Reducing Atmospheric GHGs through Sequestration

Previous chapters have evaluated the roles of forests and forest products in *preventing* GHG emissions through wood substitution, biomass substitution, modification of wildfire behavior, and avoided land-use change. This chapter considers the role of forests and forest products in *reducing* GHG emissions. Among all possible options for reducing or mitigating GHG emissions, forests are unique in that they contribute to both goals while simultaneously providing essential environmental and social benefits, including clean water, wildlife habitat, recreation, forest products, and other values and uses.

Forest Carbon Pools

As the most efficient natural land-based carbon sink, forests play an important role in global carbon cycling. The world's forests cover 4,100 million hectares (Mha) and contain 80 percent of all above-ground carbon (Dixon et al. 1994). The greatest threat to forests is land-use change and deforestation in the tropics, which contribute about 18 percent of global greenhouse gas emissions (Stern et al. 2006). Consequently, forests are critical to stabilizing carbon dioxide and oxygen in Earth's atmosphere.

Globally, forest vegetation and soils contain about 1,146,000 million tonnes (Mt) of carbon, with approximately 37 percent of this carbon in low-latitude forests, 14 percent in mid latitudes, and 49 percent at high latitudes (Dixon et al. 1994). The greatest changes in forest sequestration and storage over time have been due to changes in land use and land cover, particularly from forest to agriculture (Caspersen et al. 2000; Bolstad and Vose 2005). More recently, changes are due to conversion from forest to urban development, dams, highways, and other infrastructure.

Forestland in the United States covers 302.3 Mha (33 percent) of the land base. These forests contain 71,000 MtC, with about 35 percent in living biomass, 51 percent in the soil, and 13 percent in dead material including the forest floor (Heath, Smith et al. 2003). The average rate of sequestration from 1953 to 1997, not including wood products, is estimated at 155 MtC/yr (Heath, Smith et al. 2003). A similar estimate from direct measures in 28 eastern forests during the late 1980s to early 1990s indicated a net uptake of 170 MtC/yr above ground (Holland et al. 1999).

Productive, nonreserved forestland (timberland) in the United States constitutes 204 Mha and is commonly considered the forest base potentially available for management. The average rate of carbon uptake on timberland is approximately 0.53 tC/ha/yr, with a potential uptake capacity (estimated by IPCC 2000) of 108.1 tC/ha (Kimble et al. 2003).

Because the area of US forests is so vast, even small increases in carbon sequestration and storage per hectare add up to substantial quantities. Private forestland holds 63 percent of total forest carbon, indicating the importance of private lands in policies or incentives aimed at sequestering carbon. In western forests, most carbon per unit area is in the hemlock–Sitka spruce type, which has 353.6 tC/ha; chaparral has 105.6 tC/ha. In eastern forests, aspen-birch has 309 tC/ha, and loblolly-shortleaf pine carries 163 tC/ha (Heath, Smith et al. 2003).

Urban forests are increasingly being recognized as important carbon sinks; they cover about 28 Mha, with tree cover averaging 27 percent (Birdsey and Lewis 2003; Kimble et al. 2003). This tree cover qualifies them as "forestland," which is often defined as cover exceeding 10 percent. Nowak and Crane (2002) estimate that urban trees, which cover 3.5 percent of the US land base, store 700 MtC with an annual sequestration rate of 22.8 MtC/yr. The potential for expanding the cover and extent of urban forests for both direct and indirect benefits on mitigating climate change makes them increasingly important and potentially cost-effective in sequestering and storing carbon (McHale et al. 2007).

Typically, forest soils contain a high proportion of carbon, and management practices are consequently very important in their potential effects on carbon storage. Within forest biomes as a whole, 68 percent of the carbon is in the soil, but the proportion is 50 percent in tropical forests, 63 percent in temperate forests, and 84 percent in boreal forests (Kimble et al. 2003). In southern Appalachia, Bolstad and Vose (2005) estimated the average allocation of carbon in above-ground biomass at 37 percent, mineral soil 44 percent, coarse roots 10 percent, surface litter 8 percent, and fine roots 1 percent; percentages varied depending upon the forest system. The potential net carbon sequestration in forest soils is 48.9 to 185.8 MtC/yr, with an average of 105.9 MtC/yr (Heath, Kimble et al. 2003). Immediately after harvesting, carbon in soils increases, then declines below initial values for about a decade, and ultimately increases (Heath and Smith 2000). Given the high proportion of carbon in forest soils, management of forest ecosystems should limit exposure and potential for increased soil temperature, which increases rates of decomposition, soil respiration, and erosion (Birdsey et al. 2006).

Forest CO_2 Uptake and Sequestration. In the process of photosynthesis, trees take up CO_2 from the air and, in the presence of light, water, and nutrients, manufacture carbohydrates that are used for metabolism and growth of both above- and below-ground organs. Concurrently with taking up CO_2, trees utilize some carbohydrates in metabolism and give off CO_2 in respiration. Consequently, in evaluating the capacity of trees and forests to sequester and store carbon, the important metric is net carbon uptake and storage.

Because the chemical reactions of respiration are temperature driven, increases in air temperature critically affect net uptake and storage of carbon. Studies on Douglas-fir and pine trees in Washington and California have shown that net CO_2 uptake is markedly lower in midday under conditions of summer stress, when temperatures are high and water content in both air and soil is low (Helms 1965). With climate change–induced higher temperatures, environmental stress is likely to increase. This will lower the capacity of plants to have positive net gains in carbon uptake, which could contribute to changes in forest type boundaries. The trend is offset to some extent by a general rise in worldwide forest productivity due to CO_2 fertilization and nitrogen deposition—both, ironically, products of anthropogenic atmospheric pollution. For example, conifer plantations in northern Britain are reportedly growing 20 to 40 percent faster than in the 1930s because of increased nitrogen deposition, atmospheric CO_2, and temperature (Cannell et al. 1998).

Net rates of CO_2 uptake by broad-leaf trees are commonly greater than those of conifers, but because hardwoods are generally deciduous while conifers are commonly evergreen, the overall capacity for carbon sequestration can be similar. Mixed-species, mixed-age stands tend to have higher capacity for carbon uptake and storage because of their higher leaf area.

The capacity of stands to sequester carbon is a function of the productivity of the site and the potential size of the various pools, including soil, litter, down woody material, standing dead wood, live stems, branches, and foliage. In part, this is related to the capacity of stands to grow leaf area: the more leaves, the greater the stand capacity for photosynthesis and biomass production, but also the greater loss of CO_2 in respiration. Other stand dynamics that can influence sequestration capacity include age class distribution and shade tolerance. In the long run, stands of shade-tolerant species growing on high-quality sites typically have more leaf area, grow more wood, and sequester more carbon than stands of shade-intolerant species. On similar sites, stands of intolerant species initially have higher rates of wood production and carbon sequestration, which culminate earlier but do not grow as much wood, overall, as shade-tolerant species.

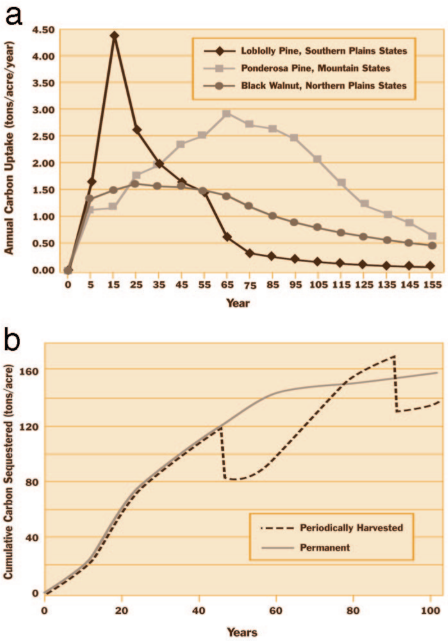


Figure 7-1. (a) Carbon sequestration rates. (b) Carbon accumulation rates for loblolly pine (Source: Richards et al. 1993).

The rate of CO_2 uptake by trees and stands is primarily a function of species, site quality, temperature, and availability of water and nutrients. Young trees and young stands have higher rates of carbon sequestration but lower levels of total amount stored; older trees and older stands have lower rates of net uptake because, as trees age, mortality and respiration are higher. However, older stands have higher carbon storage, providing carbon is not lost to insect depredations or wildfire.

Figure 7-1 illustrates two important principles. First, young trees, and fully stocked stands of young trees, have high rates of net carbon uptake that culminate earlier for rapidly growing shade-intolerant pines than for less rapidly growing, more shade-tolerant trees, which are initially slower growing but culminate growth later and sequester more carbon overall (Figure 7-1a). Thus management practices using very short rotations of trees such as poplars and eucalypts are appropriate for intensive biomass production. Second is a general relationship involving long rotations starting from bare ground: the total amount of carbon accumulated in a given stand increases over time and reaches a plateau, after which net carbon accumulation remains relatively constant as net CO_2 uptake tends to zero because of increases in stand respiration, mortality, and decay (Figure 7-1b). Indeed, the first State of the Carbon Cycle Report acknowledges that carbon absorption by vegetation, primarily in the form of forest growth, is expected to decline over time because maturing forests grow more slowly, take up less carbon dioxide from the atmosphere, and might become carbon neutral (King et al. 2007). The report suggests that older forests could become a net carbon source because of emissions from wildfires. Figure 7-1b also shows the effect of two thinnings on carbon accumulation. In particular, after thinning, between stand ages 45 and 90 years for loblolly pine, the rate of carbon accumulation reverts to the level for stand ages 20 to 45 years. These general relationships are similar to those governing the familiar relationships between periodic and mean annual wood increment.

Carbon Release from Forests. Forests also release carbon and can become net sources of carbon to the atmosphere, particularly after a disturbance or in newly regenerated stands when soils are exposed during harvesting and site preparation. After disturbance, heterotrophic soil respiration is greatest in young forests and declines as forests age. Pregitzer and Euskirchen (2004) reported that mean temperate net ecosystem productivity in forests aged 0–10, 11–30, 31–70, 71–120, and 121–200 years was −1.9, 4.5, 2.4, 1.9, and 1.7 MgC/ha/yr, respectively. As forests become older, the amount of carbon released through respiration and decay can exceed that taken up in photosynthesis, and the total accumulated carbon levels off. This situation becomes more likely as stands grow overly dense and lose vigor, and it will become more probable in areas where climate change causes higher temperatures. However, as maturing forests become less productive, they may continue to accumulate carbon in coarse woody debris, the forest floor, and the soil.

Wildfires are the greatest cause of carbon release. In 2006, 96,385 wildfires burned 3,997,467 ha in the United States. Although 83 percent were human-caused, aggressive fire suppression policies over past decades and other factors have resulted in greatly increased fire hazard conditions that tend to make wildfires catastrophic and stand-replacing. From 1997 to 2006, 24,122,967 ha burned (National Interagency Fire Center 2007). The amount of carbon released by wildfires is difficult to estimate because of the great variability in fire intensity and fuel loads. It is estimated that every dry ton of forest biomass burned releases roughly 1.3 to 1.5 tonnes of CO_2, 0.05 to 0.18 tonnes of carbon monoxide, and 0.003 to 0.01 tonnes of methane (Sampson 2004). Average emissions might be 29 tonnes of CO_2 equivalent per hectare (Sampson 2004). Therefore, the amount of greenhouse gases emitted in 2006 through wildfires could be 128 $MtCO_2$.

Climate change–induced increases in wildfire occurrence and intensity will increase the tendency for forests to become a source rather than a sink for carbon (Dale et al. 2001; Nitschke and Innes 2006; Westerling et al. 2006). Changes in the fire regime could even overshadow the direct effects of climate change on species distribution and migration (Dale et al. 2001; Nitschke and Innes 2006). Limiting the extent of wildfires through forest management would therefore contribute greatly to mitigating climate change. For example, Lippke et al. (2006) estimated that, primarily as a result of reduced forest fire emissions and increased long-lived forest production, 56 percent more carbon could be stored over a 50-year period in a managed than in an unmanaged forest in eastern Washington.

Historically, insects and disease have caused mortality on approximately 1.6 Mha/yr in the United States (Birdsey and Lewis 2003). Recent years have seen a number of large outbreaks of pine beetles and other insects that appear to be directly related to a warming climate. In 2006, the mountain pine beetle epidemic in British Columbia destroyed 9.2 Mha of lodgepole pine forests, for a cumulative effect of 14 Mha (Carrol et al. 2004; BC Ministry of Forests and Range 2007). In 2003, 1.5 Mha of pinyon pine forests in eight states of the Southwest was affected, with mortality reaching 90 percent. Tree mortality caused by insects and disease in recent years thus equals or exceeds that caused by wildfires.

Other important forest disturbances include hurricanes, ice storms, droughts, and floods. In 2005, Hurricane Katrina affected 2 Mha of forest in Mississippi, Louisiana, and Alabama, killing or severely damaging approximately 320 million large trees and releasing, over time, approximately 105 million tonnes of carbon dioxide to the atmosphere—roughly the net annual sink in US forest trees (Chambers et al. 2007). Harvesting occurs on approximately 4 Mha/yr, with 62 percent being partial harvests. Interestingly, the area harvested annually in 1907 was 3.8 Mha (Birdsey and Lewis 2003).

In general, forests may be either carbon sinks or sources, depending on their age and health. Unmanaged, older forests can become net carbon sources, especially if probable losses due to wildfires are included (Oneil et al. 2007). Because of the variable conditions of US forests, particularly overstocking on federal lands, forest management has substantial opportunities to both enhance sequestration and reduce carbon emissions, particularly by reducing carbon lost because of wildfires, insect and diseases, and avoided conversion of forests to other land uses.

Enhancing Storage and Reducing Emissions

Forests of all ages and types have remarkable capacity to sequester and store carbon. Enhancement of this capacity depends on ensuring full stocking, maintaining health, and reducing losses due to tree mortality, wildfires, insect, and disease. Addressing each of these issues requires management that controls stand density by prudent tree removal; this provides society with renewable products, including lumber, engineered composites, paper, and energy, even as the stand continues to sequester carbon. Above all, enhancing the role of forests in reducing GHGs requires keeping forests as forests, avoiding conversion to other land uses, increasing the forestland base through afforestation, restoring degraded lands, and increasing tree density on understocked areas.

The Western Forestry Leadership Coalition (2007) suggests that two active forest management approaches should be considered to enable forests to provide ecological, social, and economic benefits to society in the face of the environmental stress associated with climate change. The first approach is adaptation, which involves positioning forests to become more healthy, resistant, and resilient. The second is mitigation, in which forests and forest products are used to sequester carbon, provide renewable energy through biomass, and avoid carbon losses due to fire, mortality, and conversion. On any given area of forestland, adaptation and mitigation objectives at the same time could be either complementary or incompatible. A complementary situation would occur where activities to maintain healthy, resilient forests also reduced the risk of uncharacteristically severe wildfire, CO_2 emissions, and damage to watersheds, and where the byproducts of such activities are used to offset fossil fuel burning. Incompatible competition could occur, for example, on some parts of national forests, where the objectives of sequestering high levels of carbon may conflict with adaptation needs that require reducing carbon stocks.

Adaptation. As described in Chapter 2, climate change will likely create stress on forest systems, changing competitive relationships among species and altering the tendencies for species to be more or less successful in a given locality. In general, species are expected to move northward in latitude and upward in elevation, although there will likely be opportunistic expansions and contractions of species and communities as habitat suitability changes. Scientists suggest that existing biological communities will change as individual species move in response to changing climatic conditions and chance events. Thus, existing communities are likely to disassemble, species by species, and then reassemble, perhaps into communities or "novel ecosystems" that have no analog today (Hobbs et al. 2006). This makes predicting future plant associations exceedingly difficult.

An important question is whether management can help forest systems adapt to new environmental conditions. Can management protect, enhance, modify, or adapt to changing ecosystem values? Because past experience may no longer be a valid basis for management planning (Perschel et al. 2007; Millar et al. 2007), the first task is anticipating what kinds of changes can be used as a basis for informed decisionmaking. In particular, Breshears et al. (2005) ask, can we identify what triggers ecosystem change and how well can we judge the extent of change? It is perhaps especially important to identify the potential response of overstory, or "keystone," species—those that will rapidly alter ecosystem type if they lose vigor or die (Breshears et al. 2005). By the end of the century, the climate of 55 percent of western US landscapes may be incompatible with today's vegetation (Rehfeldt et al. 2006). Therefore, predicting the composition and distribution of future plant communities from contemporary climate profiles in large, heterogeneous physiographic regions may be impossibly complex (Rehfeldt et al. 2006).

Already, past protracted droughts and water stress have triggered large-scale dieoffs and landscape changes. In the Southwest, massive outbreaks of bark beetle infestations have occurred in ponderosa pine and pinyon pine. Not only are these accompanied by possible shifts in forest ecotones, but there are other ramifications as well, including potential runoff and erosion, effects on associated wildlife, changed competitive relations of understory species, and altered dynamics of carbon sequestration and storage. Similarly, changed climate, particularly warmer winters, appears to be responsible for triggering the current epidemic outbreaks of mountain pine beetle in the lodgepole forests of British Columbia and Colorado.

Consideration of how management might address changed climate–ecosystem relations focuses attention on modeling. However, land managers should use model results and generalizations regarding climate change with great caution. Model projections at global and regional scales may indicate climate trends with confidence, but it is much more difficult to assess trends at the local scales important to land managers. This is particularly important in topographically complex mountainous areas, where high-quality, daily meteorological data at fine spatial scales are needed (Daly et al. 2007). It is even more difficult to assess trends in biotic responses to anticipated climate change and, with confidence, judge the likelihood of shifts in species and communities of forest biota at spatial scales consistent with local management and ownerships. Management is further complicated by the need to understand interactions among landscape fragmentation and population mobility and dynamics (Halpin 1997). Responding may incur greater risk than doing nothing (Spittlehouse and Stewart 2003).

Nevertheless, models can provide very useful guides. An example is the work of Rehfeldt et al. (2006), who modeled 35 expressions of temperature, precipitation, and their interactions in the context of plant-climate relations for the western United States. They showed that global warming should increase the abundance of montane forests and grasslands at the expense of subalpine, alpine, tundra, and arid woodlands. Important factors were the ratio of summer to annual precipitation and the summer-winter temperature differential, together with complex interactions. Rehfeldt et al. suggest that although future vegetation may retain the general characteristics of deserts, grasslands, and forests, it is commonly likely to support quite different plant associations. As climate changes, plant fitness may deteriorate, which activates evolutionary processes. Modeling efforts are becoming increasingly sophisticated, and rapid advances are being made in predictive capacity. To better guide understanding and response to change, increased capability is needed in analysis at the landscape rather than the regional level (Rehfeldt et al. 2006). A good example is the effective use of models for the Greater Yellowstone Ecosystem, where temperature and temperature-related variables have been used to describe the distribution of whitebark pine in relation to tree line (Schrag et al. 2007). Insights into the adaptation of plants to changing conditions can also be obtained by reexamining the relative performance of species and varieties planted in seed orchards and progeny test sites, and consulting studies of range-wide comparisons.

So, how might management adapt to possible climate changes? A prudent approach is that the greater the uncertainty and risk, the greater the flexibility in setting both short-term and longer-term goals and decisions (Perschel et al. 2007; Millar et al. 2007). No single solution is likely to fit all future challenges, and it is best to mix strategies (Millar et al. 2007). Three adaptive strategies based on understanding ecological processes rather than structure and function are currently being discussed (Perschel et al. 2007; Millar et al. 2007): increasing resistance, increasing resilience, and assisting migration.

Increase resistance. Resistance is the capacity of an ecosystem to avoid or withstand disturbance, such as anticipated increased insect and disease epidemics and wildfires. Management actions would aim at forestalling damage and protecting valued resources, such as water, endangered species, wildland-urban interface areas, and special forest stands. Treatments to be considered include thinning of overstocked stands, prescribed burning, removal of invasive species, and restoration of native species. Since it may not be feasible to conduct treatments at the landscape scale because of fragmented ownerships and jurisdictions, implementation of this strategy could include identifying which populations are most at risk and which areas in the landscape are more likely to be buffered against the effects of changes in climate (and thus act as refugia).

The likely benefit of this approach is that it is proactive (planned and implemented before a disturbance event) and has a high probability of being successful. A potential drawback is that the scale of the disturbance could be sufficiently large to overcome the capacity of the forest to resist its effects, with negative consequences for the forested ecosystem.

Increase resilience. Resilience is the capacity of an ecosystem to regain functioning and development after disturbance. Management actions would aim at retaining desired species even if sites become less optimal. Possible treatments include 1) promoting diversity in species and age classes when replanting or conducting other treatments after a disturbance event; 2) broadening genetic variability of seedlings when reforesting after harvesting, fires, or other disturbances; 3) supporting existing forest communities while allowing transitions to new forest types; 4) identifying and enhancing possible refugia prior to disturbance; and 5) enhancing landscape connectivity so that ecological movement can take place unimpeded across the landscape, including prevention of further forest fragmentation and restoration of ecosystem processes, such as watershed function and hydrologic processes.

Likely benefits are that management can identify and plan actions in advance of a disturbance and then implement postdisturbance treatments. Planning postdisturbance actions focuses attention on which system components are most likely to be altered when changes might come about. Potential drawbacks are that actions may be taken to restore or enhance ecosystems based on past climate and experience, whereas climate change may be driving the area toward new assemblages of species. Managers should identify the appropriate vegetation communities needed for restoration forestry in conditions of change.

Assist migration. What might be needed to enable an ecosystem to adapt to changed conditions? Management actions would seek to facilitate the transition of an ecosystem from current to new conditions. Consideration would be given to introducing different, better-adapted species, expanding genetic diversity, encouraging species mixtures, and providing refugia. This approach is highly controversial—it involves taking action based on modeling and other projections for which outcomes or expectations are highly uncertain—and is in a youthful stage of development (McLachlan et al. 2007).

However, modeling at the global, regional, and landscape levels can be combined with current species climate distribution maps to suggest where tree species populations may migrate over the next century in response to various climate change scenarios. Models can possibly be used in a decision support context informing management on how to consider the potential risks and benefits of assisting migration.

Assisted mitigation might be considered in several circumstances: 1) where, after a fire or insect or disease outbreak, planting of the original species is predicted to fail; 2) on the edge of an ecotone where new species are known to be migrating into the area in a manner that validates the climate change models for the region; 3) for rare, threatened, or endangered species that are endemic to a small area and not expected to be successful in migrating without assistance; 4) new species could be added to the mix of trees being planted if these are not expected to have negative ecological consequences; and 5) where refugia have been identified as places to plant and "store" endangered species.

Assisting migration would require the development of policies and guidelines addressing the precise conditions under which species should be moved into new areas and lay out protocols for the detailed monitoring required (McLachlan et al. 2007). Because of its controversial nature and the risk of unanticipated consequences—for example, the planted species might become an invasive in its new range, or climate change might not occur in the expected manner—this level of experimentation within forested ecosystems may not win public or scientific support.

Changes in climate already appear to be occurring. It seems prudent, therefore, that adaptive approaches to management be considered. The considerable risk and uncertainty notwithstanding, the diverse values of forest ecosystems are too high to simply do nothing. The hallmarks of future forest management should be flexibility in both short-term and long-term planning, increased use of modeling, increased monitoring to detect the occurrence and direction of change, and adaptive management.

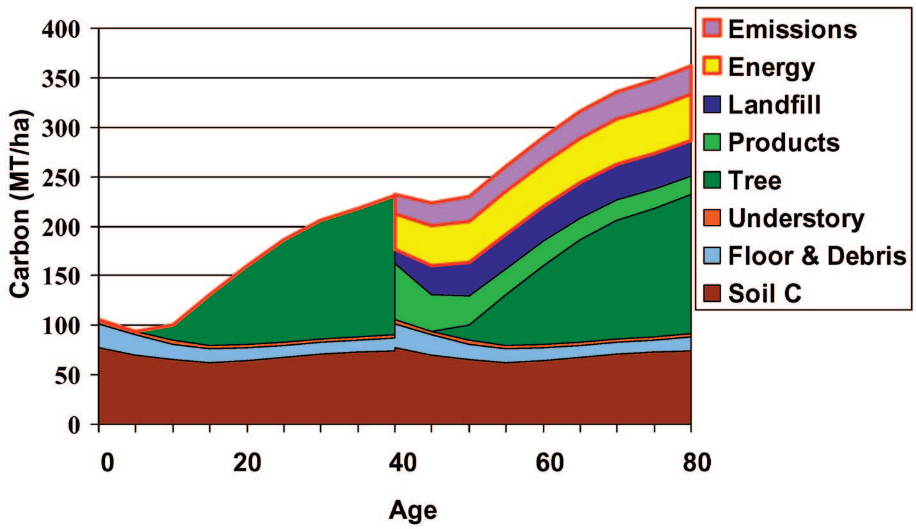
Mitigation. Whether, in the long run, managed forests can positively affect the global carbon balance compared with leaving forests unmanaged depends on several assumptions, such as the level of forest productivity, likelihood of tree mortality, uses of wood products, and extent of product substitution. Heath and Birdsey (1993), for example, projected that a no-harvest scenario sequestered more carbon. Schlamadinger and Marland (1996) commented that reduced CO_2 emissions to the atmosphere could be attained through four mechanisms: storage of carbon in the biosphere, storage of carbon in forest products, use of biofuels to replace fossil fuel use, and the use of wood products that displace other products requiring more fossil fuel for production. These authors found, over the long run, that the amount of carbon stored in the biosphere and in forest products reached a steady state, and continuing mitigation of carbon emissions depended on the extent to which fossil fuel was displaced by bioenergy and wood products. They concluded that the net carbon balance at the end of 100 years was very similar, whether trees were harvested and used for energy and traditional forest products, or the area was reforested and forest protection strategies implemented. Marland and Schlamadinger (1999) concluded that storing carbon on site in the forest and harvesting forests for a sustained flow of forest products are not necessarily conflicting options: mitigating net emissions of carbon depends on site-specific factors, such as forest productivity and the efficiency with which harvested material is used.

The issues are complex and defy easy generalizations. For some forest conditions, it is possible that early harvesting and use of wood products, while economically viable, could result in a lower rate of carbon accumulation compared with letting the forest grow to an older age before harvesting. Alternatively, focus on managing for carbon accumulation could lead to earlier harvest for some forest growth conditions. The degree to which forest management would change carbon sequestration and storage would also be influenced by whether wood use is long- or short-lived, whether the substitution offset is high or low, and whether there is high or low energy conversion efficiency.

In several cases, managed forests have been shown to sequester more carbon and have fewer emissions than unmanaged forests (Birdsey et al. 2000; Krankina and Harmon 2006; Lippke 2007; Hoover and Stout 2007). There are five prime reasons for this: 1) managed forests consist of younger trees that have higher rates of net carbon uptake; 2) managed forests are a source of wood products that continue to store carbon (in use or in landfills) for varying periods, depending on the product; 3) the use of wood products substitutes for use of alternative materials, such as steel, brick, concrete, aluminum, and plastic, all of which are based on nonrenewable resources that require much more energy in manufacture; 4) managed forests have lower greenhouse gas emissions resulting from wildfires, insect depredations, and land conversion; and 5) offset markets are more attractive for managed forests (Skog and Nicholson 1998; Lippke 2007; Krankina and Harmon 2006; OFRI 2006). Unmanaged forests can store more carbon over their lifespan above and below ground per unit area, but as they become mature, carbon accumulation reaches a steady state. Also, given fire return intervals that range from 10 to more than 100 years, there is high probability that in time, unmanaged, dense forests face a higher risk of stand-replacing fires or insect infestations than managed forests.

The modeling of stand dynamics enables a comparison of managed and unmanaged stands in terms of carbon sequestration and storage. For simplicity, researchers developed Figures 7-2, 7-3, and 7-4 for even-aged stands commencing with bare ground, but comparable diagrams could be prepared illustrating the growth of uneven-aged stands. Figure 7-2 shows the accumulation of carbon over two 40-year rotations of southern loblolly pine and illustrates the distribution of harvested carbon into diverse products and the decline in forest carbon stocks during the reforestation phase (Birdsey and Lewis 2002). Figure 7-3 illustrates the results of modeling the accumulation and distribution of carbon over four clearcutting rotations in western Washington (Oneil et al. 2007). Here, carbon in the forest has a stable trend line, and the carbon in product pools—net of energy used in harvesting, processing, and construction—steadily increases over time. The area in gray shows the substantial carbon savings associated with substitution of renewable and carbon-neutral wood products for alternative, fossil fuel–intensive building products (Oneil et al. 2007).

The top diagram of Figure 7-4 illustrates the results of modeling the growth on national forests in eastern Washington and shows the forest carbon pools assuming no management, fire disturbance, or insect or disease damage (Oneil et al. 2007). The bottom diagram is a preliminary analysis incorporating the occurrence of wildfires, which because of climate change were estimated to burn 1.7 percent of the area every decade. This approximation does not include regeneration delays and success rates, but the



NOTE: Energy and emissions are releases of C to the atmosphere

Figure 7-2. Accumulation of carbon over two 40-year rotations of loblolly pine (Source: Birdsey and Lewis 2002).

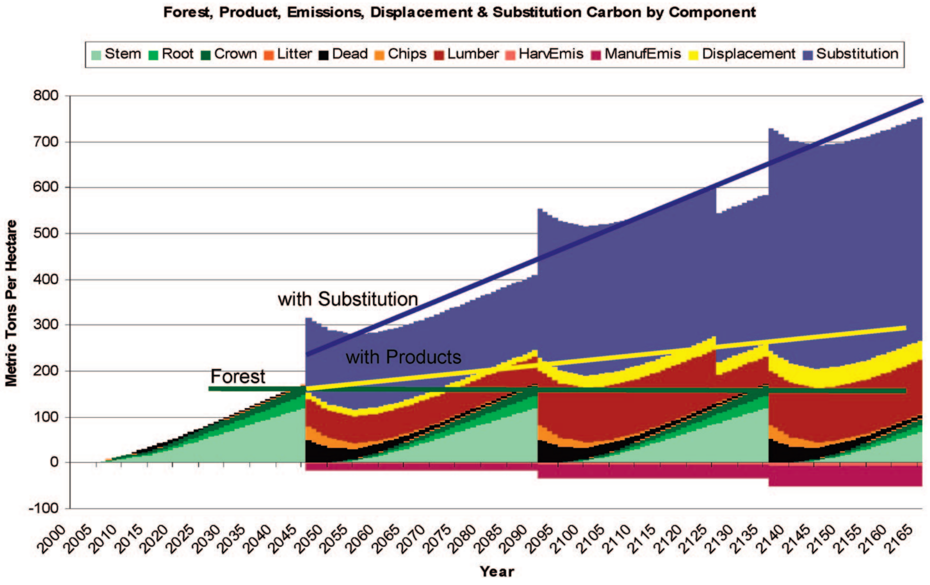


Figure 7-3. Carbon accounting over four rotations of even-aged management in Douglas-fir in western Washington (Source: Oneil et al. 2007).

model outcome suggests that unmanaged national forests in Eastern Washington would likely become a carbon source rather than a carbon sink (Oneil et al. 2007).

Silvicultural Treatments That Affect Carbon. Traditional silvicultural treatments focused on wood, water, wildlife, and aesthetic values are fully amenable to being applied to enhancing carbon sequestration and reducing emissions from forest management (Helms 1996). When considering the application of alternative kinds and levels of stand or landscape treatments in the context of multiple goals and values, managers should consider it likely that attempts to enhance the output of one value will diminish the outputs of others.

Choice of management regime. One of the primary silvicultural choices foresters face is the management regime. Currently, management regimes are chosen in consideration of the economic, site, and silvical characteristics of forest stands, along with other factors. The choice of an even- or uneven-aged management regime for a forest is likely to have little effect on above-ground carbon storage over long periods of time (multiple rotations). These two broad regimes do, however, have variable carbon uptake characteristics over short time horizons, such as a rotation. By providing continuous canopy cover, uneven-aged management is likely to provide continuous carbon uptake, depending on the periodicity and intensity of partial harvest entries. In comparison, the carbon uptake under even-aged management is strongly influenced by rotation length and the length of regeneration periods when the stand has little canopy cover. Management for carbon uptake does underscore the importance of choosing the appropriate regime for each stand. Adaptive approaches to matching the appropriate silviculture with each site as a mosaic across the forest enhance overall forest productivity and carbon uptake.

Choice of species. Initially, fast-growing, shade-intolerant species have higher rates of carbon sequestration at a younger age than more shade-tolerant, slow-growing species. However, over time, shade-tolerant species are likely to have higher stand densities and leaf area and therefore higher accumulation of carbon stocks. Mixed-species and mixed-age stands are likely to accumulate more carbon than single-species stands. Genetic selection, tree improvement, and biotechnology can enhance the rate of carbon uptake and storage by providing trees with higher net carbon uptake capacity. These trees are likely to have special application in growing short-rotation tree crops for bioenergy or cellulosic ethanol.

Slash disposal. Tops, needles, and branches that are residues from harvesting can be evaluated for the extent to which various treatments affect the carbon balance. Allowing this material to decay and return nutrients to the soil is a carbon-neutral process that takes several years, during which time the slash may increase the risk of wildfire. Burning the slash, although also a carbon-neutral process, immediately releases carbon, volatilized nitrogen, other greenhouse gases, and particulates into the atmosphere. Incorporating wood residues into the soil rather than burning it or leaving it to decay can increase or prolong carbon storage in the soil (Birdsey et al. 2006). Alternatively, depending on costs, this material could be used for bioenergy or the production of cellulosic ethanol. Removal of slash, however, may not be appropriate for sites with low productivity.

Site preparation. Site preparation is intended to give the desired vegetation greater access to limited resources, such as soil or water. In the context of carbon sequestration, a major consideration is limiting loss of

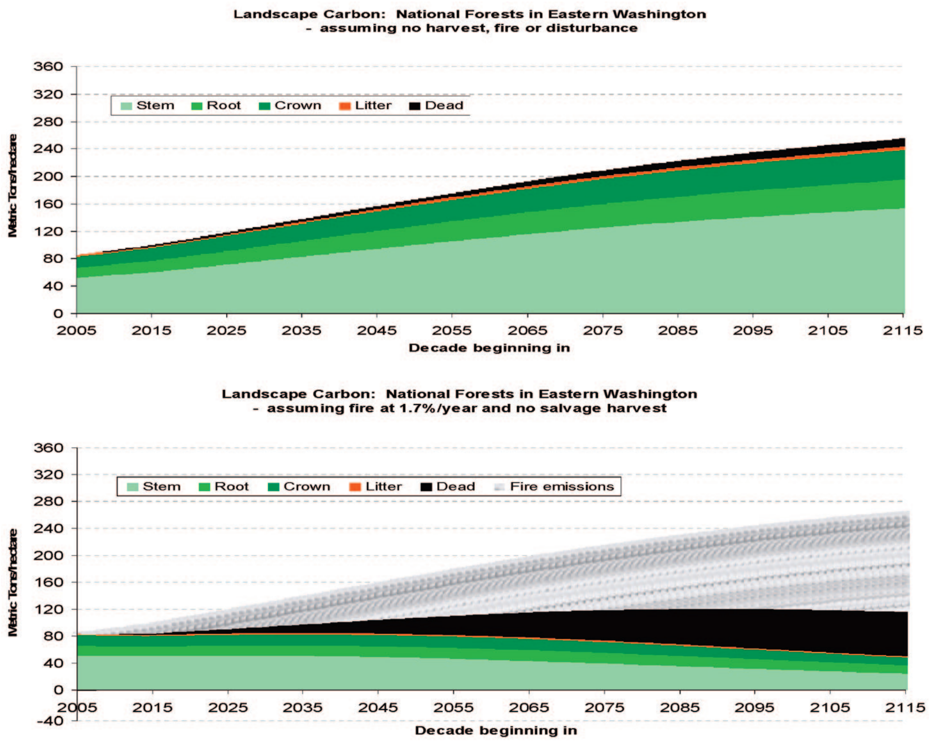


Figure 7-4. Carbon sequestration potential on national forests in eastern Washington. No disturbance compared with fire and no salvage harvest (Source: Oneil et al. 2007).

soil carbon that follows exposure during such treatments, which may increase oxidation of soil carbon, temperature (which increases respiration of soil organisms), disturbance, and in particular soil erosion. Site preparation that incorporates wood residues into the soil can increase or prolong carbon storage in the soil (Birdsey et al. 2006).

Regeneration. Whether by natural seeding, direct seeding, planting, or some mixture of treatments, regeneration should be done promptly to minimize the time soil is exposed and the canopy is open. Prompt tree regeneration also reduces the risk that the site becomes occupied by brush, which has lower leaf area and less CO_2-sequestering capacity than trees. Early brush control has been shown to have important leverage in improving wood-growing capacity and storing carbon in both the forest and stored products (CFR 2007).

Fertilizer. Sometimes applied in planted forests and in short-rotation plantations, fertilizers increase rates of growth and leaf area production and therefore the rate of carbon uptake and sequestration. In carbon accounting, however, the source of materials used as fertilizers and the source and cost of energy used in manufacture, transportation, and application must be factored in.

Thinning and partial harvesting. Thinning and partial harvesting are techniques used in even- and uneven-aged management, respectively, to control stocking levels and stand density. The operations may be either precommercial (i.e., the thinned material is not merchantable) or commercial and are designed to improve the growth of preferred trees. The basic concept is to allocate growth and leaf area among either a greater number of small-diameter trees or a fewer number of large-diameter trees. Both treatments make openings in the canopy, and in the context of carbon storage, it is preferable to conduct light, frequent thinnings rather than heavy, infrequent thinnings. The latter create larger openings in the canopy that require a longer time to regain leaf area and capacity for carbon storage.

Rotation length. Rotation length in even-aged management influences carbon accumulation because longer rotations and larger trees increase on-site storage. (In uneven-aged management, decisions on the maximum-sized tree follow the same logic.) Longer rotations in even-aged management favor carbon accumulation because less time is taken up in reforestation and rebuilding the canopy. However, longer rotations can incur larger management costs as the value growth rates of timber fall below the expected cost of money, and delay in harvesting reduces value from other uses, including carbon storage in wood products and substitution of wood for fossil-intensive products. Longer rotations and management cycles may also involve thinnings or partial cuts to maintain forest health.

Expansion of forestland (afforestation). One of the most widely recognized forestry practices for the mitigation of climate change is the afforestation of nonforested areas to increase sequestration and storage. Because forest is the most efficient land use for carbon uptake and storage, landowners with plantable acres and degraded areas that can be restored to a productive condition have a significant opportunity to sequester carbon. Whether the land was degraded by unsustainable practices or natural events, such opportunities may provide economic incentives to turn these areas back into productive forests.

Managing for Carbon. Forest management is often categorized as even- versus uneven-aged approaches. Either approach may still be appropriate at the stand level; however, at the landscape level, both approaches can be used in mosaics depending on ownership objectives and stand conditions. Incorporating carbon sequestration into the suite of management objectives focuses attention on developing and maintaining high levels of leaf area because the more leaves, the more potential for photosynthesis and carbon dioxide uptake. More leaf area also increases the potential for higher respiration rates, and consequently attention must be given to net carbon uptake under the particular growing conditions.

If the goal is to immediately sequester the most carbon in the near term, shade-intolerant species with high initial growth rates, grown at the highest stocking density the site will support and harvested at the culmination of mean annual increment, will sequester the most carbon in the shortest amount of time. This short rotation, even-aged forest management regime, repeated in perpetuity with succeeding rotations of shade-intolerant trees, is often said to sequester the most carbon. However, to determine the net amount of carbon sequestered, one must factor in 1) losses of soil and detritus carbon during disturbance for harvesting, site preparation, and other management activities; and 2) the carbon emissions associated with these harvesting and management activities.

If the goal is to sequester the maximum amount of carbon over a longer time frame, the best approach is to grow shade-tolerant species at the maximum stand density the site will support and implement a similar even-aged management regime, harvesting and replanting the whole stand at the culmination of mean annual increment. Shade-tolerant species can be grown at a higher stand density than shade-intolerant species but have lower initial growth rates that culminate later; however, the overall amount of carbon sequestered per unit of forest area will be greater. Moreover, harvesting and site preparation activities will be less frequent and thus the associated carbon emissions will be lower.

For continuous and overall maximum sequestration, mixtures of shade-intolerant and shade-tolerant species would utilize all the photosynthetic niches in the forest canopy and forest understory while maintaining overall growth rates at a thrifty level. Uneven-aged management would use a combination of individual tree selection, crown, and understory thinning, group selection, irregular shelterwood, and other intermediate cuttings to maintain a kaleidoscope of different age classes of thrifty intolerant and tolerant trees. Again, emissions would have to be calculated for the frequent management entries, as would the combined mean annual increment for all the different species and age classes of trees, which must be discounted to an annual basis.

The important carbon sequestration metric for all three of the above approaches is the area under the mean annual increment curve, which will reveal the total amount of carbon sequestered during the management cycle. This metric can then be discounted over the time period of the management cycle to calculate the average annual carbon sequestration rate for any management scenario. Below-ground carbon sequestration in root fiber, soil, macro- and microorganisms, down woody material, and other pools must also be calculated.

If the landowner's goal is to enhance the capacity of the forest to sequester and store carbon and to reduce its likelihood of becoming a source of carbon and other GHGs in the long run, the forest should be managed. This is because, in the long run, 1) management enables the maintenance of forest health, which reduces the likelihood and severity of emissions from wildfires and insect or disease mortality; and 2) it provides products that have both short- and long-term storage capacity and can substitute for fossil fuel–based materials and sources for energy, building, and other uses. Much of the technical knowledge needed to enhance sequestration and storage is available or can be adapted from traditional practices. Knowledge gaps include the effects of management on carbon pools and the extent to which enhancing carbon reduces the outputs of other forest values and uses. There is thus a need for increased monitoring and adaptive approaches to management.

Under current economic conditions, however, carbon sequestration is not likely to be a primary management objective for most forest owners (Birdsey et al. 2006). As with any type of management, goals, costs, incentives, regulations, policy, and values will drive decisions. Carbon sequestration through forest management may, however, provide forest owners who meet requisite protocols with an additional income stream from the sale of offset credits. If realized, this additional economic return could change the economic viability of some management practices, alter the intensity with which forests are managed, and influence other management decisions. The degree to which carbon sequestration opportunities influence forest management will depend heavily on such factors as the value of carbon financial instruments, the costs of program or market participation, regulatory requirements for emission controls, market-wide recognition of offset credits from forestry projects, and opportunity costs.

Debate continues regarding the relative benefits of young, managed forests compared with older, unmanaged forests in terms of efficacy of forest carbon sequestration. But all forests, under varying levels of management or no management, can provide carbon sequestration benefits, depending on their particular condition or situation. It is important to take into account the different objectives for managing forests of varying age and the associated benefits that can accrue from older, mixed age and mixed-species forests. Indeed, there are sites of low productivity where production of timber may be so slow or uncertain that managing for forest health and fire protection could be a superior carbon sequestration strategy.

Carbon Storage in Wood Products

Harvesting reduces carbon storage in the forest both by removing organic matter and by increasing heterotrophic soil respiration (Pregitzer and Euskirchen 2004). However, much of this is offset by the carbon that is stored in forest products for varying lengths of time. The carbon in those forest products, for example, may not be released for decades. Along with the benefits of consistently high sequestration levels, it is this aspect of sustainably managed forest carbon projects that provides the maximum benefits for climate change mitigation when compared with unmanaged forests, which can suddenly release huge amounts of carbon if they burn. Forest management that includes harvesting provides increased climate change mitigation benefits over time because wood-decay CO_2 emissions from wood products is delayed (Ruddell et al. 2007). Accounting for this carbon pool is critical to accurately representing forest carbon uptake and storage on a project level. A forestry project that fails to consider it may significantly overestimate emissions from the project over time (US DOE 2007).

Until recently, carbon stored in harvested wood products (HWPs) had received little recognition in international GHG mitigation programs. In fact, the 1996 United Nations Framework Convention on Climate Change guidelines for carbon accounting for countries participating under the Kyoto Protocol considered the inputs (additions) and outputs (emissions) at the national level for the HWP carbon pool to be equal (IPCC 2006). This position was revisited in 2006 in the revised IPCC guidelines, in which HWP accounting rules for Kyoto-compliant countries were presented in greater detail (IPCC 2006). The new rules facilitated a more thorough recognition of this important carbon pool, offering participating countries the option to account for carbon accumulation in this area.

In their early stages, many US climate change mitigation programs considered the harvesting of wood an immediate release of carbon. The carbon storage potential of HWPs has since become more widely acknowledged. To date, storage of HWP carbon has been recognized by some but not all domestic climate mitigation programs and registries. Although their accounting methods vary, the US Department of Energy 1605b guidelines, the Chicago Climate Exchange, the California Climate Action Registry, and the Georgia Carbon Sequestration Registry are examples of programs that now recognize this important carbon pool, though the California registry does not consider it a tradable pool at this time.

The HWP pool consists of two parts:

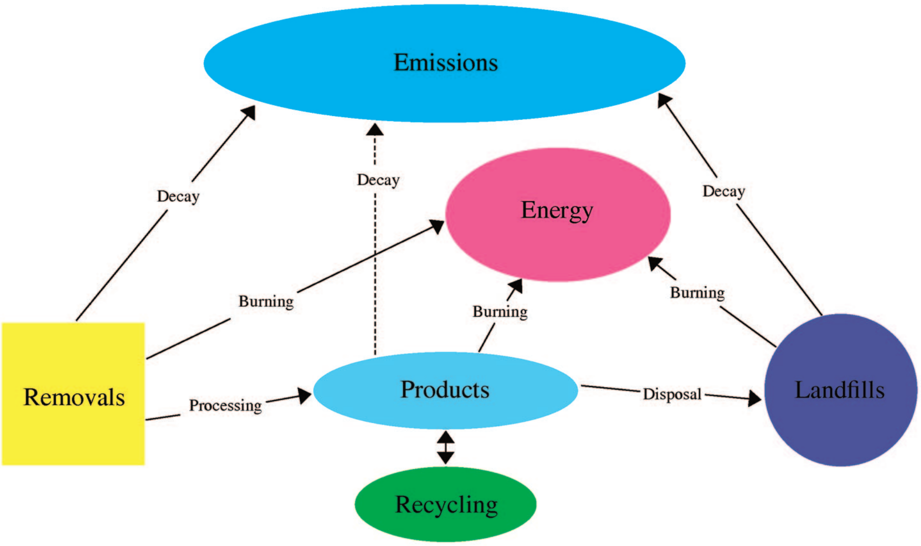


Figure 7-5. Harvested wood products pool (Source: Heath et al. 1996).

Table 7-1. Half-life for products by end use.

End use or product	Half-life (years)
New residential construction	
Single-family homes	100
Multifamily homes	70
Mobile homes	12
Residential upkeep and improvement	30
New nonresidential construction	
All except railroads	67
Railroad ties	12
Railcar repair	12
Manufacturing	
Household furniture	30
Commercial furniture	30
Other products	12
Shipping	
Wooden containers	6
Pallets	6
Dunnage	6
Other uses for lumber and panels	12
Solid wood exports	12
Paper	2.6

(Source: US DOE 2006).

wood in use, and wood discarded in landfills or recycled (US DOE 2006). Their interrelationships are illustrated in Figure 7-5. The delay in the release of carbon from HWPs depends on the manner in which the harvested wood is used. For example, carbon may be stored for decades in sawn lumber used in housing construction, but wood harvested for the production of paper may store carbon for only one to five years. Accounting approaches of the current US carbon programs vary somewhat, but most consider six basic categories of harvested wood in use: waste wood, wood used to produce energy, solid wood (lumber), composite wood products, paper products, and nonstructural panels. Each wood category has its own specific rate of decay or release to the atmosphere. One example of depreciation or half-life values for various end uses of wood products is provided in Table 7-1, which illustrates the variable decay rates specified in the US Department of Energy 1605b rules.

The accounting methods for HWPs in use fall into two main techniques. The first approach is to track, over time, the decay of materials stored in wood products and account for the specific emissions in the year in which they occur. Under this method, each harvest year is depreciated individually over a project's lifespan in accordance with the proportion of wood product types generated from the harvests. In addition to the contributions made annually to the HWP pool through harvests, annual emissions for the pool are also calculated. These calculations produce the annual net contribution to or emissions from the HWP pool. If there is a positive difference between a specific year and the previous year's HWP levels, a positive sequestration result is realized. If the result is negative, then the HWP pool has experienced net emissions and that amount would be deducted from total reported sequestration for that year. The benefits of this approach are largely in maximizing positive results over shorter project lifespans and in more project-specific accounting. There are also potential drawbacks to this approach. Over longer time frames, emissions from the HWP pool could exceed total additions, resulting in carbon deficits. Also, this accounting system is somewhat complex.

The second HWP accounting method uses established depreciation tables to calculate the quantity of carbon remaining in harvested wood (also by product class) after 100 years. Based on standard decay equations, this 100-year rule allows project owners to annually retain the net carbon credits represented by the carbon estimate for their harvested wood products. The approach is much simpler and does not create net negative flows of carbon over the project lifespan. Drawbacks include fewer project-specific calculations and potentially very conservative estimates of carbon storage in the HWP pool.

If the wood product is transferred to a landfill, the time frame for the ultimate release of its carbon into the atmosphere may be even longer. To illustrate, carbon may be stored in a paper product five years after harvest, then in a landfill for 10 years, and decomposed as emissions after yet another decade or two. In accounting for carbon storage in landfills, the current US registries are even more variable. Although accounting rules for this aspect of carbon storage currently exist, this part of the pool is less uniformly recognized by domestic carbon programs than carbon stored in wood products in use. One reason involves concerns over ownership of the carbon stored in landfills, and thus who can claim credit for the carbon sequestered.

The climate change benefits of wood products are twofold: the true value lies in the combination of long-term carbon storage with substitution for other materials with higher emissions. Although some carbon accounting systems are beginning to recognize the importance of the carbon stored in wood products, fewer incorporate the system boundaries that recognize the importance of the way wood is used. Because wood can substitute for other, more fossil fuel–intensive products, the reductions in carbon emissions to the atmosphere are comparatively larger than even the benefit of the carbon stored in wood products. Research both in the United States and internationally (Borjesson and Gustavsson 1999; Buchanan and Levine 1999; Lippke et al. 2004; Lippke and Edmonds 2006; Perez-Garcia et al. 2005; Sathre 2007; Valsta et al. 2008) has suggested that this effect—the displacement of fossil fuel sources—could make wood products the most important carbon pool of all.