MANAGING FORESTS FOR CARBON MITIGATION

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Introduction

The role of forests in carbon and climate mitigation may seem to be very straightforward. Since trees capture carbon as they grow and forests store massive quantities of it, it is easy to conclude that trees and forests should be treated as carbon sinks and left alone. But this kind of thinking reflects an incomplete understanding of the role of forests in carbon mitigation. In reality, forests have multiple roles to play in carbon mitigation, and forest management can help to optimize those roles. A new report from the Society of American Foresters,[1] based on an extensive review of numerous recent studies of forest carbon relationships, shows that a policy of active and responsible forest management is more effective in capturing and storing atmospheric carbon than a policy of hands-off management that precludes periodic harvests and use of wood products.

While acknowledging that forests have a myriad of values and that it is not appropriate to manage every forested acre with a sole focus on carbon mitigation, the report's authors conclude that national environmental and energy policies need to be based upon a shared understanding of forest carbon benefits. The research identifies four basic premises to establishing effective policies:

1. Energy produced from forest biomass returns carbon to the atmosphere that plants absorbed in the relatively recent past. It essentially results in no net release of carbon as long as overall forest inventories are stable or increasing (as is the case with forests in the United States).

2. Energy derived from burning fossil fuels releases carbon that has resided in the Earth for millions of years, effectively creating a one-way flow to the atmosphere. Whether emissions from fossil fuel combustion are ultimately taken up by land, ocean or forests, they are not returned to fossil fuel reserves on anything less than a geologic time scale.

3. Wood products used in place of more energy-intensive materials, such as metals, concrete, and plastic reduce carbon emissions, store carbon, and can provide additional biomass that can be substituted for fossil fuels to produce energy.

4. Sustainably managed forests can provide greater carbon mitigation benefits than unmanaged forests, while delivering a wide range of environmental and social benefits including timber and biomass resources, jobs and economic opportunities, clean water, wildlife habitat, and recreation.

The report emphasizes that a rational energy and environmental policy framework must be based on the premise that atmospheric greenhouse gas levels are increasing primarily because of the addition of geologic fossil fuel–based carbon into the carbon cycle. Findings indicate that forest

[1] Malmsheimer, R.W., J.L. Bowyer, J.S. Fried, E. Gee, R.L. Izlar, R.A. Miner, I.A. Munn, E. Oneil, and W.C. Stewart..2011. Managing Forests Because Carbon Matters: Integrating Energy, Products, and Land Management Policy. *Journal of Forestry* 109(7S):S5-S48, October/November.

carbon policy that builds on accumulated scientific knowledge can be an important part of a comprehensive energy policy that reduces fossil fuel consumption and provides carbon mitigation benefits while also delivering a full range of environmental and social benefits, including clean water, wildlife habitat, and recreation. This report provides a summary of the analysis completed by the Society of American Foresters and of the related research reviewed by report authors.

Forest Carbon Stocks and Flows

Forest Carbon Dynamics

About one-half the dry weight of wood is carbon. Carbon is also contained in the bark, branches, roots, and leaves of trees, and within forest litter and soils. In the growth process trees capture carbon dioxide from the atmosphere, combine it with water drawn from the ground, and produce sugars that are then converted into wood. Oxygen is released as a by-product.

Not all the carbon captured by trees ends up as long-term stored carbon. Approximately three-fourths of the carbon fixed by photosynthesis is released through ecosystem respiration. [2] In forests, about half of the respiration comes from the above-ground vegetation and half from the forest floor and forest soils. The amount of forest floor and soil respiration is proportional to how much woody debris is decomposing on site.

Forests do not accumulate carbon indefinitely. The process of forest renewal and tree growth, competition, aging, and death is ongoing. Eventually, all trees die, and when they do, their carbon moves into other pools (e.g., dead wood, soil, products, atmosphere).

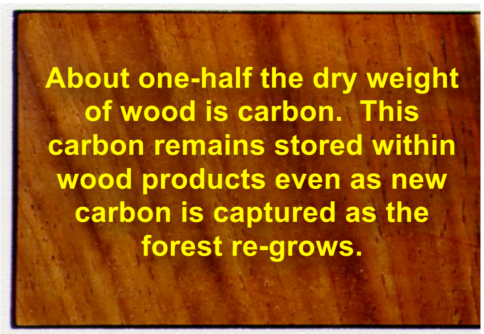
As forests grow they accumulate carbon, and large quantities of it, providing substantial climate benefits. For instance, the rate of net carbon accumulation on highly productive lands in California averages almost 0.6 tons of carbon/acre/year (Fried 2010). However, forests do not accumulate carbon indefinitely. As the average age of trees in forests increases, both carbon inventories and carbon losses to mortality increase (Stinson et al. 2011). Carbon losses from disturbances also accrue over time and are accentuated as live biomass is converted to dead biomass that then slowly releases carbon dioxide as decay occurs. Eventually, all trees die, and when they do, their carbon moves into other pools (e.g., dead wood, soil, products, atmosphere).

The process of tree growth, competition, aging, and death is ongoing. Growing trees compete with one another for light, water, and nutrients. Over time competition between them intensifies, and some die while others thrive. With increasing age the rates of growth and carbon capture slow, and net carbon storage may even decline as a result of increasing natural mortality. Growth declines are inevitable as gross primary productivity[3] is reduced by nutrient and other resource limitations, and carbon allocations shift from wood production to respiration (Ryan et al. 2004). Carbon storage decline in forest stands generally begins at 100 to 150 years of age as tree mortality losses increase, although there is variability among species and disturbance intervals.

[2] Respiration is a process whereby plants and micro-organisms breakdown carbon-containing compounds that results in the release of carbon dioxide.

[3] Gross primary productivity is a measure of the total assimilation of energy and nutrients by an organism or a plant community per unit of time.

In Swiss alpine forests storage capacity has been found to peak at about 100 years, after which forests become net emitters of carbon (Schmid et al. 2006). In contrast, 190-year-old and older ponderosa pine forests in central Oregon were found to still be accumulating carbon, although slowly (Law et al. 2003); this study found that some 85% of the woody biomass-based carbon storage in ponderosa pine was in stands older than 100 years, but that there is significant risk of carbon loss from wildfire in these stands. Alaska's Tongass National Forest, where fire is unlikely, holds 8% of the forest carbon in the United States but is approaching a state of no additional carbon sequestration because carbon emissions via microbial respiration nearly equals newly sequestered carbon via photosynthesis (Leighty et al. 2006).



Carbon is stored in the main stems, branches, bark, and roots of trees, in forest litter, and in the shallow and deep soils. Carbon makes up a considerable proportion of wood volume, amounting to about 50% of the moisture-free weight. In 2005–2010, some 24 to 25 billion metric tonnes (t) of carbon were stored in standing trees, forest litter, and other woody debris in U.S. forests, and another 20 to 21 billion t were stored in forest soils and roots (U.S. EPA 2011).

Soil carbon exists in two forms. Organic soil carbon occurs in the topmost layers and represents about 1% to 12% of forest soil carbon (Schlesinger 1997; Fisher et al. 2000; Sollins et al. 2006). Mineral-associated carbon exists at greater depths, accounting for about 90% of all soil carbon, and has the longest residence time (Gaudinski et al. 2000; Fisher et al. 2000; Jobbagy et al. 2000). Mineral-associated carbon can have residence times of hundreds to thousands of years, with carbon in the deep soil (below 1 meter) having the longest residency (Gaudinski et al. 2000; Trumbore 2000).

Natural Disturbance and Forest Carbon

Forests of all types are subject to natural effects of wildfire, windstorms, ice storms, insect and disease infestations, and decay which follows tree aging and death. Average tree age, diameter and forest stocking levels have been increasing nationwide for a number of years. While this forest growth is impressive, the downside of this trend is the resulting rise in natural mortality – a natural consequence of increasing age. These conditions have increased the probabilities of catastrophic losses. In the American West, fire and insects pose a very immediate threat of catastrophic loss of live tree carbon, potentially turning affected forests into carbon emitters.

Fire can be a major cause of carbon loss from forests, but the magnitude of loss depends on fire severity. On time scales relevant to forest carbon offsets, fires can release massive quantities of carbon, adding significant uncertainty to projections of carbon storage (Wiedinmyer and Neff 2007). Intense, stand-replacing fires in heavily stocked forests release a substantial proportion of the carbon stored above-ground, and can be so severe that substantial soil carbon stores are lost and soil structure and nutrient capital destroyed. In part because of a century of fire suppression combined with climatic factors (Littell et al. 2009; McKenzie et al. 2004, 2008), fire is now the dominant disturbance agent in most of the West and is important to consider in virtually every forest management strategy. Even in wet forests along the Pacific coast, areas not normally subject to catastrophic fire events, intense fires have occurred.

Although high-severity wildfire can release significant amounts of carbon from soil pools, the loss can be reduced through well-designed fuel reduction programs based on thinning and prescribed fire. Stephens et al. (2009) accounted for storage in harvested wood products and documented emissions from prescribed fire, thinning treatments, and a combination of both, with and without a subsequent fire. They found that thinning treatments produced fewer emissions than under a non-management strategy for almost any plausible assumption of fire probability, and that the effectiveness of thinning/prescribed fire combinations in reducing carbon emissions increased as the likelihood of fire increased.

Low-severity wildfires and prescribed fires have little effect on soil carbon and may even increase mineral soil carbon through deposition and mixing of partially burned or residual organic matter into the surface mineral soil (Johnson and Curtis 2001; Hatten et al. 2005; Hatten et al. 2008). Conversely, high-severity wildfire decreases soil carbon stocks by 10% to 60% (Baird et al. 1999; Hatten et al. 2008; Bormann et al. 2008). Recovery rates after moderate- to high-severity fire may be similar to a post-harvest scenario, provided soil productivity is not damaged.

Mortality wrought by insects and disease can rival that of fire and is a significant factor in carbon emissions over time in forests across the United States. These agents tend not to reduce dead biomass and soil carbon pools (as does fire). For example, bark beetle outbreaks generate considerable quantities of dead wood but may cause no change in soil respiration rates (Morehouse et al. 2008). The effect of insects and disease on forest carbon over time depends in large part on whether the agent attacks all the tree species in a stand or only a few. As long as unaffected trees are present in significant numbers, the leaf area and growth potential of the site "transfers" to the surviving trees – at least some of the surviving trees claim access to the growing space vacated by trees that succumb. If the dead-tree carbon can be recovered, via salvage harvest for wood products or energy, the effect on stand carbon trajectories would be similar to the effects of a thinning. However, if a stand is a monoculture or an agent attacks all tree species, reversals in carbon storage may be significant, especially if salvage through harvesting is not an option. Some agents, including exotic invasive pests, may have the potential to prevent certain tree species from becoming reestablished at a site. This can represent a longer-term impact, essentially changing the capacity of a site to store carbon unless alternative species with equivalent growth potential are available.

Carbon Implications of Forest Harvesting

Harvesting and Forest/Forest Products Carbon Pools

It is a simple fact that harvesting removes carbon from forests. Despite the near-term impact on forest carbon stores, there are clear benefits of sustainable forest management. Forest management done responsibly helps to:

- prevent overstocking and reduce risks of catastrophic fire, disease, and insect infestation thereby protecting the long-term carbon storage capacity of forests;
- capture a portion of what would otherwise be natural mortality and associated release of carbon;
- create new carbon pools within long-lived forest products; and

- avoid substantial fossil carbon emissions when wood is used in place of high energy intensity products and materials, or when used as a source of energy in place of fossil fuels.

Forests managed so as to optimize carbon benefits are typically of younger average age than unmanaged forests. These forests sequester carbon rapidly and are managed so as to reduce and capture mortality. Over-crowding and high natural mortality are avoided through thinning, a practice that also enhances growth of remaining trees. Older forests tend to have higher carbon densities than younger forests, but low or near-zero rates of additional carbon sequestration as they reach maturity.

In the United States forest cover has increased and net growth has exceeded removals for more than 70 continuous years, translating to increasing carbon stocks.

Temperate forests worldwide continue to expand as carbon sinks even though large quantities of wood products are removed from these forests annually. The quantity of carbon stored within forest products is continuing to increase as well. In the United States forest cover has increased and net growth has exceeded removals and mortality for more than 70 continuous years, which has resulted in increasing carbon stocks, despite the removal of over 850 *billion* cubic feet of timber during that time frame. The current rate of carbon accumulation in temperate forests may decline, however, if the average age of the forest continues to increase.

The rate of net carbon accumulation in U.S. forests during the period 2005–2007 is estimated to have been 220 million metric tons per year. In addition, carbon continues to accumulate in harvested wood products pools. The annual rate of carbon accumulation within wood products in use and in landfills was estimated at about 28 to 29 million tons during the same 2005-2007 period. This rate of storage in products equates to 12-13% of the rate of sequestration within forests, and 20- 21% of the annual additions to non-soil forest carbon stocks (U.S. EPA 2011). Rates of accumulation in harvested wood products were notably lower in 2008–2010 because of the sharp decrease in overall economic activity and home construction.

Carbon within wood products is stored for the life of the product. Carbon is stored in the structure of homes and other wooden buildings, within furniture, and within a myriad of other long-lived products that contain wood. Across the whole United States, carbon removed from the atmosphere by forest growth or stored in harvested wood products each year is equal to 12% to 19% of annual fossil fuel emissions (Ryan et al. 2010; U.S. EPA 2010).

Harvesting and Soil Carbon

The effect of harvesting and replanting on soil carbon is difficult to generalize, as much depends on the initial soil depth, the depth to which soil is sampled, and the strategies employed following harvesting to replenish the forest. Harvesting and thinning alter soil carbon cycling by altering the supply of root and litter inputs, disturbing the soil surface, and changing temperature and moisture regimes. These changes all tend to increase respiration rates; however, they also move some forest floor carbon into deeper, mineral soil layers. Measured effects tend to be slight in the short term, with carbon decreases concentrated in the forest floor and near the soil surface. On the other hand, harvesting appears to add to mineral carbon stores or to not affect them.

A few meta-analyses and review papers conclude that the net effect of harvest is a reduction in soil carbon, with forest and soil type determining the magnitude of carbon loss (Johnson and Curtis 2001; Jandl et al. 2007; Nave et al. 2010). Johnson and Curtis, for example, reviewed 26 studies of the impacts of forest harvesting on soil carbon, concluding that forest harvesting, on average, had little or no effect on soil carbon and nitrogen. Jandl et. al. (2007) confirmed harvest-related losses of carbon from the organic (upper) layers of soil, but also found that carbon storage capacity within deep soils can be enhanced by increasing forest productivity. Nave et al. (2010), after a review of 432 reported responses of soil carbon to harvesting in temperate forests worldwide reported an 8% average reduction in soil carbon stocks after harvesting, over all forest and soil types studied, noting that the forest floor was the only soil layer to show an overall, significant change in C storage following harvest. They also reported an average increase in deep mineral soil concentrations of 19%. One study found that even whole-tree harvesting for biomass production has little long-term effect on soil carbon stocks if surface soil layers containing organic material are left on site, nutrients are managed, and the site is allowed to regenerate (Powers et al. 2005). Forest thinning and competition control have a much smaller disturbance on soil characteristics and therefore affect soil carbon stocks less.

The impacts of forest harvesting on soil carbon can be different in old forests. Heavy or stand replacement harvesting has been shown to release a great deal of carbon in high-volume old-growth stands where catastrophic losses are unlikely. So much carbon can be released that it may take decades before the new stand demonstrates greater net uptake of carbon than if the old-growth had been left alone (Janisch and Harmon 2002). Such stands, which are found almost exclusively on public lands, are rarely harvested or even actively managed in the United States today. In old forests where catastrophic losses are likely (e.g., in drier forest types where fire or insects cause disturbance and mortality) the carbon calculations are different. In this case, active management can provide carbon benefits.

It is important to recognize that forests are living and dynamic systems that undergo change with or without management. Choosing not to manage has its own carbon consequences.

Reducing tree density and carbon stocks in forests managed for commercial products decreases risks. Management can address the risk of financial and carbon losses due to episodic disturbances, such as wildfires or severe storms. At the same time, management results in increasing carbon storage within wood products. On the other hand, a no-harvest strategy focused on increasing forest stocks can increase the volume of carbon stored in the forest in the near-term. However, a no-harvest strategy can mean missed opportunities for greater carbon mitigation over the longer-term, and also increase the risk of loss. It is important to recognize that forests are living and dynamic systems that undergo change with or without management. Choosing not to manage has its own carbon consequences.

Forest Products, Bioenergy, and the Substitution Effect

Building Products Manufacture and Use

Forests store carbon, and so do wood products. Evaluations of carbon flows show that conversion of wood to useful products can significantly reduce overall societal carbon emissions. To understand the overall forest sector impact on atmospheric carbon, a clear understanding of material and energy flows is needed. Thorough analysis shows that sustainably managed forests can provide a steady flow of forest products, which when substituted for energy intensive and fossil fuel intensive products can help to offset the flow of carbon dioxide from fossil carbon reserves to the atmosphere.

A key factor in the carbon benefits of forest products is that they have lower embodied energy (the amount of energy it takes to make products) than comparable products. The manufacture of forest products is also far less reliant on fossil fuels than other products because forest industries generate much of their energy needs from biomass. As a result, there is a beneficial substitution effect when wood is used in place of other types of building materials. This substitution results in: 1) the consumption of significantly less energy, and considerably less fossil energy, and 2) lower emissions of carbon, and particularly fossil carbon. The magnitude of the substitution effect varies by use and product, but on average every 1 ton of wood used avoids the addition of 2.1 tons of carbon (or 7.7 tons of carbon dioxide) to the atmosphere.

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The following table (Table 1) is based on a life cycle inventory[4] comparing the construction of two functionally equivalent wall systems (Edmonds and Lippke 2004). The data illustrates the substitution effect. Shown is consumption of fossil fuels associated with exterior wall designs in a warm-climate (Atlanta area) single family dwelling beginning with raw material extraction and through construction. In this case using concrete, rather than lumber, for construction of the exterior walls of a home results in consumption of 2.5 times the fossil fuel energy and even greater increases in emissions of fossil carbon than when using lumber. The substitution effect of using concrete, rather than wood, can be quantified as a 38 percent increase in total energy consumption, a 150 percent increase in fossil fuel consumption, and greater than 150 percent increases in fossil carbon emissions.

[4] A life cycle analysis begins with a careful accounting of all the measurable raw material inputs (including energy), product and co-product outputs, and emissions to air, water, and land; this part of an LCA is called a life cycle inventory (LCI).

Table 1
Consumption of Fossil Fuel Energy in Production of Exterior Wall Systems in a Warm-Climate Home in the U.S. Southeast

	Fossil fuel energy (MJ/ft^2)	
	Lumber-framed wall	*Concrete wall*
Structural components[a]	6.27	75.89
Insulation[b]	8.51	8.51
Cladding[c]	22.31	8.09
Total[d]	37.09	92.49

[a] Includes studs and plywood sheathing for the lumber-framed wall design and concrete blocks and studs (used in a furred-out wood stud wall) for the concrete wall design.
[b] Includes fiberglass and six-mil polyethylene vapor barrier for both designs.
[c] Includes interior and exterior wall coverings. Exterior wall coverings are vinyl (lumber-framed wall design) and stucco (concrete wall design). Interior wall coverings are gypsum for both designs.
[d] Includes subtotals from structural, insulation, and cladding categories.

Similar studies have compared other building materials. In comparisons of wood with steel framing with an average recycled content, the manufacture of wood framing has been found to require one-half or less of the total energy, and one-fourth to one-fifth the fossil energy. Similar results are obtained when comparing wood, concrete, aluminum, and plastics. Consequently, there are large differences in emissions of fossil carbon associated with these various materials, with substantially lower carbon emissions linked to production of wood building products than potential substitutes. In addition, the large quantity of carbon stored within wood also sets this material apart from potential substitutes. No other common building material comes close to having the carbon storage capacity of wood.

Energy from Wood

There are direct carbon benefits to the substitution of woody biomass for fossil fuel energy. When the use of fossil fuels is avoided, a greenhouse gas offset occurs when the fossil fuel and associated carbon remains underground and the flow of fossil carbon to the atmosphere is reduced.

Bioenergy (heat and electrical power) production from wood is attractive since only a small amount of fossil fuel is needed to produce bioenergy. Approximately one unit of fossil fuel is needed for every 25 to 50 units of bioenergy (Matthews and Robertson 2005; Börjesson 1996; Boman and Turnbull 1997; McLaughlin and Walsh 1998; Matthews and Mortimer 2000; Malkki and Virtanen 2003). Net carbon emissions from the generation of a unit of electricity from biomass can be 10 to 30+ times lower than emissions from fossil-based electricity generation, depending on the systems and fuel types being compared (Cherubini et al. 2009; Mathews and Robertson 2005; Boman and Turnbull 1997; Mann and Spath 2001; Matthews and Mortimer 2000).

Although energy self-sufficiency is one reason for pursuing the development of woody biomass-to-energy initiatives (EISA 2007), there are other reasons to use woody biomass as an energy source. In the West, wildfire risk is high and increasing, and removing excess biomass to reduce risks is desirable in many cases. Reduction of fire risks while maintaining other forest values often entails removing low-value biomass from the forest, a practice that promotes growth of higher-value trees for multiple benefits. Without a market for biomass (i.e., for bioenergy and biofuel) the costs of fire risk reduction are prohibitive, reducing greatly the likelihood of action.

Potential advantages notwithstanding, there are concerns that if too many bioenergy and biofuel plants are established, they will not be sustainable over the long run. In response, several states, such as Minnesota, Wisconsin, and Pennsylvania have developed woody biomass removal guidelines to ensure that bioenergy plants can operate sustainably, meeting long-term environmental, ecological and economic needs. Forest certification programs which are widely used in the U.S. provide similar management protocols for fuel harvests.

There can be environmental trade-offs involved in removing harvest residuals where the residuals have value in maintaining site productivity and biodiversity. Studies suggest that the productivity of most sites is largely resilient to removal of harvesting residuals. Documentation of negative effects on site productivity due to biomass removal is rare. However, studies also consistently show neutral or positive impacts on species diversity from forest thinning due to increased structural complexity, but lower abundance of cavity- and open-nesting birds and invertebrates following removal of large quantities of downed coarse woody debris and/or standing snags (Riffell et al. 2011). Effects of harvesting coarse and particularly fine woody debris on other taxa do not appear to be great, although there have been few studies of these practices (Riffell et al. 2011). These results indicate the need for care in the planning and execution of biomass removal.

All things considered, the available supply of biomass for energy, including forestry biomass, depends upon a number of factors. The total amount that is physically available may be limited by environmental, economic, and policy considerations. Even ambiguity in policy language may limit supply; for instance, current federal policy that contains numerous and often conflicting definitions of biomass appears to be hindering policy implementation and development of biomass markets. On the other side of the biomass supply equation, supplies may be increased by continued investments in forest productivity and declining use of traditional forest products. Overriding all of these factors will be preferences of forest landowners who are motivated by both economic reality and sustainability considerations.

Forest Carbon Policies

At the national level, increasing net carbon sequestration rates in forests, using wood products rather than fossil fuel–intensive products, and using forest residues for energy will reduce greenhouse gas (GHG) emissions. While some project-based carbon accounting rules consider the volume of carbon in harvested wood products, none at this point account for avoided emissions through the substitution effect. Unfortunately, rules that ignore or undercount benefits and risks can result in conclusions that encourage less than optimum carbon mitigation practices.

Forestry offset protocols have been created to serve different purposes. Some were created as part of cap-and-trade programs, either mandatory or voluntary, or as part of emissions reduction programs. Others were developed independently but have since been adopted by others. Although the concept of offsets is the same, the number of carbon credits generated for the same project can differ dramatically depending upon the sets of carbon pools allowed and the baseline approach employed.

Forestry offset projects generally can be classified as afforestation, reforestation, forest management, forest conservation, or forest preservation. The estimates of net climate benefits from forest management, conservation, or preservation projects depend largely on the assumptions about the carbon storage and substitution benefits of wood products; this is less true for afforestation and reforestation projects. For an offset project to have any effect on net GHG emissions to the atmosphere, the net amount of carbon sequestered must be additional to what would have occurred anyway. For forest projects, additionality is relatively easy to establish when new trees are planted and maintained but considerably more difficult to demonstrate when based on what did not or will not happen (e.g., "I was going to harvest in 10 years but instead will wait 30 years"). If forest carbon credits are used to permanently offset industrial emissions, a forest project must demonstrate permanence by ensuring that initial emissions are balanced by an equivalent amount of new carbon storage over time. However, strict project-level guarantees or insurance increase the cost of forest carbon credits. Also, U.S. forestry projects that increase in-forest carbon sequestration through a short-term reduction in harvests may have national market leakage rates that approach 100% (i.e., virtually all of the reduction in harvest will simply be shifted elsewhere) if harvests from non-project forests are used to meet consumer demand.

> **"In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit."**
>
> *Intergovernmental Panel on Climate Change, Fourth Assessment Report (2007)*

Carbon accounting protocols differ greatly in their requirements for monitoring and verification, carbon measurement, and third-party certification. For instance, when six different forest carbon protocols were applied to the same southern pine plantation by Galik et al. (2009), break-even carbon prices ($/t$CO_2$e) had a 20-fold range depending on a given protocol's rules about baseline values, reversals, leakage, and uncertainty. Thus, there is significant potential for confusion, variability, and even fraud in carbon accounting. Moreover, transaction costs per unit of land were found to also vary substantially, by as much as a factor of five.

The measurement challenges and relatively high transaction costs inherent in forest carbon offset systems motivate consideration of other policies that can promote climate benefits from forests without requiring project-specific accounting. For example, market prices for building and energy products that reflect emissions, economic incentives for tree planting, and credible information disclosure on the relative climate impacts of different products could prove more effective at a national scale. This is essentially what was suggested by the Intergovernmental Panel on Climate Change in their Fourth Assessment Report (IPCC 2007): "In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit."

Summary

Forests are an integral component of the global carbon cycle and may change in response to climate change. U.S. forest policies can foster responsible management actions that will provide measurable reductions in carbon emissions over time while maintaining forests for environmental protection and societal benefits, such as timber and non-timber forest products, vibrant rural communities, clean water, and wildlife habitat. Founded on the four premises outlined in the introduction of this report, the essential policy recommendations are:

1. **Keep forests as forests and manage appropriate forests for carbon.**

   Forests provide substantial carbon benefits and retention of forested land is therefore an important component of any carbon mitigation strategy. Active management is also important so as to capture the greatest carbon mitigation potential. Forests undergo change with or without management, and choosing not to manage has its own carbon consequences. Young, healthy forests are carbon sinks. As forests mature, they generally become carbon-cycle neutral or even carbon emission sources because net primary productivity declines, natural mortality increases, and the probability of massive carbon loss increases over time. If a forest is unmanaged, decay of trees killed by natural disturbances—windstorms, fire, ice storms, hurricanes, insect and disease infestations—emits carbon without providing the carbon benefits available through product and energy substitution.

2. **Recognize that substantial quantities of carbon are stored in wood products for long periods of time.**

   Wood is one-half carbon by weight, and it lasts a long time in service—and often for a long time after being retired from service. Placing wood into long term use adds to carbon pools outside the forest, leveraging the carbon capturing ability of forests.

3. **The substitution effect is immediate, irreversible, and cumulative and should be recognized in development of policy instruments.**

   Compared with products made of non-renewable materials, wood products require vastly less fossil fuel–derived energy to produce. As a consequence, when wood products from sustainable managed forests are appropriately substituted for energy intensive alternatives there are very substantial carbon benefits that accumulate over time. The substitution effect similarly applies to production of energy from biomass rather than from fossil fuels.

4. **It is imperative in policy development that objective, science-based analyses are used, that holistic thinking that encompasses the full suite of options in forest management be employed, and that particularly close attention be paid to assumptions and models underlying analyses.**

   Conserving forests for recreational, aesthetic, and wildlife habitat goals has been a strong policy driver in the United States in recent decades. Evidence of increasing losses to disturbances and decreasing rates of carbon accumulation in maturing forests, particularly in the western U.S., suggests that a strategy that precludes management may not produce intended global climate benefits. In assessing policy options, it is important to recognize that tracking the allocation of forest carbon across live and dead trees, understory shrub and herbaceous vegetation, soils, the forest floor, forest litter, harvested wood products, and energy wood is far more difficult than conducting traditional inventories of commercially valuable wood volume. Understanding the dynamics of these allocations, how they are affected by stand age, density, and management, and how they will evolve with climate change is fundamental to fostering the capacity for sustainably managed forests to remove carbon dioxide (CO_2) from the atmosphere.

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