in other countries (known as "joint implementation") as well as within the United States. Relatively few domestic forestry projects have been reported under the §1605(b) program. A reason to report under the program has been the expectation (or hope) of receiving retroactive credit if a carbon credit system were ever established. Whether such credit would be given and whether reported data are deemed sufficiently reliable remain open, and possibly contentious, questions.

Conclusions

Forests store substantial amounts of carbon. The amount stored, however, changes over time as forests grow and die. Land use changes and forestry practices alter the level and rates of carbon storage, while "leakage" (shifting production) may offset some of the increases in forest carbon sequestration. Whether and how to account for this carbon sequestration in policies and programs to mitigate climate change has been controversial. Under the 1997 Kyoto Protocol of the 1992 United Nations Framework Convention on Climate Change (UNFCCC), developed nations agreed to specified reductions in their emissions of greenhouse gases, especially carbon dioxide. The Protocol allows some carbon sequestration as a way of meeting the specified reductions. The Bush Administration has rejected the Protocol and withdrawn from the continuing activities under the Protocol. Nonetheless, accounting for the carbon absorbed by forests and soils (and how much credit is due) continues to be discussed internationally; and the U.S. Congress has held hearings on forest carbon sequestration.

The role of forestry and land use in mitigating climate change has been controversial. Forests are enormously variable, with a broad array of plant species (both trees and understory vegetation) and substantial differences in the diversity of plant (and animal) species they contain. The myriad permutations of forest plants and soils present formidable obstacles for estimating existing carbon

[66] For a description of these programs, see CRS Report RL32940, *Agriculture Conservation Programs: A Scorecard*, by Jeffrey A. Zinn and Tadlock Cowan.

stocks and the carbon sequestration and release that result from forestry activities. The carbon consequences of timber harvesting have been particularly controversial.

Because of the scientific uncertainties, as well as differences in the types and extent of forests among nations, reaching agreement on ways to account for carbon sequestration in forests has been difficult. Some argue for a broadly inclusive accounting, others for a more conservative approach. “Land-based” or “activity-based” models are generally proposed for estimating changes in carbon storage. However, the ambiguous language and terminology used by proponents contribute to the inherent difficulties of measuring baseline carbon stocks, land uses, the carbon impacts of various activities, and “leakage” (shifting land or product uses). Furthermore, the enormous diversity of forest types and widespread disputes over the carbon consequences of various practices (which result at least partly from the diversity of forests) make it difficult to generalize about the opportunities to mitigate global climate change through forest carbon sequestration. It is likely that research to reduce some of these ambiguities and uncertainties will be an ongoing element in the efforts of nations to deal with carbon sequestration—and with concerns about climate change.

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