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A Synthesis of the Science on Forests and Carbon for U.S. Forests

Michael G. Ryan, Mark E. Harmon, Richard A. Birdsey, Christian P. Giardina, Linda S. Heath, Richard A. Houghton, Robert B. Jackson, Duncan C. McKinley, James F. Morrison, Brian C. Murray, Diane E. Pataki, and Kenneth E. Skog

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SUMMARY

Forests play an important role in the U.S. and global carbon cycle, and carbon sequestered by U.S. forest growth and harvested wood products currently offsets 12-19% of U.S. fossil fuel emissions. The cycle of forest growth, death, and regeneration and the use of wood removed from the forest complicate efforts to understand and measure forest carbon pools and flows. Our report explains these processes and examines the science behind mechanisms proposed for increasing the amount of carbon stored in forests and using wood to offset fossil fuel use. We also examine the tradeoffs, costs, and benefits associated with each mechanism and explain how forest carbon is measured.

Current forests are recovering from past land use as agriculture, pasture, or harvest, and because this period of recovery will eventually end, the resulting forest carbon sink will not continue indefinitely. Increased fertilization from atmospheric nitrogen deposition and increased atmospheric carbon dioxide may also be contributing to forest growth. Both the magnitude of this growth and the future of the carbon sink over the next hundred years are uncertain. Several strategies can increase forest carbon storage, prevent its loss, and reduce fossil fuel consumption (listed in order of increasing uncertainty or risk):

- Avoiding deforestation retains forest carbon and has many co-benefits and few risks.
- Afforestation increases forest carbon and has many co-benefits. Afforesting ecosystems that do not naturally support forests can decrease streamflow and biodiversity.
- Decreasing harvests can increase species and structural diversity, with the risk of products being harvested elsewhere and carbon loss in disturbance.
- Increasing the growth rate of existing forests through intensive silviculture can increase both forest carbon storage and wood production, but may reduce stream flow and biodiversity.
- Use of biomass energy from forests can reduce carbon emissions but will require expansion of forest management and will likely reduce carbon stored in forests.
- Using wood products for construction in place of concrete or steel releases less fossil fuel in manufacturing. Expansion of this use mostly lies in the non-residential building sector and expansion may reduce forest carbon stores.
- Urban forestry has a small role in sequestering carbon but may improve energy efficiency of structures.
- Fuel treatments trade current carbon storage for the potential of avoiding larger carbon losses in wildfire. The carbon savings are highly uncertain.

Each strategy has risks, uncertainties, and, importantly, tradeoffs. For example, avoiding deforestation or decreasing harvests in the U.S. may increase wood imports and lower forest carbon elsewhere. Increasing the use of wood or forest biomass energy will likely reduce carbon stores in the forest and require expansion of the area of active forest management. Recognizing these tradeoffs will be vital to any effort to promote forest carbon storage. Climate change may increase disturbance and forest carbon loss, potentially reducing the effectiveness of management intended to increase forest carbon stocks. Finally, most of these strategies currently do not pay enough to make them viable. Forests offer many benefits besides carbon, and these benefits should be considered along with carbon storage potential.

Cover photo credit: *Old-growth forest in the Valley of the Giants in Oregon.*
Photo by Mark E. Harmon, Oregon State University.
Inset: Logs harvested at Manitou Experimental Forest in Colorado.
Photo by Richard Oakes, USDA Forest Service.

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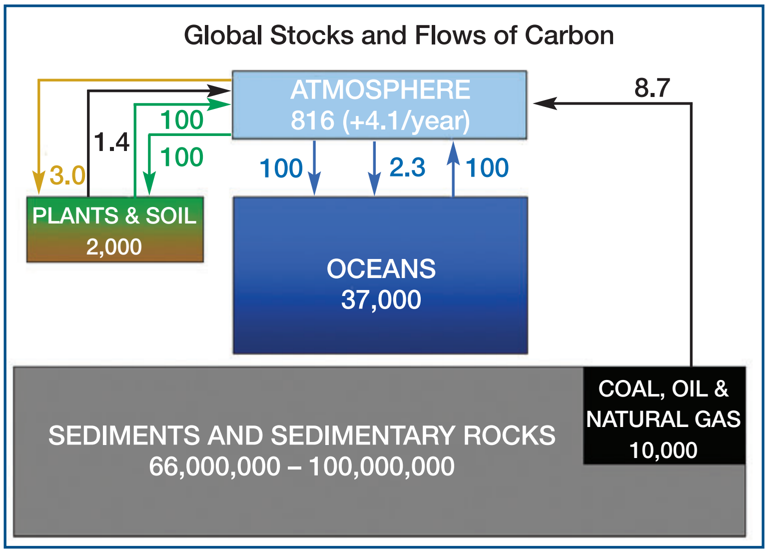
Introduction

The movement of carbon between the earth and its atmosphere controls the concentration of carbon dioxide (CO_2) in the air. CO_2 is important because it is a greenhouse gas and traps heat radiation given off when the sun warms the earth. Higher concentrations of greenhouse gases in the atmosphere cause the earth to warm. Before the Industrial Revolution, the concentration of CO_2 in the atmosphere was less than 280 parts per million. The burning of fossil fuel for energy and the clearing of forests for agriculture, building material, and fuel has led to an increase in the concentration of atmospheric CO_2 to its current (2010) level of 388 parts per million. This current level far exceeds the 180-300 parts per million found over the last 650,000 years.

As a result of rising CO_2 and other greenhouse gases in the atmosphere, global surface temperatures have increased by 0.74°C (1.3°F) since the late 1800s, with the rate of warming increasing substantially. As more CO_2 is added to the air, temperatures will continue to increase and the warmer earth will have an impact on the earth's climate, climate variability, and ecosystems. Rain and snowfall patterns will shift, and extreme weather events may become more common. Some regions that currently support forests will no longer do so, and other regions that currently do not support forests may become suitable for forest growth.

Forests store large amounts of carbon in their live and dead wood and soil and play an active role in controlling the concentration of CO_2 in the atmosphere (Figure 1). In the U.S. in 2003, carbon removed from the atmosphere by forest growth or stored in harvested wood products offset 12-19% of U.S. fossil fuel emissions (the 19% includes a very uncertain estimate of carbon storage rate in forest soil). U.S. forest growth rates are thought to be higher than those before European settlement because of recovery from past land use and disturbance, but the current growth rate will not continue indefinitely.



Courtesy of Richard A. Houghton, Woods Hole Research Institute, 2009.

Figure 1. *Plants and soil play a large role in the global carbon cycle as shown by global stocks (boxes) and flows (arrows) of carbon in petagrams (1000 teragrams). Numbers in light blue and green are the historical fluxes between the oceans and the atmosphere and plants and soil and the atmosphere that would have occurred without human influence. The number in dark blue is the additional ocean absorption of CO_2, resulting from increased CO_2 in the atmosphere since the Industrial Revolution. The numbers in black are the fluxes to the atmosphere from fossil fuel combustion or deforestation. The number in brown is the flux from the atmosphere to the land, mostly from forest regrowth. The measured atmospheric increase of 4.1 petagrams per year is not equal to the sum of the additions and withdrawals because they are estimated separately and with associated uncertainties.*

Given the role that U.S. forests play in offsetting CO_2 emissions, our report asks: 1) Which human actions influence forest carbon sinks (storage rates) and can these sinks be enhanced for a meaningful period of time through management and use of forest products? and 2) What are some of the major risks, uncertainties, tradeoffs, and co-benefits of using forests and forest products in proposed carbon emission mitigation strategies?

The purpose of our report is to answer these questions, or, if answers are not yet available, to present the best current information. We present the state of knowledge on the role of forests in the carbon cycle in a straightforward manner so that it can be understood by forest managers, policymakers, educators, and the interested public. We begin with a description of the forest carbon cycle and biophysical effects. We then present details on the strategies that have been proposed for using forests to slow the amount of CO_2 entering the air.

These strategies include:

- *Avoiding deforestation* – Keeping forests intact.
- *Afforestation* – The restoration of forest on land that has been without forest cover for some time, and the establishment of forest on land that has not previously been forested.
- *Forest management: decreasing carbon loss* – Increasing the harvest interval and/or decreasing harvest intensity.
- *Forest management: increasing forest growth* – Use of improved silvicultural practices, genetic improvement, and rapid regeneration.
- *Forest management: thinning to reduce fire threat.*
- *Urban forestry* – Planting trees in urban areas for carbon storage and shading for energy savings.
- *Biomass energy* – Using fuel from wood and biomass in place of fossil fuel.
- *Carbon storage in forest products and substitution* – Storing carbon in long-lived forest products (such as lumber) and substituting forest products for products (such as steel and concrete) whose manufacture releases much more CO_2 than does the processing of wood.

We then discuss carbon offsets and credits, how forest carbon could be monitored to determine whether changes result in the desired outcomes, and what the costs would need to be for carbon to encourage changes. We also discuss some of the uncertainties inherent in the use of forests for carbon storage, because changes in climate, population, and land use may lower projected carbon storage. We especially note the potential loss of carbon that might occur with increased disturbance in a warmer climate. Finally, we provide conclusions and recommendations.

Forests and carbon

Carbon in the forest

Forest carbon storage differs from many other mechanisms that control atmospheric CO_2 because forests have a life cycle during which carbon stocks, gains, and losses vary with forest age. Carbon enters a forest through photosynthesis, where leaves capture the energy in sunlight and convert CO_2 from the atmosphere and water into sugars that are used to build new leaves, wood, and roots as trees grow (Figure 2). About half of the CO_2 that is converted to sugars is respired by living trees to maintain their metabolism, and the other half produces new leaves, wood, and roots. As they grow, trees shed dead branches, leaves, and roots and some of the trees die. Microorganisms decompose this dead material, releasing CO_2 back to the atmosphere, but some of the carbon remains in the soil. Live and dead trees contain about 60% of the carbon in a mature forest, and soil and forest litter contain about 40%. The carbon in live and dead trees (50% of their biomass) varies the most with forest age.

Carbon can leave the forest in several ways besides tree and microorganism respiration. Forest fires release stored carbon into the atmosphere from the combustion of leaves and small twigs, the litter layer, and some dead trees and logs, leaving behind a great deal of stored carbon in dead trees and soil. Storms and insect outbreaks also kill trees and increase the amount of material available for decomposition. Harvesting removes carbon from the forest, although some of it is stored in wood products (preventing its immediate release to the atmosphere) and some is available for use as biomass energy (displacing fossil fuel use). In addition, water can remove carbon from a forest either by transporting soil and litter away in streams (especially from erosion after fire) or by transporting soluble carbon molecules created during decomposition. After fire, other disturbance, or harvest, regenerated forests will eventually recover all of the car-

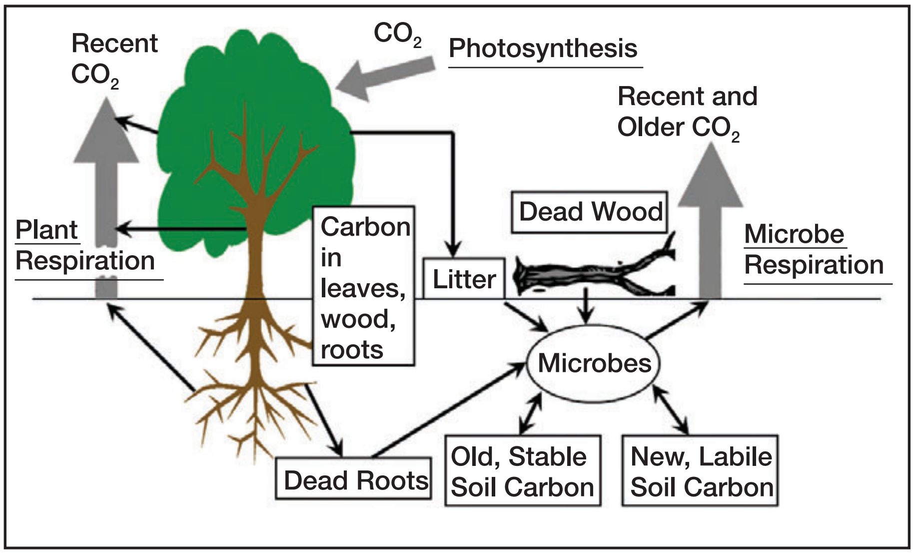


Figure 2. Flows of carbon from the atmosphere to the forest and back. Carbon is stored mostly in live and dead wood as forests grow.

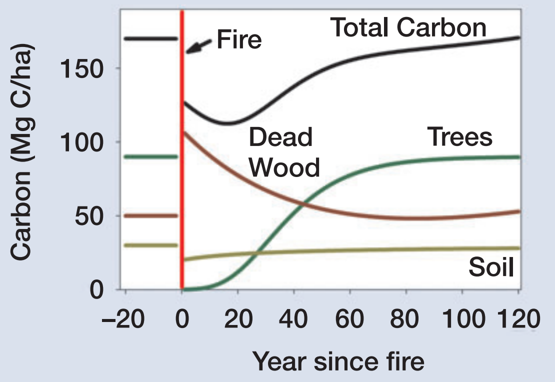


Figure 3. If a forest regenerates after a fire, and the recovery is long enough, the forest will recover the carbon lost in the fire and in the decomposition of trees killed by the fire. This figure illustrates this concept by showing carbon stored in forests as live trees, dead wood, and soil and how these pools change after fire. (Adapted from Kashian and others 2006. BioScience 56(7):598-606.)

bon lost so that a complete cycle is carbon neutral regarding storage if the recovery is long enough (Figure 3). But if disturbances increase, as is projected with climate change, a fire, storm, or insect outbreak may occur before the ecosystem recovers the carbon it had prior to the disturbance. In that case, the amount of carbon stored on the landscape will decrease.

Forests are biological systems that continually gain and lose carbon via processes such as photosynthesis, respiration, and combustion; whether forests show a net gain or loss of carbon depends on the balance of these processes. The observation that carbon is lost from forests has led to the notion that carbon cannot be permanently stored in forests. However, this view ignores the inevitable increase and eventual recovery of carbon that follows most disturbances. Thus over time, a single forest will vary dramatically in its ability to store carbon; however, when considering many different forests over a large area or landscape, such "boom and bust" cycles may not be apparent because the landscape is composed of forest stands that are in different stages of recovery from disturbance or harvesting (Figure 4).

To determine how quickly carbon increases in a forest system, it is important to know the starting point or "baseline." A forest that already stores a substantial amount of carbon is likely to lose carbon when converted to something else, and a system with the potential to store carbon but that does not currently store much is easier to convert to one that stores more carbon (Figure 5). A forest's timeline for increasing carbon storage is important because carbon must be removed quickly to reduce CO_2 in the atmosphere and thereby slow global warming.

While the biological processes of photosynthesis, respiration, and decomposition are similar for all forests, their relative importance differs by forest type and location. Some forests grow more rapidly, but dead trees in fast-growing forests also decompose more rapidly. In addition, disturbances vary regionally: for example, fire disturbance is more common in the western U.S. and hurricanes more common in the East. Forests are managed in different ways with varying harvest intervals and regeneration practices that will influence the optimum strategy for storing more carbon. Each forest has a different potential to store carbon. For example, this potential is particularly high in the Pacific Northwest where forests are relatively productive, trees live a long time, decomposition is relatively slow, and fires are infrequent. The differences between forests must therefore be taken into consideration when determining how they should be managed to store carbon.

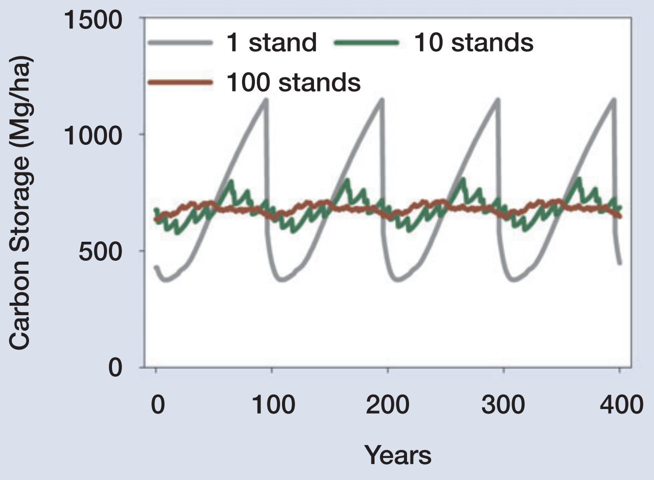


Figure 4. Management actions should be examined for large areas and over long time periods. This figure illustrates how the behavior of carbon stores changes as the area becomes larger and more stands are included in the analysis. As the number of stands increases, the gains in one stand tend to be offset by losses in another and hence the flatter the carbon stores curve becomes. The average carbon store of a large number of stands is controlled by the interval and severity of disturbances, as shown in Figure 7. That is, the more frequent and severe the disturbances, the lower the average becomes. (Courtesy of Mark E. Harmon, Oregon State University, 2009.)

Carbon from the forest

All forest products eventually decompose, but before they do, they store carbon. Some products have a short lifespan (such as fence posts) and some a longer lifespan (for example, houses) – the longer the lifespan, the more carbon is stored. Disposed forest products in landfills can have a very long lifespan; however, the decomposition in landfills generates methane, which is a much more potent greenhouse gas than CO_2, reducing the carbon storage benefit. In addition, wood and bark that are burned to run a mill or heat houses, or made into liquid biofuel, lower emissions from fossil fuel use. Once the carbon leaves the forest, it becomes more difficult to track and measure than carbon in the forest, particularly because imports and exports must then be tracked.

Biophysical effects may cause warming or cooling

Forests have other influences on climate besides that of carbon; these are known as biophysical effects (Figure 6) and include the reflection of solar radiation and transpiration of water vapor. Trees are dark and absorb more radiation than other types of land cover, such as crops or snow-covered tundra. Therefore, converting non-forested land to forest can warm the land and air. Evergreen trees absorb much more energy than deciduous trees in the winter and burned forests absorb more than unburned forests, so species and disturbance can also alter the energy absorbed by forests. In addition, transpiration from forests may have a cooling effect by contributing to the formation of clouds that reflect sunlight.

Biophysical effects sometimes act in a direction opposite to that of the effects of storing or releasing CO_2. For instance, whereas converting cropland to forest will sequester more CO_2, which *reduces* global warming, it will also increase solar absorption, which *increases* warming. Generally, biophysical effects on climate are not as strong as the effects of greenhouse gases. Biophysical effects will be most important in evaluating the benefits of afforestation because the land use change will cause large differences. Unfortunately, current estimates of biophysical effects are uncertain because few studies have been done.

Strategies for increasing carbon stores in forests

1. Avoiding deforestation

Deforestation, or the conversion of forest land to other uses, has a significant impact on global CO_2 emissions. Globally, deforestation converts approximately 90,000 km^2 (about the size of Indiana) of forests per year (0.2% of all forests) to other land uses. Deforestation annually releases 1,400-2,000 teragrams of carbon (10^{12} grams; see Box 1 for units) to the atmosphere, and two-thirds of this release occurs in tropical forests. The amount of carbon released by deforestation equals 17-25% of global fossil fuel emissions every year and is roughly the amount of U.S. annual fossil fuel emissions. If current deforestation rates continue, more than 30,000 teragrams of carbon could be released to the atmosphere from deforestation in the Amazon alone by the year 2050.

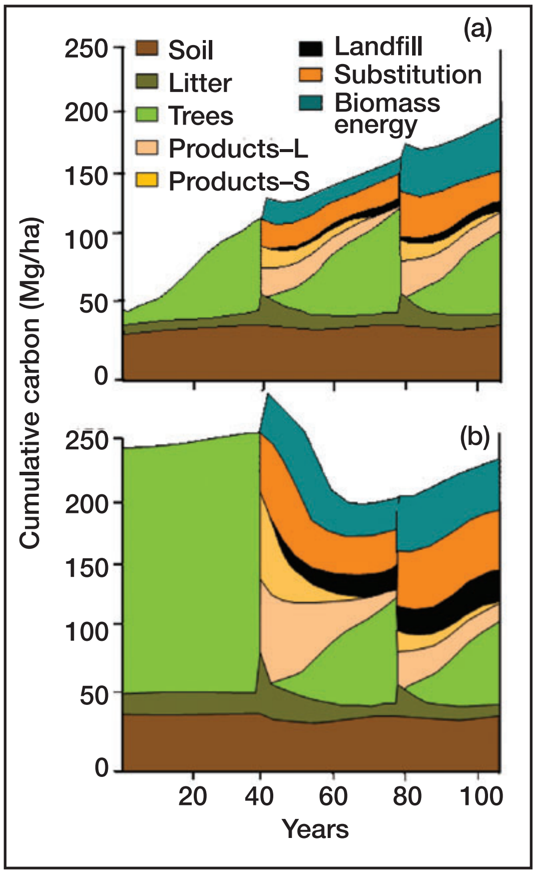


Figure 5. *Projections of carbon storage and fossil fuel displacement if all biomass is used shows considerable storage and offsets for (A) a project that reestablishes forests with periodic harvests. Harvesting a high-biomass old growth forest (B) shows carbon losses, even under the best possible scenario, for several harvests. At each harvest, forest biomass (and thus carbon stock) is removed for use in long- and short-lived wood products ('Products-L' and 'Products-S', respectively) substituted for more carbon-intensive products, and for biomass energy to displace emissions from fossil fuel use. Because substitution generates more fossil fuel savings than the carbon it contains, substitution would yield a greater carbon benefit after harvest than that which is stored in the biomass. The biomass energy and substitution fossil fuel savings accumulate but represent only hypothetical carbon benefits, as currently little biomass energy use and substitution occurs in the U.S. (Adapted from IPCC 2007.)*

In the U.S., forested area increased 0.1% per year from 2000-2005, and this gain in forested area is partially responsible for the current forest sink of 162 teragrams of carbon per year. The net growth in forested area results from both deforestation and afforestation: About 6,000 km^2 are deforested annually, but more than 10,000 km^2 of non-forest are afforested. The net increase in forestlands results from changes in land use and possibly from reduced demand for U.S. timber.

Although the U.S. forest carbon sink benefits from increased forest area, these carbon benefits need to be weighed against the global consequences of land use change within the U.S. If afforestation or avoided deforestation in the U.S. pushes crop and cattle production to other countries, it can lead to deforestation

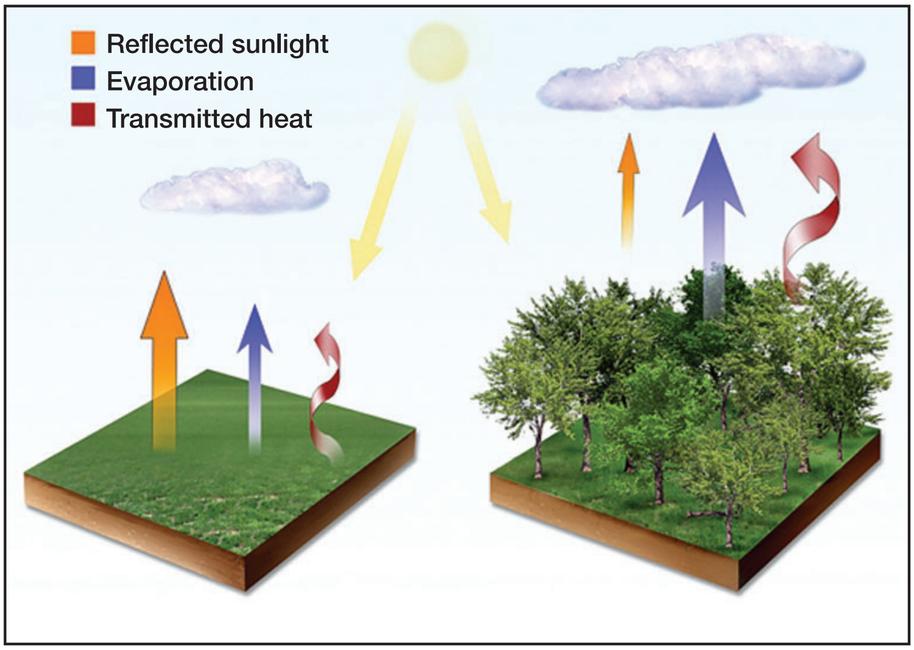


Figure 6. Biophysical effects of different land use can have important impacts on climate. Cropland reflects more sunlight than forest, produces less water vapor, and transmits less heat. (From Jackson et al. *2008. Environmental Research Letters 3:article 044006.)*

and loss of forest carbon elsewhere to create pasture and cropland. Carbon loss associated with such deforestation – especially in the tropics – is greater than carbon gain associated with tree growth from afforestation in the U.S.

Forest retention in the western U.S. may be even more important in the future as climate changes. Our warming climate is very likely causing, at least in part, the current increase in forest fire size and intensity, insect outbreaks, and storm intensity. If forest regeneration fails because the disturbances or regeneration conditions are outside of the ecological norms, disturbances can convert forests to meadows or shrublands. When this type of deforestation occurs, substantial carbon is lost to the atmosphere and not recovered by the ecosystem. Tree planting would help recover forest carbon where natural regeneration fails.

Box 1. UNITS FOR CARBON

When discussing regional, national, or global carbon stores and fluxes, the numbers get large quickly. We report carbon in teragrams (10^{12} grams). Other reports may use other units, so we provide a conversion table below. For stand- or forest-level stores and fluxes, we use megagrams (Mg) per hectare (10^6 grams). Our report uses carbon mass, not CO_2 mass, because carbon is a standard "currency" and can easily be converted to any other unit. Many reports give stocks and fluxes of the mass of CO_2, not carbon. To convert carbon mass to CO_2 mass, multiply by 3.67 to account for the mass of the O_2.

1000 teragrams (Tg)	1 petagram (Pg)
1000 teragrams	1 billion metric tonnes
1000 teragrams	1 gigatonne
1 teragram	1 million metric tonnes
1 teragram	1 megatonne
1 megagram (Mg)	1 metric tonne
1 metric tonne	0.98 U.S. long ton
1 metric tonne per hectare	0.4 U.S. long tons per acre
carbon (C) mass * 3.67	carbon dioxide (CO_2) mass

There are not many risks associated with avoidance of deforestation. Three to note, however, would be risks related to highly fire-prone ecosystems near human settlement, economic consequences for not developing agricultural or pasture land, and an increase in forest products harvested elsewhere. On the other hand, avoiding deforestation has many of the co-benefits identified in Box 2.

2. Afforestation

We define afforestation as both reestablishing forests on land that has been without forest cover for some time and the establishment of forest on land that has not previously been forested (note that some entities involved in carbon markets and reporting use different definitions for this term). Afforestation can remove substantial CO_2 from the atmosphere. Between 1850 and 2000, global land-use change resulted in the release of 156,000 teragrams of carbon to the atmosphere, mostly from deforestation. This amount is equivalent to 21.9 years of global fossil fuel CO_2 emissions at the 2003 level.

The rate of carbon storage in tree growth varies with species, climate, and management, ranging widely from about 3-20 megagrams (Mg, 10^6 grams) per hectare per year. In the continental U.S., the highest potential growth rates are found in the Pacific Northwest, the Southeast, and the South Central U.S. Much land currently in pasture and agricultural use in the eastern U.S. and in the Lake States will naturally revert to forests if left fallow, while reestablishing forests in many western forests requires tree planting.

The benefits of afforestation (outlined in Box 2) are enhanced where forests include a substantial proportion of native species. Planting native species or allowing natural succession to recreate the forest that historically occupied the site will yield the greatest benefits for species diversity and wildlife habitat and the lowest risk for unintended consequences. Because native species often grow more slowly than exotics or trees selected for improved growth, restoration of the historical ecosystem may yield lower carbon accumulation rates than other forest reestablishment practices. Planting monocultures of non-native or native improved-growth species on historical forest land will likely yield greater carbon accumulation rates but fewer benefits in terms of biodiversity.

Afforestation can have negative consequences, too. Planting forests where they were not present historically can have drawbacks such as lower species diversity (if trees are planted in native grassland), changes in water table, and a higher energy absorption compared to the native ecosystem. In addition, afforestation generally reduces streamflow regardless of the ecosystem type because trees use more water than grass or crops. Conversion of agricultural or grazing lands to forest reduces revenue from agricultural products. If afforestation efforts include the addition of nitrogen fertilizer, emissions of nitrous oxide (a greenhouse gas roughly 300 times as powerful as CO_2) will increase.

Box 2. CO-BENEFITS OF FORESTS

Our report focuses on forests seen through the lens of carbon, and only carbon. However, forests are managed for many purposes, and carbon storage and the growth of wood for products and fuel to offset fossil fuel use are far from the only reasons forests are valuable. Forests also provide many other ecosystem services that are important to the well-being of the U.S. and its inhabitants: protection of watersheds from erosion, nutrient retention, good water quality, reduction of peak streamflow and an increase in base streamflow, wildlife habitat and diversity, recreational opportunities and aesthetic and spiritual fulfillment, and biodiversity conservation. Americans are strongly attached to their forests. In some cases, managing strictly for carbon would conflict with other co-benefits of forests. The option of avoided deforestation retains the co-benefits of forests and the carbon in forest ecosystems, while afforestation adds these co-benefits in addition to increasing carbon storage. Even simple forests, such as plantations, generally reduce erosion, regulate streamflow, and increase wildlife habitat and biodiversity compared to crops or livestock pasture because the frequency of harvest or stand–replacing disturbance is much less for forests.

3. Forest management: decreasing carbon loss

Lengthening the harvest interval or reducing the amount removed in a harvest will store more carbon in the forest. The greater the increase in harvest interval over the current level, the higher the increase in carbon storage. For example, a five-year increase in the harvest interval would lead to a 15% increase in carbon storage if the harvest interval was changed from 25 to 30 years, but only a 4% increase if the interval was changed from 55 to 60 years (Figure 7). A 50-year increase from 25 to 75 years would increase carbon storage 92% (Figure 7).

The carbon impact of reducing the amount of trees removed in a harvest also varies with the harvest interval. For example, reducing the harvest from 100% to 20% of the live trees would increase the average forest carbon stock by 97% for a 25-year harvest interval, but only by 30% for a 100-year harvest interval (Figure 7). Some natural forests are dominated by small disturbances that kill a few trees at a time. Reducing harvest amounts in these systems from complete removal of trees to simply a percentage, for example, could mimic the natural disturbance regime common to the northeastern and midwestern United States. In addition, reducing harvests could be desirable in public forests that are managed for multiple purposes, such as recreation, biodiversity, and water.

These strategies would be most suitable in forest regions with active management and a high potential to store carbon, such as those with long-lived species and slowly decomposing dead plant matter, which are common in the Pacific Northwest. The carbon benefit of either of these practices will depend on the temporal and spatial scales at which they are administered – applying these practices over longer timeframes and larger landscapes leads to greater carbon benefits.

In addition to an increase in carbon storage, benefits of decreased harvesting also include an increase in structural and species diversity. On the other hand, the costs are an increased risk of carbon loss due to disturbance and the potential for increased harvesting elsewhere to compensate for the reduction in forest products generated.

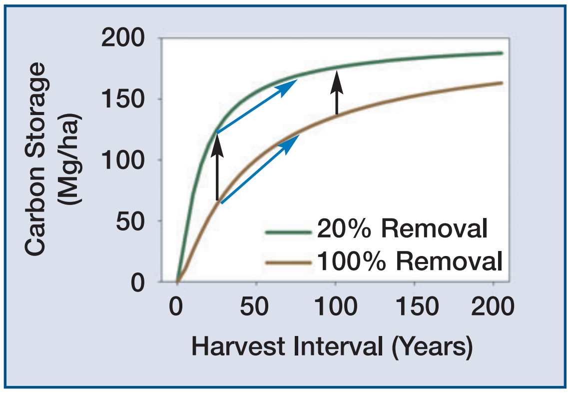


Figure 7. Average carbon stored on a landscape will vary with the time between harvests (harvest interval) and how much biomass is removed each harvest. Lengthening the harvest interval will have a greater effect for harvests where removals are high (blue arrows show an increase in harvest interval from 25 to 75 years). Decreasing harvest intensity from 100% of trees to 20% of trees (black arrows) will have a greater effect for shorter harvest intervals. (Courtesy of Mark E. Harmon, Oregon State University, 2009.)

4. Forest management: increasing forest growth

In addition to afforestation, another strategy for increasing carbon storage is to increase the growth rate of existing or new forests. Management practices that can increase forest growth include: regenerating harvested or damaged forests, controlling competing vegetation, fertilizing, planting genetically improved trees, and selecting species for superior productivity. Yield gains from these practices can be impressive. In pine forests in the southern U.S., tree breeding has improved wood growth (and carbon storage rate) by 10-30%, and fertilization can show 100% gains for wood growth. For southern

Figure 8. A hydro-axe is used to grind up trees to reduce canopy fuel loads and lower the risk of crown fire. Photo by Dan Binkley, Colorado State University.

U.S. pines, operational plantations using improved seedlings, control of competing vegetation, and fertilization grow wood four times faster than naturally regenerated second-growth pine forests without competition control. The potential to increase forest growth varies by climate, soil, tree species, and management.

Increases in carbon stocks will generally be proportional to increases in growth rates. That is, a 10% increase in growth will result in a 10% increase in carbon stocks, assuming that the harvest interval and amount harvested do not change. As shown in Figure 3, the rate of forest growth will naturally slow down as the forest ages. Management decisions for increasing carbon stocks should take into account forest growth over time, the amount of timber that would end up in wood products if the forest were harvested, and how long the harvested carbon would remain sequestered in the wood products. Knowledge of these variables will help determine when or whether to harvest.

The area of forestland in the U.S. that could be managed to increase forest growth includes more than 500 million acres and consists of almost all U.S. public and private forestland, excluding remote and reserved areas such as national parks. However, even reserved areas could potentially be managed to restore damaged ecosystems, which could also lead to increased forest growth.

Increasing forest growth through management has benefits and costs. The benefits include increased wood production and the potential for planting species and genotypes adapted to future climates. The costs include reducing the carbon benefit by emissions of nitrous oxide from forest fertilization, reduced water yield (faster growth uses more water), and a loss of biodiversity if faster growth is accomplished by replacing multi-species forests with monocultures.

Box 3. THINNING AND CARBON

Thinning is an effective forest management technique used to produce larger stems more quickly, reduce fire risk, and increase tree resistance to insects and disease. Thinning increases the growth of the remaining individual trees, but generally decreases overall forest wood growth until the remaining trees grow enough to re-occupy the site. The carbon stock in a thinned stand is generally lower than that in an unthinned stand. If the harvested trees are used for biomass energy or long-lived forest products, these carbon benefits may compensate for the lower biomass and the wood growth of the thinned stand. Because of lower overall growth of a thinned stand, even 100% use of the harvested trees for products or biomass energy may not produce a total carbon benefit greater than that of the higher storage and storage rate in an unthinned stand. The net carbon consequences of thinning will depend the most on whether the harvested trees are used for long-lasting wood products or biomass energy, but also on the change in risk of a crown fire relative to the probability of fire occurring, the species, the site, the thinning regime, and the length of the harvest interval.

5. Forest management: fuel management to reduce fire threat

Fuel management uses thinning (Box 3) to lower foliage biomass to reduce the risk of crown fire because crown fires are difficult, if not impossible, to control. Fuel management occurs in forests with a variety of historical fire regimes – from forests where historical forest density was lower and the natural fires were mostly surface fires, to forests with stand-replacement fire regimes in which crown fires naturally occurred. Fuel management temporarily lowers the carbon stored in forest biomass and dead wood because the thinned trees are typically piled and burned or mulched and then decompose.

If a crown fire burns through a forest that was thinned to a low density, the fire may change from a crown to a surface fire in which many of the trees can often survive the fire. In contrast, many or all of the trees in an unthinned stand will be killed by a crown fire. This contrast in survival has led to the notion that fuel treatments offer a carbon benefit: removing some carbon from the forest may protect the remaining carbon.

There are two views regarding the science on carbon savings through fuel treatments. Some studies have shown that thinned stands have much higher tree survival and lower carbon losses in a crown fire, or have used modeling to estimate lower carbon losses from thinned stands if they were to burn. However, other stand-level studies have not shown a carbon benefit from fuels treatments, and evidence from landscape-level modeling suggests that fuel treatments in most forests will decrease carbon, even if the thinned trees are used for biomass energy. More research is urgently needed to resolve these different conclusions because thinning to reduce fuel is a widespread forest treatment in the U.S. We recommend that such research focus on the landscape scale because carbon loss in thinning needs to be placed in the context of the expected fire frequency and extent, and the potential for regeneration after fire. Regardless of the outcome of such research, the carbon benefits of fuel treatments can be improved by using the harvested trees for wood or biomass energy.

Figure 9. Sycamores lining Sycamore Street in Los Angeles, California. Photo by Diane E. Pataki, University of California, Irvine.

6. Urban forestry

Urban forestry offers very limited potential to store carbon, but we address urban forests here because of the large interest in using them to offset carbon emissions and because urban trees provide many co-benefits, including aesthetic benefits and environmental advantages in addition to carbon sequestration. The potential for carbon offsets of greenhouse gas emissions through urban forestry is very limited for two reasons: 1) urban areas make up only a small fraction of the U.S. landscape and 2) urban forests are intensively managed and may require large energy, water, and fertilizer inputs for planting and maintenance.

Urban forests can have important biophysical effects on climate. Trees have a cooling effect on local temperatures due both to shading effects and to evaporative cooling in transpiration. Shading intercepts incoming radiation in the daytime, which can reduce both day and night surface temperatures. When trees are planted very close to buildings, they cool building temperatures and reduce the fossil fuel emissions associated with air conditioning. When urban forests are planted over very large regions, the climate effects are less certain, as trees can have both warming (absorption) and cooling effects.

The higher the maintenance required for urban trees, the less likely they will help mitigate climate change. In some regions, cities are located in what would naturally be forested areas; thus, urban forests serve to restore forests to land that was previously deforested. In such regions, trees may have relatively low maintenance requirements. In cities located in grasslands and deserts, urban forests require large amounts of irrigation water for maintenance.

Because of these many tradeoffs, the following factors must be taken into account to determine the net climate impact of urban trees: 1) the carbon storage rate of the trees, 2) fossil fuel emissions from energy associated with planting and maintenance, 3) fossil fuel emissions resulting from the irrigation process, 4) nitrous and nitric oxide emissions from fertilizer use, and 5) the net effect of trees on local air temperature and its impact on building energy use. These factors are likely to be highly variable by region and by species.

7. Biomass energy, carbon storage in products, and substitution

Biomass energy

The use of forest biomass energy prevents carbon emissions from fossil fuel use. In 2003, biomass energy was 28% of the U.S. renewable energy supply and 2% of the total U.S. energy use. Biomass energy is used primarily for electric power in the forest products industry and for residential heating. In the future, biomass may become an important feedstock for liquid biofuels.

If cost were not a constraint and the public supported this use of forests, U.S. forests could potentially provide energy production offsetting 190 teragrams of fossil fuel carbon emissions per year, or the equivalent of 12% of U.S. fossil fuel emissions in 2003 (as discussed further in *Environmental costs* below). It has been estimated that by 2022, forest biomass feedstocks could produce 4 billion gallons of liquid biofuel per year (offsetting 2.6 teragrams of fossil fuel carbon emissions).

Figure 10. Logs harvested at Manitou Experimental Forest in Colorado. Photo by Richard Oakes, USDA Forest Service.

Carbon storage in wood and paper products

In the U.S., forest products are stored in two major "pools": those that are in use, and those held in landfills. Current additions of carbon to these pools from trees harvested in the U.S. are greater than decomposition losses from these pools, so carbon stored in these pools is increasing. In 2007, the net increase in carbon stored as products in use and in landfills was 30 teragrams of carbon (offsetting 1.7% of 2003 U.S. fossil fuel emissions), with about two thirds of the 30 teragrams being net carbon additions to landfills. Recently, additions have been declining due to decreases in U.S. timber harvests.

Carbon is also accumulating in "products in use", primarily in buildings. The total carbon held in single and multifamily homes in 2001 was about 700 teragrams of carbon. Annual net carbon accumulation in landfills is larger than that for products "in use" because about 80% of wood and 40% of paper decays very slowly under the anaerobic conditions in landfills. However, these same anaerobic conditions that slow decomposition also produce methane, a greenhouse gas with greater than 25 times the warming potential of CO_2. Because only 50% of methane is captured or oxidized before release, methane release reduces the carbon storage benefits in landfills. If we were to use the 30 teragrams per year of forest products currently going into landfills as biomass energy, we would offset 1.2% of U.S. fossil fuel use, lower emissions of methane, and extend the life of landfills.

Substitution

Carbon emissions can be offset by substituting wood products for products such as steel and concrete, which generate more greenhouse gas emissions in their production. A review of studies suggests that if wood products containing one unit of carbon were used in buildings as a substitute for steel or concrete, fossil fuel emissions from manufacturing would be reduced by two units or more. Opportunities for increased substitution in the U.S. will mostly need to be found outside of the housing industry because most housing is already built using wood.

Environmental costs of biomass energy and forest products use

The carbon benefits of increasing the use of wood for biomass energy and for product substitution would require more intensive forest management over a much broader area than currently occurs. For example, to obtain the aforementioned 190 teragrams per year of biomass energy would involve harvesting all of the current annual net forest growth in the U.S. To do that would require intensive management on much of the U.S. forest estate and would reduce the carbon stored in the forest. If branches and foliage were to be removed for biomass energy, fertilization would likely be needed to replace the nutrients removed to maintain productivity. Additionally, dead wood will decrease and soil carbon may decrease under harvesting, creating a carbon debt that will require time to pay off.

Links between strategies

Strategies can be combined to increase the carbon benefit. For example, Figure 5 shows that the maximum potential benefit from a project that reestablished forest increases if the stand is periodically harvested and the wood is used for substitution and the biomass used for fuel. Increased wood use for forest products and biomass energy would be compatible with afforestation, increasing forest growth, and fuel management to reduce fire threat. However, increased wood use may conflict with increasing carbon stores on the landscape from reducing harvests and avoiding deforestation. Increased forest growth would be compatible with reducing harvests and avoiding deforestation if the increased growth frees land for these other uses.

Carbon offsets and credits

A carbon offset is a reduction in greenhouse gas emissions (or an increase in carbon sequestration) by one entity, which can compensate for – or "offset" – emissions by another entity. The latter can thus continue with business as usual and avoid directly reducing its own emissions. Offsets are typically traded (bought and sold) as "carbon credits." Typically, offset projects are certified, which instills confidence that the offsets are real and enables the associated carbon credits to be sold or traded to those who voluntarily wish to reduce their reductions or are regulated to do so. In the U.S., carbon credits are traded as part of a voluntary market, and the certification process varies widely. Europe, which ratified the Kyoto Protocol, has a regulated carbon market. Some of the forest management strategies discussed in this paper could "earn" carbon credits, such as afforestation, decreasing harvest intensity, increasing forest growth, use of biomass energy, and substitution.

Figure 11. Tree harvesting at Manitou Experimental Forest in Colorado. Photo by Richard Oakes, USDA Forest Service.

Carbon offsets require *additionality*, meaning that the carbon benefits occur directly as a result of an action deliberately taken to increase carbon sequestration. Additionality is required because reducing greenhouse gas emissions over business as usual is a goal and because no one wishes to pay for something that would happen anyway. Demonstrating additionality for forest activities requires that the activity be compared against a baseline scenario without activity. Demonstrating additionality is relatively straightforward for afforestation, urban forestry, and biomass energy use because the "starting point" can be quantified. It is much more complex for management that reduces carbon outputs or increases forest growth because larger areas need to be monitored for a longer time to validate increased carbon storage. It is also difficult to show additionality for the strategy of avoiding deforestation because carbon storage does not necessarily increase if forests are simply retained.

Many traders of forest carbon credits are also concerned with permanence, because carbon credits associated with the offset are sold before the management is fully implemented. Some forest carbon can be temporarily lost in a disturbance or harvest. It can also be lost with land use changes, some of which can preserve the option of forest reestablishment (such as change to agriculture or pasture) and some of which do not (urban development). For land maintained as forest, forest carbon storage can be considered permanent as long as the climate remains suitable because the landscape will maintain a level of carbon determined by the disturbance or harvest interval.

The most serious concern in any effort where forest management is changed for carbon benefits is leakage – changes outside of the project boundary that reduce or eliminate the carbon benefit. For example, afforesting agricultural land in the U.S. may increase deforestation elsewhere to meet the demand for food. Or, subsidizing forest carbon in the U.S. could decrease harvests, increase imports of wood and wood products, and lead to increased forest harvest – and thus reduced forest carbon – elsewhere. Leakage occurs, but is very difficult to measure because of its global nature and the difficulty of identifying cause and effect.

Although carbon offsets and credits feature prominently in comprehensive climate-and-energy legislation and may be critical to a society-wide effort to address climate change, other systems for increasing forest carbon sequestration may be simpler than carbon offsets. For example, direct payments to landowners for a particular land use (as in the current Conservation Reserve Program) could ensure desired management, and could reward avoided deforestation. Land-use regulation could also be used to force behavior that sequesters carbon (for example, minimum harvest intervals or requirements to plant trees on agricultural lands).

Measuring, monitoring and verifying carbon offsets

As the U.S. does not have a regulated carbon market, this discussion of monitoring and verifying carbon offsets is based on processes

Figure 12. *Regeneration in Yellowstone National Park 19 years after the 1988 fires, with Dan Kashian (Wayne State University). Photo by Mike Ryan, USDA Forest Service.*

outlined for voluntary markets. Carbon management begins with a project design that has been validated by scientific study to increase carbon storage rates compared to baseline rates. Once additional carbon accumulates, credible and accepted measurement and monitoring methods must be used to document carbon gains. Next, many offset projects and activities demonstrate that they do not cause leakage, but not all voluntary markets require this important but difficult step. Finally, an independent verification confirms that the project was installed correctly, is performing as projected, and that the carbon reporting is valid.

Measurement of carbon at various scales

At the scale of individual forest stands, adequate measurements (accurate to about 20%) can be made to estimate the carbon stored in trees, plants, dead wood, and in litter on the forest floor using standard inventory methods. Improvements to these methods would likely involve increased monitoring costs. Stand-level measurements of belowground stocks are more difficult because of the large cost of sampling soil carbon and fewer equations for estimating belowground biomass. Soil and belowground carbon monitoring should receive attention in accounting for forest carbon because forest harvest may cause an average loss of 8% of soil carbon stocks and 30% of the organic layer (forest floor) carbon.

At the landscape level, projects can be monitored and verified using remote sensing. Remote-sensing methods enable direct monitoring of forest age, cover types, and disturbance. Changes in carbon stores can be estimated with this information using ecosystem or accounting models. Monitoring at the regional level assesses the large-scale impact of carbon management. The Forest Inventory and Analysis National Program conducts a national-level strategic forest inventory based on a combination of on-the-ground measurements of all forest carbon pools and remotely-sensed observations. The inventory produces estimates of forest age, cover types, and disturbance and uses modeling for components that are difficult to measure.

Carbon stored in wood products is more difficult to monitor than carbon in the forest. Carbon in solid wood products in structures could be estimated using current census data with deductions for the fraction of products that are imported. Rates of accumulation for all forest products could also be monitored using data on production rates, recycling rates, and discard rates (to landfills). Biomass energy use could be tracked through surveys of biomass energy facilities.

How should carbon stores be measured?

Since carbon-storage projects take place across many different scales (stand, landscape, regional, and national) and jurisdictions, multiple methods of measurement are needed. A list of approved methods for measuring carbon pools should include the minimum number of pools to be measured with methods having minimal bias (that do not lead to frequent over- or under-counts of carbon) as well as the minimum frequency of measurements. There is an inherent level of uncertainty associated with any method for measuring carbon, and there is a practical need to decide how to treat this uncertainty in decision-making. If we use high-end estimates for forest carbon storage, we may over-promise what forests can do and obscure the need for mitigation actions in other sectors. Given the urgent need to meet climate change mitigation objectives and the high risks to society associated with failing to meet them, we recommend discounting carbon estimates where they are uncertain. As sampling frequency and specificity increase, uncertainty should decrease, but costs will also rise. Individual groups or entities can decide which approved method should be used for each project based on a cost-benefit ratio, weighing cost against gaining potential carbon benefit. The potential for leakage and accounting for and underestimating disturbance losses can be reduced by implementing a national-level accounting system that validates the carbon storage at a national scale.

Economics of forest carbon

Most of the strategies for increasing forest carbon storage or the use of forest products would require carbon to have a substantial value through credits for offsets or through some other mechanism to compensate those that have an economic interest for additional costs or foregone profit. To sequester an additional 200-330 teragrams of carbon in forests (the equivalent of offsetting 13-21% of 2003 U.S. fossil fuel emissions) would require payments of between $110-$183 per metric tonne of carbon, or 23-60 billion dollars per year. The per-tonne payment requirement reflects the economic value of the current use. For example, for afforestation, landowners would expect compensation for both their lost agricultural revenues and for the cost of planting trees. For lengthening the harvest interval, landowners would need compensation for the reduced product flow.

Although the total costs of such an undertaking are large, the costs of implementing these forest activities to sequester carbon are often far less than the cost of reducing the same amount of greenhouse gas emissions by other means, such as through the transportation or electric power sectors. Therefore, forests can play a key role in reducing the overall cost of achieving greenhouse gas emission reduction targets. Economic modeling of U.S. climate policy proposals consistently shows that forest carbon sequestration and other “offset” activities can significantly lower the cost of complying with the proposed regulations.

Climate change and other risks to forest carbon storage

The potential to increase carbon storage in forests needs to be weighed against the projected increases in disturbances promoted by a changing climate that will lower carbon storage. Climate change may also make regeneration after disturbance more difficult or render the current tree populations genetically unsuitable. Finally, population increase and exurban development will decrease the general amount of forested area. Because disturbances are likely to increase in the future, we recommend conservative estimates of potential gains from forest carbon management.

A potential negative effect of forest management strategies to enhance carbon storage is that, as forest carbon storage increases, there is a potential for greater loss of carbon stores from forest fires, insect outbreaks, hurricanes, windstorms, and ice storms. Climate change threatens to amplify these risks by increasing the frequency of these disturbances. If climate change increases the frequency of disturbance, as observational and modeling studies for the U.S. suggest, many forests could release significant amounts of carbon to the atmosphere over the next 50-100 years – simultaneous with efforts to harness CO_2 emissions. It is important to remember that, at the landscape level over the long term, disturbance does not cause a net loss of forest carbon…as long as the forest regenerates. But if the frequency and/or severity of disturbance increase substantially, long-term carbon storage at the landscape scale *will* be reduced because the fraction of the landscape with large, older trees (that have high carbon stores) will decline. Climate change could also increase soil decomposition, leading to carbon losses from a part of the ecosystem that we consider to be relatively stable and that contains about 40% of the total carbon in U.S. forests.

The largest risk to carbon storage from disturbance is that the forest may not regenerate and instead be replaced by a meadow or shrubland ecosystem, losing much carbon in the process. As a result of past fire suppression, we see this happening currently in the western U.S. as high-severity fires occur in ecosystems that are adapted to low-severity fire regimes. Although actions are being taken to reduce the fire risk, the carbon-related effects are currently unknown. Climate change may also increase the likelihood that forests will not regenerate sufficiently since highly adapted species and genotypes may have a difficult time growing under altered climatic conditions.

Conclusions and Recommendations

U.S. forests and forest products currently offset 12-19% of U.S. fossil fuel emissions, largely owing to recovery from past deforestation and extensive harvesting. Increased nitrogen deposition and atmospheric CO_2 compared to historical levels may also be contributing to increased forest growth, but the science supporting their contribution is uncertain because of a limited number of experiments and the difficulty in assessing change over the diverse forests of the U.S.

How long will U.S. forests remain a carbon sink? Since 1940, forest regrowth in the U.S.

has recovered about a third of the carbon lost to the atmosphere through the deforestation and harvesting that occurred from 1700-1935 (Figure 13). To recover the remaining two-thirds of the carbon that was lost would require reestablishing forests in a significant portion of what is now agriculture and pasture land. However, reforesting this part of the U.S. (almost all land east of the Mississippi) is not feasible from an economic and food-security perspective. Today's recovery from the forest clearing and wood-based economy of the 1800s and early 1900s will likely sustain carbon storage rates at the current rate for decades, but not indefinitely.

But, forest carbon storage only gets us part of the way. Even under the best scenarios, the amount of carbon storage potential is finite. Strategies that combine increased use of forest products to offset fossil fuel use (such as use of biomass energy and substitution), in conjunction with increasing carbon storage on forested landscapes, are likely to produce the most sustainable forest carbon benefits.

Every strategy we examined has tradeoffs. Avoiding deforestation and increasing the harvest interval in the U.S. may move timber production elsewhere, resulting in no net benefit for carbon in the atmosphere. Reestablishing forests has great potential but will also displace current land uses such as farming and pasture. Increasing forest product use and forest biomass energy will require more active forest management over larger areas than currently occurs and may lower forest carbon stores. Intensive silviculture can increase growth, but decrease streamflow and biodiversity. Forest products in landfills increase carbon storage, but the resulting methane emissions pose a problem. A better use for waste material, therefore, is energy production. Recognizing these tradeoffs will be vital to any effort to promote forest carbon.

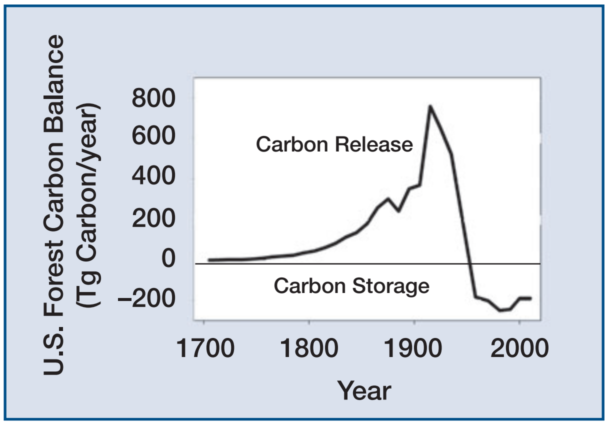


Figure 13. The carbon balance of the U.S. forest sector shows that clearing for agriculture, pasture, development, and wood use released ~42,000 Tg of carbon from 1700 to 1935, and recovered about 15,000 Tg of carbon from 1935-2010. (Used with permission, from Journal of Environmental Quality 35:1461-1469 (2006))

Because forest carbon loss poses a significant climate risk and because climate change may impede regeneration following disturbance, avoiding forest loss and promoting regeneration after disturbance should receive high priority as policy considerations. Forest loss moves a large portion of the carbon sequestered in forests into the atmosphere, particularly where the loss includes not only trees but also the decomposition of soil carbon. Because of climate change, increasing threats from disturbance, and continued population growth and resulting exurban development, we cannot assume that all existing forests will remain. Because there is a high likelihood that climatic patterns will shift and the frequency of disturbances will increase – potentially making existing tree species less suited to their environment – it would be prudent to focus on regeneration after disturbance to help ensure maintenance of forests.

The various strategies for storing carbon in forests have different associated risks and levels of uncertainty. Retaining forests (which also includes regenerating after disturbance) and afforestation both involve low levels of uncertainty regarding carbon consequences and therefore low risk to carbon storage – aside from the risks of carbon loss in disturbance or that the deforestation will simply happen elsewhere. The carbon benefits of using biomass energy and long-lived forest products are also fairly certain, as long as forests regenerate. Lengthening harvest intervals involves a bit more risk because disturbance would occur in forests with higher carbon stores and because decision-makers can change harvest intensity quickly relative to forest growth.

Regardless of the risks and uncertainties, any policy to encourage forest carbon storage should: 1) promote the retention of existing forests; 2) account for other greenhouse gas effects, such as methane and nitrous oxide emissions and biophysical changes; 3) account for harvest moving elsewhere indirectly caused by changes in management with the project boundary; 4) recognize other environmental benefits of forests, such as biodiversity, nutrient management, and watershed protection; 5) focus on the most robust and certain carbon storage benefits in any compensation scheme; 6) recognize the difficulty and expense of tracking forest carbon, the cyclical nature of forest growth and regrowth, and the extensive movement of forest products globally; 7) recognize that the value of any carbon credit will depend on how well the carbon can be measured and verified; 8) acknowledge that climate change and population growth will increase the potential for forest loss and may keep large-scale projects from reaching their full potential; 9) recognize the tradeoffs; and 10) understand that the success of any carbon mitigation strategy depends on human behavior and technological advances in addition to forest biology. Finally, because CO_2 remains in the atmosphere for more than 100 years, any action to avoid further emissions should be undertaken as soon as possible.

Few forests are managed solely for carbon – rather, carbon storage serves as a co-benefit that accompanies or perhaps helps pay for other ecosystem services provided by forests (Box 2). As we have discussed above, elevating carbon storage to the primary focus of management could potentially impede the other co-benefits of forests. A focus on carbon storage to the detriment of other ecosystem services would be short-sighted.

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