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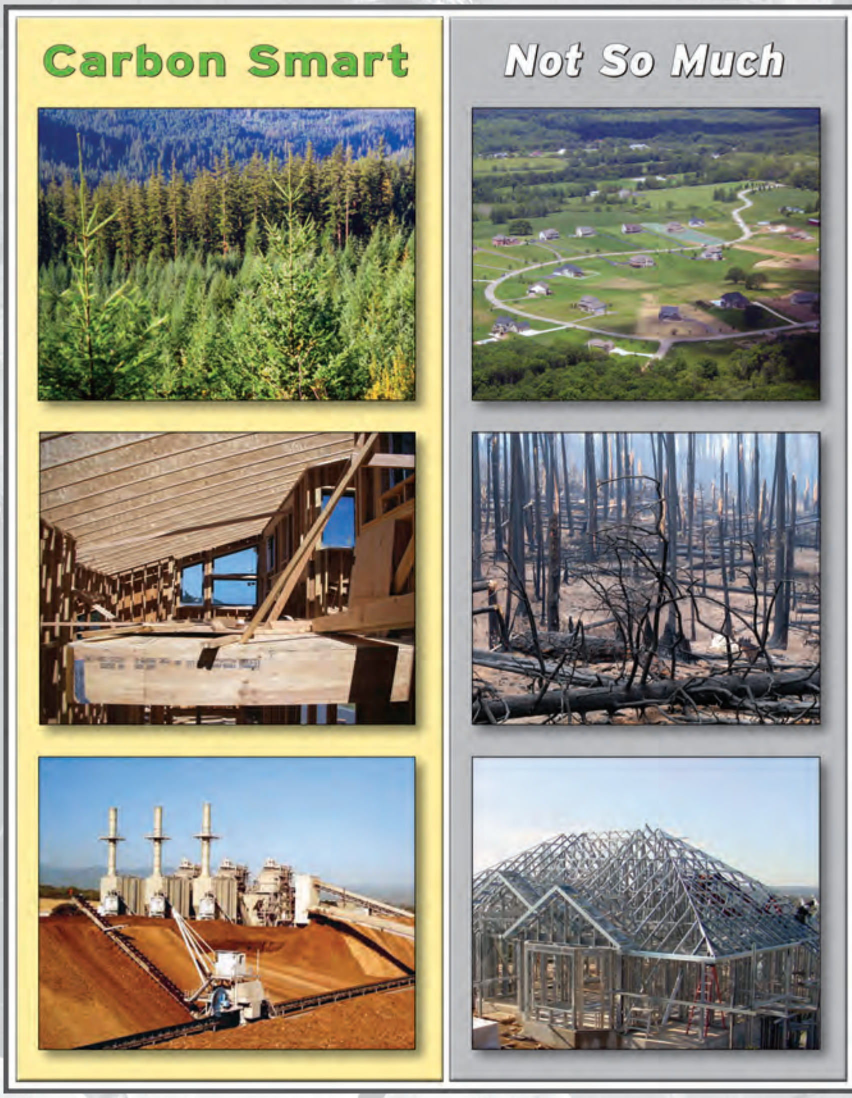

Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy

A Society of American Foresters Task Force Report

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SAF Mission
The Society of American Foresters (SAF) is the national scientific and educational organization representing the forestry profession in the United States. Founded in 1900 by Gifford Pinchot, it is the largest professional society for foresters in the world. The mission of the Society of American Foresters is to advance the science, education, technology, and practice of forestry; to enhance the competency of its members; to establish professional excellence; and, to use the knowledge, skills, and conservation ethic of the profession to ensure the continued health and use of forest ecosystems and the present and future availability of forest resources to benefit society. SAF is a nonprofit organization meeting the requirements of 501 (c) (3). SAF members include natural resource professionals in public and private settings, researchers, CEOs, administrators, educators, and students.

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1. Forests are a fundamental source of global health and human welfare,
2. Forests must be sustained through simultaneously meeting environmental, economic, and community aspirations and needs,
3. Foresters are dedicated to sound forest management and conservation, and
4. Foresters serve landowners and society by providing sound knowledge and professional management skills.

conclusion

DEPARTMENTS

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JoF Journal of FORESTRY

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Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy

Robert W. Malmsheimer, James L. Bowyer, Jeremy S. Fried, Edmund Gee, Robert L. Izlar, Reid A. Miner, Ian A. Munn, Elaine Oneil, and William C. Stewart

ABSTRACT

The United States needs many different types of forests: some managed for wood products plus other benefits, and some managed for nonconsumptive uses and benefits. The objective of reducing global greenhouse gases (GHG) requires increasing carbon storage in pools other than the atmosphere. Growing more forests and keeping forests as forests are only part of the solution, because focusing solely on the sequestration benefits of the forests misses the important (and substantial) carbon storage and substitution GHG benefits of harvested forest products, as well as other benefits of active forest management.

Forests and global climate are closely linked in terms of carbon storage and releases, water fluxes from the soil and into the atmosphere, and solar energy capture. Understanding how carbon dynamics are affected by stand age, density, and management and will evolve with climate change is fundamental to exploiting the capacity for sustainably managed forests to remove carbon dioxide from the atmosphere. For example, even though temperate forests continue to be carbon sinks, in western North America forest fires and tree mortality from insects are converting some forests into net carbon sources.

Expanding forest biomass use for biofuels and energy generation will compete with traditional forest products, but it may also produce benefits through competition and market efficiency. Short-rotation woody crops, as well as landowners' preferences—based on investment-return expectations and environmental considerations, both of which will be affected by energy and environmental policies—have the potential to increase biomass supply.

Unlike metals, concrete, and plastic, forest products store atmospheric carbon and have low embodied energy (the amount of energy it takes to make products), so there is a substitution effect when wood is used in place of other building materials. Wood used for energy production also provides substitution benefits by reducing the flow of fossil fuel–based carbon emissions to the atmosphere.

The value of carbon credits generated by forest carbon offset projects differs dramatically, depending on the sets of carbon pools allowed by the protocol and baseline employed. The costs associated with establishing and maintaining offset projects depend largely on the protocols' specifics. Measurement challenges and relatively high transaction costs needed for forest carbon offsets warrant consideration of other policies that promote climate benefits from forests and forest products but do not require project-specific accounting.

Policies can foster changes in forest management and product manufacture that reduce carbon emissions over time while maintaining forests for environmental and societal benefits. US policymakers should take to heart the finding of the Intergovernmental Panel on Climate Change in its Fourth Assessment Report when it concluded that "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." 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. Forest carbon policy that builds on the scientific information summarized in this article can be a significant and important part of a comprehensive energy policy that provides for energy independence and carbon benefits while simultaneously providing clean water, wildlife habitat, recreation, and other uses and values.

Keywords: forest management, forest policy, forest carbon dynamics, carbon accounting, carbon offsets, life cycle assessment, building products substitution, bioenergy

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Preface

Forest Management Solutions for Mitigating Climate Change in the United States (Malmsheimer et al. 2008), by the Climate Change and Carbon Sequestration Task Force of the Society of American Foresters (SAF), evaluated the implications of global climate change for forests and addressed the role of forestry and forests in mitigating climate change. Since that task force issued its report, the science and policies involving forests' roles in climate change policies have evolved rapidly. Moreover, questions have arisen regarding how changes in the amount of forest biomass used for energy and the trading of forest carbon for pollution credits (offsets), motivated in part by climate change concerns, will affect global climate benefits related to forests, forest ecosystems, and traditional forest products industries.

In May 2010, SAF created a new task force to address those issues and analyze United States' forests, climate change, and energy policies. This article summarizes and examines our current understanding of forest carbon stocks and flows; climate–forest interactions; biomass use and feedstock issues; wood–fossil fuel substitution effects; and forest carbon policies. Our analysis focuses on US rather than international forests and forest policies, although we do examine pertinent international developments.

This article and the task force's other products are the result of hundreds of hours by dedicated SAF volunteers. Many individuals assisted with the preparation of this article. We would especially like to thank Kelsey Delaney (SAF) for her administrative assistance and support of the task force, Sally Atwater (Editorial Arts) for editing the article, Ken Skog (US Forest Service) for his assistance with data clarification in Section 5, Brad Smith (USFS Program Manager, Forest Inventory Analysis) for providing Figure 1 in Section 4, and David Cleaves, Elizabeth Reinhardt, and David Wear (US Forest Service) for their assistance coordinating the review of this article by agency experts.

Three individuals initially drafted small sections of this article. Dr. Jeffery Hatten (Mississippi State University) contributed the soil carbon dynamics in Section 2, Dr. Demetrios Gatziolis (USFS PNW Research Station) assisted on section 6's assessment of carbon via remote sensing, and Dr. Marcia Patton-Mallory (USFS PNW Research Station) contributed to Section 6's discussion of the strategic balance in managing carbon risk. In addition, this article was reviewed, in whole or in part, by the reviewers listed here and by others who wished to remain anonymous. To all of these individuals, the authors express their sincere thanks. Their efforts significantly increased the article's accuracy and scope.

We have arranged this article topically. We believe that this organization will be useful to most readers. However, one consequence of this arrangement is that we discuss topics at various spatial and temporal scales in each section. We have attempted to alert readers to these scale changes throughout the article.

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Executive Summary

The United States needs many different types of forests: some managed for wood products plus other benefits and some managed for nonconsumptive uses and benefits. Management decisions must account for local conditions; landowners' objectives; and a broad set of environmental, economic, and societal values. This article considers how various forest and wood use strategies can reduce accumulation of greenhouse gases (GHG) in the atmosphere.

The global carbon system stores carbon in various pools (stocks). Oceans and both forested and nonforested lands emit carbon to and absorb carbon from the atmosphere in a two-way flow (flux). In contrast, carbon removed from fossil fuel reserves acts as a one-way flow because regardless of 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 timescale. Although there are many uncertainties in measuring carbon stocks and flows globally, the objective of reducing global GHGs suggests the importance of increasing carbon storage in pools other than the atmosphere. Growing more forests and keeping forests as forests are only part of the solution. Focusing solely on forests' sequestration benefits misses the important (and substantial) carbon storage and substitution GHG benefits of harvested forest products, as well as other benefits of active forest management.

An assessment of the consequences of managing forests as part of a carbon mitigation strategy needs to consider all those elements as an integrated whole across spatial and temporal scales. Policies that ignore how forests fit into the broader economic, environmental, and social framework can fall far short of the possible reductions in carbon emissions and lead to counterproductive mitigation strategies that are environmentally and economically unsustainable. Effective solutions require a wider perspective that consider among many other things, the role of forests as a source of products for society and the effects of those products on GHG concentrations.

US environmental and energy policies need to be linked or at least be based on mutual recognition and should be based on four basic premises grounded in the science summarized in this article:

1. Sustainably managed forests can provide carbon storage and substitution benefits while delivering a range of environmental and social benefits, such as timber and biomass resources, clean water, wildlife habitat, and recreation.
2. Energy produced from forest biomass returns to the atmosphere carbon 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 US forests).
3. Forest products used in place of energy-intensive materials such as metals, concrete and plastics (a) reduce carbon emissions (because forest products require less fossil fuel-based energy to produce), (b) store carbon (for a length of time based on products' use and disposal), and (c) provide biomass residuals (i.e., waste wood) that can be substituted for fossil fuels to produce energy.
4. Fossil fuel–produced energy releases carbon into the atmosphere that has resided in the Earth for millions of years; forest biomass–based energy uses far less of the carbon stored in the Earth thereby reducing the flow of fossil fuel–based carbon emissions to the atmosphere.

US policies can encourage management of forests for all the carbon and energy benefits of forests and forest products while sustaining ecosystem health and traditional forest biomass uses. The scientific information in this article can be used as the basis for developing sound forest carbon policies.

Forest Carbon Stocks and Flows

Tracking the allocation of forest carbon across live and dead trees, understory shrub and herbaceous vegetation, the forest floor, forest litter, soils, 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 exploiting the capacity for sustainably managed forests to remove carbon dioxide (CO_2) from the atmosphere.

Carbon flux is usually estimated as change in carbon stocks. Several complications—deciding what comparisons or "pools" to include and what models, equations, and coefficients to rely on, accounting for uncertainty and error, and even definitions of "tree" and "forest"—conspire to make consistent, universally accepted estimates grounded in objective science very scarce. On average, carbon in the boles of live trees, the best-sampled and most easily modeled component of forest carbon inventories, represents less than half the carbon in the forest.

Unmanaged forests do not provide additional climate benefits indefinitely. The age when annual forest carbon storage increments begin to decline varies but generally occurs in the first 100–150 years as tree mortality losses increase. In most of the American West, fire and insects pose a very immediate threat of catastrophic loss of live tree carbon, turning affected forests into carbon emitters. In the rest of the United States, insect, disease, and storm-related conversion of live carbon to dead carbon eventually slows, stops, and sometimes reverses net sequestration.

Old forests have some of the largest carbon densities but typically low or near-zero rates of additional carbon sequestration and higher probabilities of loss. For example, 85% of the woody biomass–based carbon storage in ponderosa pine forests in central Oregon is in stands older than 100 years where annual accumulation is slowing and the risks of carbon loss due to wildfire are high and often increasing. Regeneration harvest in high-volume old-growth could release carbon that would not be used for products or energy. However, these stands are found almost exclusively on public lands and are rarely harvested or even actively managed in the United States today.

Soil carbon can have residence times as long as thousands of years, as long as it is deep in the soil profile or associated with minerals. The effect of harvest 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 postharvest site preparation. The measured effects tend to be slight in the short term, with carbon decreases concentrated in the forest floor and near the soil surface and carbon increases occurring in the deep mineral soil layers. Whole-tree harvesting for biomass production has little long-term effect on soil carbon stocks if surface soil layers containing organic material (O horizon) are left on site, nutrients are managed, and the site is allowed to regenerate. Converting agricultural and degraded lands to forests or short-rotation woody crops increases aboveground carbon stocks as well as soil carbon stocks.

Fuel treatments designed to reduce fire hazard and other stand manipulation that promotes resilience by reducing potential losses due to insects, diseases, or storms cannot eliminate risk but can reduce the scale of tree mortality and associated carbon emissions. The carbon losses from disturbances accrue over time as the live biomass is converted to dead biomass that slowly releases carbon dioxide via enhanced microbial respiration.

Including the boreal forests of Alaska and the tropical island forests, 53% of the area of US forests is timberland (i.e., forests that are available for periodic harvesting) of naturally regenerated origin, much of which is managed; 7% is forest plantations; and 40% is reserved or low-productivity forest. The carbon dynamics of each forest type are strongly influenced by the long-term sustainability of the forests, the types of wood products that are harvested, and the life-cycle carbon consequences of the various products.

After accounting for the wood used for energy in sawmills and paper mills, the annual growth of forest carbon is split among growth in live-tree inventories (28%), harvested wood products (23%), energy (18%), and natural mortality and logging residues (31%). These end uses each have unique carbon storage characteristics and trajectories. The distribution of total forest growth varies considerably among regions, with the South producing more products, the North and Pacific Coast harvesting a smaller fraction of new growth while still producing considerable products, and the Rocky Mountain region having the highest fraction of total growth converting into deadwood.

Since 1985, annual US wood production has stayed roughly constant, at 420 million m^3, while consumption increased to 550 million m^3 by 2005. Counting the increased forest carbon sequestration in the United States as new global carbon sequestration overstates the benefits, however, because of the substitution of Canadian for US wood products.

Climate–Forest Interactions

With forests covering approximately 30% of Earth's land surface and storing about 45% of terrestrial carbon, forests and global climate are closely linked in terms of carbon storage and releases, water fluxes from the soil and into the atmosphere, and solar energy capture. Estimates of the carbon, water, and energy balances of forests differ, however, depending on the atmospheric model or forest cover and forest inventory model used.

Not all the carbon captured by trees ends up as stored carbon. Approximately three-quarters of the carbon fixed by photosynthesis is immediately released through ecosystem respiration. In forests, about one-half of the respiration comes from aboveground vegetation and one-half from the forest floor and forest soils. The increase in forest floor and soil respiration is proportional to how much woody debris—whether from natural mortality or logging residues—is decomposing on site.

Temperate forests continue to increase as carbon sinks even though large quantities of wood products are removed from these forests annually. The current rate of carbon accumulation in temperate forests may decline, however, if the average age of forests continues to increase. Changing climate may also adversely impact carbon sequestration rates. Significant increases in the shift from live-tree to dead-tree biomass from fires and beetles in western North America have generated interest in changing forest management approaches to respond to climate-related stresses. Some researchers believe that seed sources and silvicultural methods must be matched to predict climatic conditions to maintain or increase productivity.

Recent data on tropical forest cover have significantly lowered the estimates of net GHG emissions related to tropical deforestation overall and suggest a need for a greater focus on deforestation in areas where carbon-rich peat soils are disturbed. When the broad range of feedbacks is considered, tropical forests are considered by most observers to be the most effective forests in terms of overall climate benefits provided per unit of area or biomass.

Links between water and carbon flux are seen in all forest types but most strongly in the tropics. The most significant water flux link between forests and the atmosphere is the evaporative cooling from tropical forest canopies, which has a positive relationship with cloud formation and rainfall patterns. In semi-arid areas in tropical and temperate regions, research has pointed to a tradeoff between increased carbon storage in new trees and reductions in streamflow available to other plants and animals.

A significant energy flux related to forests at the global level is the drop in the albedo when dark-colored trees expand at the expense of snow-covered areas with little or no tree cover. A lower albedo decreases the fraction of solar energy that is reflected into the atmosphere. The albedo effect is most important on the northern edge of the boreal region; it is measurable but less significant in temperate regions.

Biomass Use and Feedstock Issues

Feedstock supply depends not just on supply-and-demand curves but also on biomass availability; harvesting, delivery, and other costs; landowner objectives; and national, regional, state, and local laws, regulations, and policies. Forest biomass includes residues from forest stand improvements, timber harvests, hazardous-fuel reduction treatments, forest health restoration projects, energy wood plantations, and other similar activities. Regional variations influence the United States' potential feedstock supply of biomass and ultimately the location of bioenergy facilities. Readily available forest biomass supply encompasses woody biomass by type and US region that is economically available based on standard and existing logging configurations.

Expanding forest biomass use for either biofuels or energy generation may compete with traditional forest products, but it may also produce benefits through competition and market efficiency. Changes in feedstock use are controversial and a point of contention for competing industries (paper and pulp versus bioenergy), environmental and other nongovernmental organizations (who are concerned about industrial-scale biomass production), private landowners (who see opportunities for additional revenue streams), and public land managers (who need markets for low-quality material removed from overgrown forests).

Biomass feedstock supply will be affected by landowners' preferences based on price, investment-backed expectations, and environmental considerations, all of which are affected by government energy and environmental policies. Short-rotation woody crops, such as shrub willow, hybrid poplar, southern pine, and eucalyptus, have the potential to increase woody biomass feedstocks from both forestlands and converted agricultural lands.

Energy, Products, and Substitution

Forests store carbon, and so do wood products. Evaluation of carbon flows shows that conversion of wood to useful products can significantly reduce overall societal carbon emissions. To arrive at a cogent picture of the overall forest sector effect on atmospheric carbon, we need to understand the material and energy flows as inputs and outputs within well-defined system boundaries. Then, we need to integrate the effects across system boundaries to understand the many ways in which substitution of harvested wood products for fossil fuels and fossil fuel–intensive products can offset the flow of carbon dioxide from fossil carbon reserves to the atmosphere.

Forest products have lower embodied energy (the amount of energy it takes to make products) than comparable building products, so there is a substitution effect when wood is used in place of steel, aluminum, concrete, or plastic. That substitution effect varies by use and comparable product but on average, every 1 tonne (t) of wood used removes 2.1 t of carbon from the atmosphere.

Wood products store carbon for the life of the product. At the end of their lives, wood products can be reused, recycled, burned for energy, or landfilled. If they are landfilled, the carbon contained within them can be stored for a long period of time, but there can also be a substantial GHG cost because of methane emissions, particularly from paper decomposition. This suggests that incentives should be high to reuse paper and wood, recycle it, or burn it to recover at least its heating value.

A sustainably managed forest can produce a continual flow of wood products and biomass for energy while at the same time maintaining or increasing carbon stocks. Determining the effects of forest harvesting for wood products or bioenergy production requires a landscape-level analysis over time. For instance, in harvesting woody biomass for use in generating energy, carbon is removed from the forest, reducing forest carbon stocks, and that carbon is liberated as biomass is converted to energy. However, as long as harvests and mortality do not exceed net growth across the forest, carbon stocks remain stable or increase through time and the total carbon sequestration potential of the forests is maintained. In addition, the products removed from the forest provide a long-term carbon benefit equal to the avoided emissions from fossil fuels less any fossil energy used to harvest and transport the biomass feedstock.

Sustainable forest management helps ensure a neutral carbon cycle on the forestland base. Carbon storage in wood products and wood use for energy from material harvested from that land base is an additional carbon benefit beyond the forest.

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 GHG emissions. However, project-based accounting rules that ignore or undercount nonproject benefits and risks can result in project-based conclusions that differ from a more comprehensive national or international accounting.

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 schemes. Others were developed independently but have been adopted by one or more programs. Although the concept of offsets is the same, the amount of carbon credits generated for the same project can differ dramatically depending on the sets of carbon pools allowed and the baseline approach employed.

Protocols for forestry offset projects usually include the following elements: eligibility, carbon sequestration calculation procedures, baseline requirements, carbon pools, crediting period, leakage, permanence, and reversals. The costs associated with establishing and maintaining forestry offset projects depend largely on the protocols' specifics. Because protocols differ greatly in their requirements for monitoring and verification, carbon measurement, and third-party certification, the transaction costs per hectare also vary substantially, by as much as a factor of five.

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, the forest project must show 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, US forestry projects that increase in-forest carbon sequestration through a short-term reduction in harvests may have national market leakage rates that approach 100% if harvests from nonproject forests meet consumer demand.

Modeled benefits of forest carbon offset projects are highly variable and dependent on assumptions, including estimates of forest carbon flux. Determining with precision whether a threshold flux for a given area has been or will be achieved is difficult with the technology available today.

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 treeplanting, and credible information disclosure on the relative climate impacts of different products could prove more effective at a national scale.

Integrating Forests into a Rational Policy Framework

Forests are an integral component of the global carbon cycle and may change in response to climate change. US forest policies can foster changes in forest management that will provide measurable reductions in carbon emissions over time while maintaining forests for environmental and societal benefits, such as timber and nontimber forest products, vibrant rural communities, clean water, and wildlife habitat. Policies founded on three tenets reflecting the stocks and flows of woody biomass can ensure that US forests will produce sustainable carbon, and environmental and societal benefits.

1. Keep Forests as Forests and Manage Appropriate Forests for Carbon

For more than 70 continuous years, US forest cover has increased and net growth has exceeded removals and mortality. Therefore, carbon storage is increasing in the United States. In some forests (e.g., old-growth), other considerations and other benefits will outweigh carbon benefits. However, forests will 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 and the decay of trees killed by natural disturbances—windstorms, fire, ice storms, hurricanes, and 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—often for a long time after being retired from service. Substantial volumes of wood go into construction products and structures: even during the midst of the recent "Great Recession" (2007–2009), US housing starts exceeded 440,000 annually. Additional wood is used for furniture and other products, which at the end of their useful lives may be converted to energy. Paper may go into long-term use (e.g., books) or be recovered from the waste stream for energy production. Other wood—construction debris, yard waste, and unrecycled paper—winds up in landfills, where it often deteriorates more slowly than is generally assumed. In total, the rate of carbon accumulation from wood products in use and in landfills was about 88 million tonnes of carbon dioxide equivalents (CO_2e) in 2008, about 12% of the rate of sequestration in forests.

3. The Substitution Effect Is Real, Irreversible, and Cumulative

Compared with steel, aluminum, concrete, or plastic products, considerably less energy, and vastly less fossil fuel–derived energy, is required to make wood products. The low embodied energy of wood building products, structures, furniture, cabinets, and other products has been well documented through life-cycle assessments. Not only is the quantity of energy used in manufacturing wood products low compared with other materials, but the quantity of fossil energy is comparatively very low: one-half to two-thirds of the energy used by the North American wood products industry is bioenergy. For instance, compared with steel framing with an average recycled content, the manufacture of wood framing requires one-half or less the total energy and one-fourth to one-fifth the fossil energy.

Conserving forests for recreational, aesthetic, and wildlife habitat goals has been a strong policy driver in the United States over the past few decades, especially in the Pacific Coast and Northeast regions. Evidence of increasing losses to disturbances that are not captured in forest growth modeling and decreasing rates of carbon accumulation in maturing forests suggests that a strong conservation-oriented strategy may not always produce significant global climate benefits. The climate benefits of active forest management are most apparent when the substitution benefits that occur in the consumer sector are included. As we move forward with policy discussions regarding the many positive roles of US forests at local, national, and global scales, it will be imperative that objective, science-based analysis and interpretations are used and that particularly close attention is paid to the assumptions underlying the analyses.

US policymakers should take to heart the finding of the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report when it concluded that "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" (IPCC 2007a, p. 543). A rational energy and environmental policy framework must be based on the premise that atmospheric GHG levels are increasing primarily because of the addition of geologic fossil fuel–based carbon into the carbon cycle. Forest carbon policy that builds on the scientific information summarized in this article can be an important part of a comprehensive energy policy that promotes energy independence and delivers carbon benefits while providing essential environmental and social benefits, including clean water, wildlife habitat, and recreation.

Introduction

The United States needs many different types of forests: some managed for wood products plus other benefits and some managed for nonconsumptive uses. Management decisions must account for local conditions; landowners' objectives; and a broad set of environmental, economic, and societal values. This article considers how various forest and wood use strategies can reduce accumulation of greenhouse gases (GHG) in the atmosphere.

Carbon Framework

A simplified representation of the global carbon system shows that carbon is stored in various pools (stocks) with dynamic flows (fluxes) between the pools (Figure 1-1). The oceans, and lands, both forested and nonforested, emit carbon to and absorb carbon from the atmosphere in a two-way flow. In contrast, carbon removed from fossil fuel reserves acts as a one-way flow because regardless of 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 timescale. Although there are many uncertainties in measuring carbon stocks and flows globally, the objective of reducing global GHGs suggests the importance of increasing carbon storage in pools other than the atmosphere. Growing more forests and keeping forests as forests are only part of the solution because focusing solely on the sequestration benefits of the forests misses the important (and substantial) carbon storage and substitution GHG benefits of harvested forest products.

An assessment of forest management as part of a carbon mitigation strategy needs to consider all of those elements as an integrated whole across spatial and temporal scales. Policies that ignore how forests fit into the broader economic, environmental, and social framework can fall far short of possible reductions in carbon emissions and lead to counterproductive mitigation strategies that are environmentally and economically unsustainable. Effective solutions require a wider perspective that considers, among many other things, the role of forests as a source of products for society and the effects of those products on GHG concentrations.

Forest Carbon Policies

US environmental and energy policies need to be linked or at least be based on mutual recognition and should be based on four basic premises grounded in the science summarized in this article:

1. Sustainably managed forests can provide carbon storage and substitution benefits while delivering a range of environmental and social benefits, such as timber and biomass resources, clean water, wildlife habitat, and recreation.
2. Energy produced from forest biomass returns to the atmosphere carbon that plants absorbed relatively recently from the atmosphere; it essentially results in no net release of carbon as long as overall forest inventories are stable or increasing (as is the case with US forests).
3. Forest products used in place of energy-intensive materials, such as metals, concrete, and plastic, (a) reduce carbon emissions (because forest products require less fossil fuel–based energy to produce), (b) store carbon (for a length of time based on products' use and disposal); and (c) provide biomass residuals (i.e., waste wood) that can be substituted for fossil fuels to produce energy.
4. Fossil fuel–produced energy releases carbon into the atmosphere that has resided in the Earth for millions of years; forest biomass–based energy uses far less of the carbon stored in Earth thereby reducing the flow of fossil fuel–based carbon emissions to the atmosphere.

US policies can encourage management of forests for all the carbon and energy benefits of forests and forest products while sustaining ecosystem health and traditional forest biomass users. The scientific information in this article can be used as the basis for developing sound forest carbon policies.

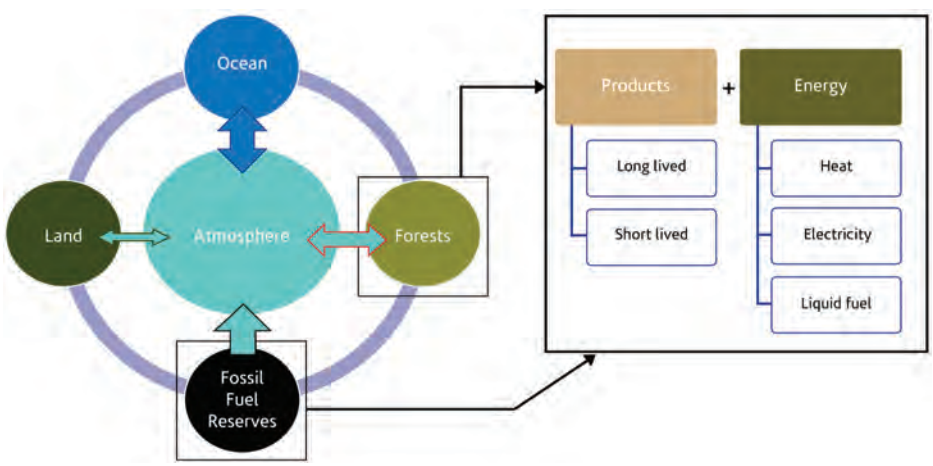

Figure 1–1. Major global carbon pools, their interactions, and forest and fossil fuel products. (Source: Adapted from Lippke et al. 2011.)

Forest Carbon Stocks and Flows

US forests were in carbon balance with the atmosphere (emissions approximately equal to sequestration) from the beginning of Euro-American settlement to 1800. Subsequently, forests were cleared for agriculture and construction, resulting in significant emissions of carbon until 1950. These same forests are now significant carbon sinks (Pacala et al. 2001) because of forest regrowth in areas where agriculture was abandoned (Birdsey et al. 2006), fire suppression in western forests, increased productivity of planted forests, and forest management activity. These factors were responsible for a carbon flux as large as −390 teragrams (Tg; trillion grams)/year as recently as the 1990s (Houghton et al. 2000). (By convention, carbon sequestration is represented as negative flux and carbon emissions as positive flux.)

US forests today are known to function as a substantial carbon store, with woody biomass carbon stocks averaging nearly 58 Mg (million grams)/ha, estimated via remote sensing (Myneni et al. 2001), and nearly 84 Mg/ha, estimated via inventory statistics (US Environmental Protection Agency [EPA] 2010). Carbon flux reported for the entire forested area of the United States ranges from −141 (Myneni et al. 2001) to −183 (Birdsey et al. 2000) to –192 (US EPA 2010) Tg of C/year, not accounting for storage in harvested wood products. Both stocks and flux vary greatly by region, forest type, site class, owner group, and reserve status. For example, inventoried aboveground live and deadwood average carbon stocks in California range from 13 Mg/ha for pinyon-juniper to 360 Mg/ha for redwood (Christensen et al. 2008). Carbon flux on highly productive national forest lands in California averages −1.25 Mg/ha per year versus 0 Mg/ha per year for low-productivity (nontimberland) forests (Fried 2010). Han et al. (2007) report a sink size for an 11-state region in the southern United States as −130 Tg of C/year and assert that this is sufficient to capture 23% of greenhouse gas (GHG) emissions in that region. Across the whole United States, carbon removed from the atmosphere by forest growth or stored in harvested wood products is equal to 12–19% of fossil fuel emissions (Ryan et al. 2010, EPA 2010).

Forest Carbon Trajectories

Forest carbon constitutes about one-half of the bone-dry forest biomass. When we consider the temporal dynamics of carbon in the forest, therefore, it can be helpful to think of how forest biomass fluctuates over time at the stand level. In forest types that are predominantly even-aged, either because of management choice or natural disturbance regimes, a stand is initiated (via afforestation or reforestation after a fire, harvest, or other stand-replacing disturbance), grows (using photosynthesis to extract carbon from the atmosphere and distribute it to leaves, stem, and roots), and ultimately dies (via harvest or other stand-replacing disturbance or conversion to a nonforestland use). Management activities, such as thinning, fertilization, and hazardous fuel removal, may occur along the way. Where stand-replacing disturbance is rare or management emphasizes selection harvest, the birth and death of trees in a stand is continuous or episodic, resulting in a stand-level trajectory of forest carbon without pronounced peaks and valleys. In such forests, gross primary productivity and allocation of forest carbon among live and dead trees, understory shrub and herbaceous vegetation, forest floor, litter and soils are ever changing. Understanding these dynamics and how allocations change with stand age, density, and management is essential to identifying opportunities to manage forests to increase their capacity to remove carbon dioxide (CO_2) from the atmosphere (Litton et al. 2004).

Stand-Scale Trajectories

A newly regenerating forest behaves as a net carbon source to the atmosphere because the above- and belowground remains of woody plants in the antecedent forest are subject to decay and heterotrophic (microbial) respiration. In a study of disturbance types in evergreen forests in seven disparate regions of the United States, Thornton et al. (2002) found that peak emissions related to disturbance occurred 2 years after the disturbance, and that emissions could exceed sequestration for up to 16 years—until the live trees grew to a size at which their absorption of carbon exceeded the onsite losses from decomposition of the predisturbance forest. If an old-growth stand, in which disturbance or harvest leaves behind high volumes of large-diameter deadwood, the period in which emissions exceed sequestration could be as long as 20–30 years (Harmon and Marks 2002). Assuming sufficient stocking, a stand of pole-sized trees is well positioned to accumulate woody biomass carbon at an increasing rate for several decades, barring excessive disturbance, but at some point, growth decelerates.

Because carbon sequestration rates peak in the first 100–150 years in most even-aged stands as tree mortality losses increase, older stands tend to be weak sinks at best. Nonetheless, analysis of forest inventory plots shows that in rare cases (e.g., very wet forests on Washington's Olympic Peninsula), forest carbon stores may continue to increase for as long as 800 years. A few old-growth forests can achieve truly massive (more than 1,100-Mg of C/ha) carbon stocks (Smithwick et al. 2002), and researchers are increasingly documenting that some old-growth forests can continue to have greater sequestration than respiration as long as they are not affected by stand-terminating disturbances. Luyssaert et al. (2008) also found positive net ecosystem productivity in forests as old as 800 years in the boreal region, but they noted that many stands had experienced, and will continue to experience, stand-terminating disturbances.

Growth decline is ultimately inevitable, however, as gross primary productivity is reduced by nutrient and other resource limitations and carbon allocation shifts from wood production to respiration (Ryan et al.

2004). Ponderosa pine forests older than 190 years in central Oregon remain weak carbon sinks, with a mean flux of −0.35 Mg of C/ha per year (Law et al. 2003). From a landscape perspective, 85% of the woody biomass-based carbon storage in ponderosa pine forests in this area is found in stands older than 100 years and faces a significant risk of carbon loss from wildfire. Diminished sink strength at even younger ages has been widely documented. In Swiss alpine forests, storage capacity was found to peak at 100 years, after which forests were net emitters of carbon (Schmid et al. 2006). An Austrian study that also accounted for wood products and bioenergy offsets found that overall carbon storage was greatest in unmanaged stands over a 100-year horizon, but that the effective storage could well be much less because the standing carbon was vulnerable to unforeseen disturbances (Seidl et al. 2007). The 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 will soon equal newly sequestered carbon via photosynthesis (Leighty et al. 2006).

At some point, reduction of carbon stocks in any individual stand is also inevitable. Carbon may be emitted through natural disturbance or harvesting. Typically, a large fraction of forest carbon from a harvested stand is sequestered in long-lived forest products or converted to bioenergy. Although carbon emissions from producing bioenergy may be the same as emissions from natural disturbance, the latter achieves no carbon benefit. An accurate portrayal of forest carbon and the carbon benefits and costs of any harvested products requires looking at a large number of forests stands of different ages, the amount of carbon sequestered in products, and the likely effects of disturbances.

Forest-Scale Trajectories

Whereas forest carbon dynamics at stand scale are driven by growth, harvest, and mortality, at the forest scale they are affected at least as much by the distribution of forest area by age class or successional state and management regime. More than one-third of the forest area of Yellowstone Park, e.g., is of a single age class, born after the fires of 1988. Now undergoing a period of rapid growth and accumulating carbon, these forests still have 91–99% of their carbon in coarse woody debris and mineral soil; the mature lodgepole pine forests elsewhere in the park have 64% of their carbon in live trees (Litton et al. 2004). The carbon lost in the 1988 fires may not be recovered for 230 years (Kashian et al. 2006). In this and less extreme cases, the carbon implications of disturbance are greatly influenced by the amount of the previous stand used in harvested wood products and bioenergy; in the Yellowstone case, this was zero. Late-successional forests, like the federally protected wilderness and parks in the West, hold tremendous carbon stores but have low rates of carbon accumulation compared with younger forests. The carbon stores of very large forest areas—those consisting of thousands of stands spanning a broad range of age and successional development classes—have achieved an approximately steady-state plateau (Harmon et al. 2001). However, this "carbon plateau" may trend up or down with changes in growth rates and natural and human disturbance frequency and magnitude, all of which may result from climate change (Latta et al. 2010, Smithwick et al. 2007).

Management and Forest Carbon Capture

Eventually, all trees die, and when they do, their carbon moves quickly (e.g., fire, windthrow, or harvest) or slowly (e.g., insect attack or disease infestation) into other pools (e.g., deadwood, soil, products, or atmosphere). The process of forest renewal and tree growth, competition, aging, and, eventually, death is ongoing. Environmentally sensitive use of forest mortality offers the opportunity to capture some permanent carbon benefits via long-term storage in products and/or substitution for fossil fuel energy. Depending on other objectives, these benefits can be captured using a wide variety of management-driven removals, including sanitation, mechanical fuel treatment, thinning, selection harvest, regeneration harvest, and salvage logging, albeit with varying implications for economic feasibility and residual stand conditions. Such benefits do not accrue when dead and dying trees are left in the woods to emit carbon via heterotrophic respiration, and when capture opportunities are missed, there are no second chances. The timing of removals, however, can be important.

Regeneration harvest in a high-volume old-growth stand releases a great deal of carbon—so much, in fact, that it may take decades before the new stand establishes greater net uptake of carbon (after accounting for storage in wood products, slash disposal, emissions from deadwood and other harvest-killed vegetation, and soil carbon emissions) than if the old-growth had been left alone (Janisch and Harmon 2002). However, such stands, which are found almost exclusively on public lands, are rarely harvested or even actively managed in the United States today, and in any case, are unlikely to be considered candidates for bioenergy feedstocks because their value as energy feedstock is low compared with the high social values placed on old-growth forests. Where catastrophic losses are likely (e.g., in drier forest types where fire or insects drive shorter disturbance intervals), the carbon calculus is different. In this case, management that involves periodic harvest provides a range of societal benefits. Regenerated young stands continue to sequester new forest carbon, and products derived from the harvested wood store carbon for various lengths of time *and* provide substitution benefits that show up in national GHG accounts in lower emissions from fossil fuel burning.

Forests can be managed to maximize carbon sequestration. Even-aged rotations synchronized to culmination of mean annual increment* lengthen the period during which current annual increment (1 year's addition to the live-tree carbon pool) exceeds the maximum MAI. Across an ownership, shorter rotations may reduce maximum sequestration on currently managed sites but can generate additional discounted net revenue that could be invested to increase growth in other forests. Rotations longer than maximum MAI reduce the capacity for long-term storage in harvested wood products and, at least in some systems, increase the risk of catastrophic carbon loss. Reducing stocks in forests managed for commercial products may reduce the financial and carbon risks of losses to episodic disturbances, such as wildfires or severe storms, and potentially increase the average value of the products produced; increasing stocks may increase the rate of carbon accumulation but also increase loss risk. Although any kind of harvest releases at least

* MAI; i.e., the point at which average annual woody carbon accumulation, calculated as total carbon divided by stand age, peaks and begins to fall.

Table 2-1. Carbon flux in the US forestry sector in 2008, excluding energy sector and product substitution benefits.

Carbon pool	2008 flux[a] Tg CO_2e[b]	Percentage of total
Forest	−704	89[c]
Aboveground biomass	−397	50
Belowground biomass	−79	10
Deadwood	−26	3
Litter	−56	7
Soil organic carbon	−146	18
Harvested wood	−88	11
Products in use	−24	3
Wood in landfills	−64	8
Total net flux	−792	100

[a] Carbon sequestration is negative flux; carbon emissions is positive flux.
[b] Tg CO_2e, teragrams of carbon dioxide equivalent; to obtain teragrams of C from Tg CO_2e, divide the latter by 3.667. Source: US EPA (2010).
[c] Percentages of forest carbon pool do not add up to 89 due to rounding.

some carbon to the atmosphere, thinning and selection harvests typically have a lower emissions density per unit area because they produce less slash and residual organic matter (e.g., down wood and dead roots). Compared with regeneration harvests, thinning and selection also result in a far shorter delay before net carbon uptake is restored, because the residual stand maintains greater carbon sequestration capacity than does a clearcut. Even-aged harvests have a somewhat longer-lasting effect on net carbon flux because there is no residual stand to sequester carbon, and seedlings must grow for several years before they become a significant carbon sink.

Estimates of US Carbon Flux by Pool

Table 2-1 shows the estimated US forestry sector annual flux in teragrams of carbon dioxide equivalent (CO_2e) for 2008, the most current year available (US EPA 2010), as reported under international carbon protocols. This framework calculates net changes between consecutive, annual estimates for five forest pools and two harvested wood pools. Note that only one-half of the flux is estimated to occur in the aboveground, live-tree pool—the pool that is most commonly considered in carbon accounting analyses. Of the aboveground forest carbon, current measurement procedures are more accurate for the boles of trees of the species and sizes that have typically been used to produce products, and considerably less accurate for noncommercial species and for the branches, tops, and roots of all trees. As currently reported, estimates for all other forest pools are derived from models, in which their assumptions may lead to inaccuracies. For example, deadwood is modeled as a fraction of live wood, and soil carbon density is assigned by forest type. Although definitive conclusions are elusive because of changes in inventory measurements and protocols since 1990, the US forest carbon sink has been reported as weakening due to increasing forest age and time since farmland abandonment, climate variability, and increasing frequency and severity of natural disturbances (some resulting from many years of fire suppression). Moreover, it appears that climate change will increase the frequency of disturbance in forest ecosystems (e.g., Hurtt et al. 2002, Dore et al. 2008, Pan et al. 2008).

Carbon Trajectories in Forest Soils

Soil carbon, both in litter layers and associated with soil minerals, occurs in a heterogeneous mix of organic materials (Hedges et al. 2000). Soil carbon is the largest actively cycled terrestrial carbon pool (Schlesinger 1997, Hedges et al. 2000, Jobbagy and Jackson 2000) and can have residence times of hundreds to thousands of years (Gaudinski et al. 2000, Trumbore 2000). These attributes imply that soils may be an attractive pool to sequester carbon for long periods (Oldenburg et al. 2008). Forest management and disturbances affect soil carbon stocks through changes in carbon fluxes and carbon quality, and the magnitude and direction of these changes tend to be highly variable by region and situation.

The simplest conceptual model of soil carbon is that of two pools of labile and recalcitrant carbon that have short and long residence times, respectively. Generally, the most labile carbon is organic (e.g., O horizons and belowground particulate organic matter) and represents about 1–12% of forest soil carbon (Schlesinger 1997, Fisher et al. 2000, Sollins et al. 2006). Mineral-associated carbon represents more than 90% of all soil carbon and has the longest residence time (i.e., oldest ^{14}C age) (Fisher et al. 2000, Gaudinski et al. 2000, Jobbagy and Jackson 2000). Mineral-associated carbon is protected from mineralization through its chemical stabilization with mineral surfaces (particularly reactive minerals such as iron oxides) (Kleber et al. 2005, Mikutta et al. 2006) and physical protection within soil aggregates (Six et al. 2002). Additionally, 36–41% of all soil carbon can be found below 1 m in depth (Jobbagy and Jackson 2000), where it has been found to have very long residence times (thousands of years; Trumbore et al. 1995).

Litterfall and root turnover (rhizodeposition) are the major inputs of carbon to soil carbon pools and are closely related to net primary productivity (Schlesinger 1997). Root inputs of carbon account for 56–71% of mineral soil carbon (Rasse et al. 2005). Most carbon entering soil pools in forested systems decomposes and is emitted through heterotrophic soil respiration (Hanson et al. 2000, Subke et al. 2006). An increase in this heterotrophic soil respiration caused by global warming may be a positive feedback mechanism of climate change (Raich and Schlesinger 1992). Stabilization of carbon entering the soil system depends on the carbon content of the soil horizon it enters. Carbon entering a carbon-rich or carbon-saturated surface horizon may accumulate at a constant rate but have a very short residence time. On the other hand, carbon entering a carbon-poor soil horizon has more potential to be stabilized in a mineral-associated recalcitrant pool because of the larger proportion of reactive mineral surface area. Because surface soil horizons in forest soils are near saturation, an increase in carbon stores here is unlikely. Mineral soil at depth (e.g., more than 50 cm) has much lower carbon concentrations and therefore may have the capacity to stabilize carbon; however, inputs of carbon to this depth are also low.

Harvesting and thinning operations alter soil carbon cycling by cutting the supply of root and litter inputs, disturbing the soil surface, and changing temperature and moisture regimes, all of which tend to increase heterotrophic respiration rates; however, they also move some forest floor carbon into deeper, mineral soil layers. A few meta-analyses and review articles 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). Nave et al. (2010) reported an 8% average reduction in soil carbon stocks after harvesting over all forest and soil types studied. However, most of the studies covered sampled only the top 20 cm of soil, or even just the forest floor, so these losses are primarily the result of a reduction in litter layer mass and organic matter inputs from growing trees; they may also reflect the sampling challenges of accurately tracking forest floor carbon over time (Federer 1982, Yanai et al.

2003). Harvesting either has no effect on mineral soil carbon or leads to increases (Slesak et al. 2011). Harrison et al. (2011) report that for a variety of ecosystems and treatments, valid estimation of changes in ecosystem carbon was not even possible without sampling soil deeper than 20 cm. Even whole-tree harvesting for biomass production may have little long-term effects on soil carbon stocks if O horizons are left undisturbed and nutrients are managed (Powers et al. 2005). Forest thinning and competition control have a much smaller disturbance on soil characteristics and therefore affect soil carbon stocks less. In addition, by reducing the likelihood of stand-replacing wildfire and fire severity at the soil surface, thinning and fuel reduction treatments may reduce future losses of soil carbon.

Forest fertilization may increase or decrease soil carbon stores by increasing net primary production (+), shifting production to aboveground vegetation components (−), increasing soil carbon mineralization (−), and depressing some enzyme activity (+) (Jandl et al. 2007, Van Miegroet and Jandl 2007). Effects of forest fertilization on soil carbon have been found to be site-specific, but most studies show an increase in soil carbon stock (Johnson and Curtis 2001). However, fertilization of forests has been linked to increased soil emissions of nitrous oxide (N_2O, a GHG 300 times stronger than CO_2), so this must be factored in when selecting the best management strategy to mitigate GHG concentrations (Matson et al. 1992, Castro et al. 1994). The production of fertilizer itself also results in carbon emissions because the production processes are energy intensive.

The influence of short-rotation woody crops and afforestation on soil carbon stocks appears to depend primarily on previous land use, management practices, and soil characteristics (Tolbert et al. 1997, 2002, Guo and Gifford 2002, Post and Kwon 2000, Sartori et al. 2006). Conversion of agricultural and degraded lands to forest or short-rotation woody crops is likely to increase soil carbon stocks. Lands used for perennial crops or pasture typically have higher carbon concentrations than annually tilled lands, so afforestation may or may not increase soil carbon stocks. Depending on the aforementioned factors, short-rotation woody crops may increase soil carbon up to 0–1.6 Mg/ha per year for decades before the soil reaches a new equilibrium (Guo and Gifford 2002, Post and Kwon 2000, Sartori et al. 2006).

Fire can be a major cause of carbon loss from forests, but the magnitude of loss depends on fire severity. 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, 2008). Conversely, high-severity wildfire decreases soil carbon stocks by 10–60% (Baird et al. 1999, Bormann et al. 2008, Hatten 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. 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 mechanical thinning and prescribed fire.

Given the variable properties of soils, determining soil carbon stores is more expensive (many samples are required) than inventory-based accounting for aboveground, live-tree carbon stores. The high variability of soils and inability to take repeated measures on exactly the same soil make accounting for soil carbon flux over time even more challenging. Many researchers have developed sampling protocols for soil carbon stores (e.g., Shaw et al. 2008) or the effects of different treatments (e.g., Homann et al. 2001). The magnitude and spatial dependence of soil variability differ among soil types, so a one-size-fits-all approach to soil sampling does not work (Ayres et al. 2010). The Forest Inventory and Analysis (FIA) (US Forest Service 2011) program of the US Forest Service collects soil carbon data to a depth of 20 cm across the United States on phase 3 plots (one per 96,000 ac). This sampling intensity and limited sampling depth are insufficient to account for soil carbon across the United States; however, it may help in refining a sampling system that characterizes soils for a given region, forest type, and soil type to support a targeted soil carbon inventory program.

Carbon Flux from Forest Disturbances

As the average age of trees in forests increases, both carbon inventories and carbon losses to mortality increase (Stinson et al. 2011). In the West, where public forests predominate, the average stand age is 90 years; for private forests in the East, it is 47 years. In Canada, the average stand age for managed forests is 92 years, and in Europe it is 48 years (Bottcher et al. 2008). US western forests are similar to those of western Canada (Kurz et al. 2008a, Stinson et al. 2011) in their high carbon inventories as well as current high losses to mortality from fires and insects. The younger European forests are estimated to have much higher net carbon sequestration rates and much lower losses to mortality (Luyssaert et al. 2010). The fraction of total growth in merchantable volume that ends up as mortality is now nearly twice as high on national forests (0.33 in the East and 0.36 in the West) as on timberlands outside the national forests (0.19 in the East and 0.22 in the West; Smith et al. 2009). Thus, management that anticipates disturbance is a more compelling idea for western forests than for forests elsewhere. If carbon values rise and more efficient recovery technologies develop, natural disturbances may be seen as opportunities to capture carbon benefits via bioenergy from dead trees that would otherwise emit carbon with no compensating benefits. Understanding the disturbance processes that drive mortality and the fate of the dead biomass—whether it is left in the forest to emit carbon over time or collected and used—is a significant but often overlooked component of forest carbon dynamics.

Fire

Increased reliance on in-forest carbon storage usually increases carbon emissions when fire does occur (Hurteau et al. 2008). In the West, fire poses the greatest risk of forest carbon emissions, which are very difficult to quantify because of spatial and temporal heterogeneity: extreme interannual variability has stymied efforts to determine even the existence of a trend in emissions (Liu et al. 2005). Over the long term, assuming no trend in fire return intervals, emissions from fires are balanced against carbon sequestration by the growing forest. On timescales relevant to forest carbon offsets, fires can release truly massive quantities of carbon (averaging 293 Tg of C/year in 2002–2006, a period of high fire activity), adding significant uncertainty to projections of likely reductions in carbon emissions (Wiedinmyer and Neff 2007). In part because of a century of fire suppression (Agee and Skinner 2005), combined with climatic factors (McKenzie et al. 2004, 2008, Littell et al. 2009b), 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, catastrophic fires have occurred (e.g., the Tillamook Fire in Oregon's Coast Range).

Intense, stand-replacing fires in heavily stocked stands can be so severe that substantial soil carbon stores are lost and soil structure and nutrient capital are destroyed, delaying regeneration and/or leading to slower regrowth. Treatments that reduce ladder fuels and understory vegetation in general are frequently recommended to reduce fire severity and the probability of crown fire (Brown et al. 2004, Agee and Skinner 2005). Numerous studies have attempted to assess various combinations of thinning, prescribed fire, and understory and down wood removal for their capacity to maximize stored carbon and reduce the risk of catastrophic forest carbon loss (e.g., Lee et al. 2002, Li et al. 2007, Boerner et al. 2008, Chiang et al. 2008, Hurteau and North 2010). Most of these studies have not accounted for the carbon stored in harvested wood products and the carbon benefits of offsetting fossil fuel–generated energy, let alone the substitution benefits of using wood instead of building materials which are more fossil fuel intensive. Counting all removals as instantaneous emissions, they generally conclude that fuel treatments increase carbon emissions. Counting fire-induced mortality in untreated stands as forest ecosystem carbon (e.g., Reinhardt and Holsinger 2010) provides an accurate estimate immediately after a fire but neglects the significant differences in photosynthesis and respiration between live and dead trees over the next few decades.

Such omissions preclude meaningful interpretation of study results because fuel treatments reduce the likelihood of catastrophic carbon loss via wildfire and, analogous to portfolio diversification, capture some portion of the forest carbon for products and energy (and associated carbon benefits) well before a stand reaches full rotation age (or experiences a stand-terminating disturbance). Carrying less in-forest volume (and carbon) is thus a desirable objective of such treatments. Finkral and Evans (2008) show how wood use can tip the balance toward net carbon benefits. In a retrospective, model-based analysis of four large western fires, Hurteau et al. (2008) found that had the forests been thinned before the fire, carbon emissions could have been significantly reduced. Stephens et al. (2009) accounted for storage in harvested wood products and documented emissions from prescribed fire, mechanical treatment, and a combination of both, with and without a subsequent fire. Relative to the control, mechanical treatment produced less emissions for almost any plausible assumption of fire probability, and the other options produced less emissions as the likelihood of fire increased (they resulted in much greater treatment emissions but much less posttreatment wildfire emissions).

In some cases, frequent fuel treatments (thinning combined with prescribed fire) have been known to reduce site quality (Gough et al. 2007). Over the past 10 years, a comprehensive literature on fuel treatments (e.g., Graham et al. 2009, Cathcart et al. 2010, Reinhardt et al. 2010) has specifically addressed the effects of biomass removal treatments on fire behavior and the consequent carbon benefits. Fire and forest managers increasingly understand that such treatments rarely prevent fire but, when successful, tend to change fire type from crown to surface and reduce both fire intensity and carbon emissions. When natural regeneration after fire is unlikely to occur, artificial regeneration can increase carbon storage over time.

Insects and Disease

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); e.g., bark beetle outbreaks generate considerable quantities of deadwood but may cause no change in soil respiration rates (Morehouse et al. 2008). Their effect on forest carbon over time depends in part on whether the agent attacks all tree species in a stand or only a few. As long as unaffected trees are present in significant numbers, leaf area and growth potential of the site "transfer" to the surviving trees, at least some of which claim access to the growing space vacated by trees that succumb. If the dead-tree carbon can be recovered (e.g., via sanitation harvest for wood products or energy), the effect on stand carbon trajectories would be little different than a thinning. However, if the stand is a monoculture or the agent attacks all tree species, reversals in carbon storage may be significant, especially if salvage is not an option. Some exotic invasive pests may prevent preinfestation tree species from becoming reestablished, essentially changing the capacity of a site to store carbon unless alternative species with equivalent growth potential are available. Given the cost of fighting invasions and infestations, managing forests for resilience—such as by encouraging species diversity and managing stand density—may be the most feasible approach.

Insect infestations can heighten the risks of severe crown fire (and thus the potential for large emissions of carbon from the live-tree pool) not because they create deadwood but because the resulting change in stand structure tends to promote ladder fuels (Bigler et al. 2005, Lynch et al. 2006). Decreased susceptibility to surface fire after spruce beetle infestation (Kulakowski et al. 2003) is possibly caused by increased forest floor moisture. The prodigious amounts of deadwood produced by infestations elevate the potential for high-severity fire and substantial carbon emissions when fires do occur.

Weather-Related Disturbances

Windthrow, hurricanes, and ice storms can be locally significant. A study of ice damage under climate change found that thinned stands were more susceptible to ice damage but that ice damage became less likely under a changed climate (McCarthy et al. 2006). A single Katrina-sized hurricane has the potential to convert the live-tree equivalent of 10% of US annual carbon sequestration into deadwood, much of which would be inaccessible and unrecoverable. Longer-term carbon losses result from the delay in reestablishing full leaf area in hurricane-damaged stands (McNulty 2002). Whether and how such disturbances might be managed to reduce carbon emissions is unknown.

Land-Use Change

In contrast with tropical forests, where land-use change is the leading driver of change in carbon stores and sequestration capacity, the forested area in the United States is essentially stable, with recent changes being well within the margin of error (USDA 2009). Smith et al. (2009) report FIA estimates of 337,000 ha added to forested area each year between 1997 and 2007, on a base of 302 million ha. Statistics compiled by US EPA (2010, Chapter 7) from FIA, USDA's Natural Resources Inventory, and the Multi-Resolution Land Cover Consortium suggest substantial, bidirectional flux in area between grass and cropland and forest, with more area entering than leaving forest. Moreover, a relatively small share (35%) of the area reported to have left forest ends up in agricultural use, whereas 65% goes to settlements. Thus, the FIA-reported net annual increase in forestland area likely underestimates the carbon storage gains because many of the forests converted to settlements retain all or most of their forest biomass. For example, in the western and northern states, the growth in the area of the wildland–urban *intermix* (where homes are scattered within a matrix of wildland vegetation) dwarfs that of the wildland–urban *interface* (where areas of high housing density abut areas of undeveloped wildland vegetation; Hammer et al. 2007). Even urban forests can retain as much as 30–50% of the standing forest carbon storage of their antecedent wildland forest and may grow faster because of the wider tree spacing, better control of competing vegetation in landscaped yards, and irrigation and fertilization by homeowners. Urban forests cannot duplicate all the functions of their wildland counterparts. The mere presence of humans reduces habitat quality for many species, but such forests can accumulate substantial quantities of carbon. However, eventual capture of that carbon in harvested wood products or as bioenergy (which would enable urban forests to sequester yet more carbon via tree growth) is a nascent opportunity at best. Kline et al. (2004) found reduced incidence of forest management activity, including thinning and other harvest activity, in forests near settlements. Some micromills already glean timber supplies from urban tree removal (e.g., Urban Hardwood Recovery 2010), and wood removed in urban settings has been used for bioenergy production and district heating in St. Paul, Minnesota, but it is doubtful that urban trees' carbon benefits (of in situ storage, long-term product storage, and substitution) will ever approach what is possible on undeveloped but managed forests.

Forest Carbon Accounting

Minimizing net emissions to the atmosphere requires paying attention to sources and sinks both within the forest (net inventory growth and mortality) and in the consumer sector, where wood products can substitute for energy- and emissions-intensive materials such as concrete, steel, aluminum, plastic, heating oil, and coal (see Section 5).

Table 2-2. Area of US forestland, timberland, reserved forest, and low-productivity forest, by region (million hectares).

Region	Total forestland	Timberland Total	Timberland Natural	Timberland Planted	Reserved forest	Low-productivity forest
South	87	83	64	18	1	3
North	70	66	64	2	2	1
Pacific Coast	86	30	26	4	18	38
Rocky Mountains	61	29	28	0	8	24
Interior Alaska	46	3	3	0	11	32
Tropical Islands	2	NA	NA	NA	NA	NA

Source: Smith et al (2009).

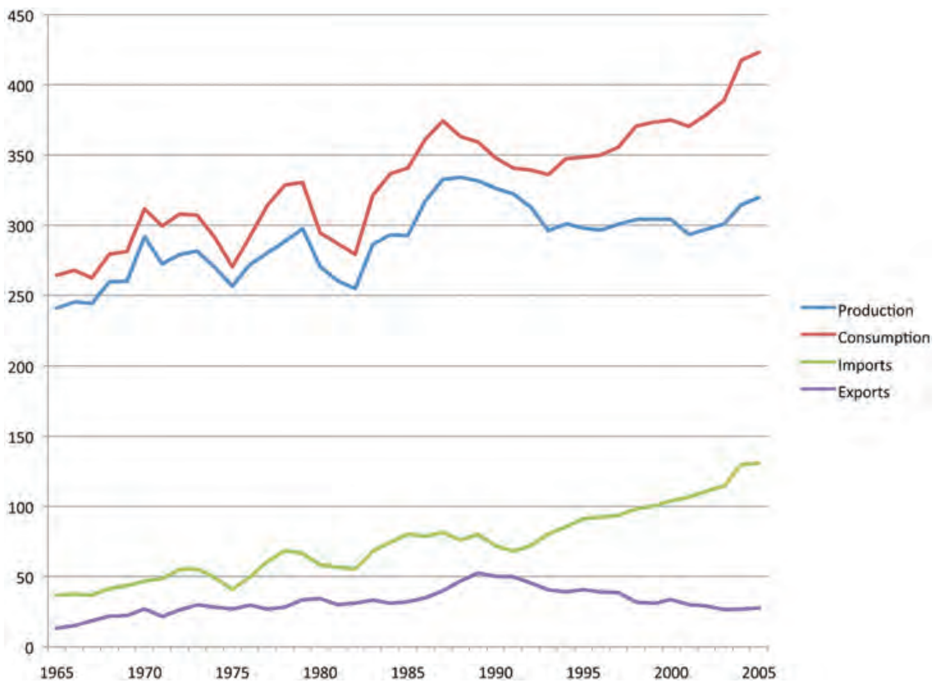

Figure 2-1. Trends in US industrial roundwood, 1965–2005 (million cubic meters). (Source: Howard (2007).)

The summary here provides national and regional context on the patterns of the movement of forest carbon from forests and into wood products and energy.

Across the United States, forests differ in how they are managed and how much carbon is removed to make products and energy. Table 2-2 presents the area of forestland across six major regions. We focus on timberland, the more productive forest, in the first four regions (i.e., excluding interior Alaska and the tropical islands, where timberland is scarce) because the data come from a common, contemporary database (the assessments for the Resources Planning Act). This provides a more regionally nuanced view of US forests and their potential to generate climate benefits. These timberlands represent about 60% of all US forest area and approximately 90% of the nation's productive forests (the remainder is generally in parks, wilderness, or other reserved areas typically off-limits to active management and considered inaccessible). Although all forests may be subject to significant disturbances spawned by climate change, mitigation via vegetation management is most likely feasible only on accessible timberland.

Since 1980, domestic production of roundwood has fluctuated around 300 million m^3 of wood products while consumption has increased by more than 20% (Figure 2-1). Most of this gap has been filled with imports from Canada and other countries. Because harvesting in Canada had to increase to fill this gap, Canadian forest carbon stocks are lower than they would have been otherwise. As a result, counting the increased forest carbon sequestration in the

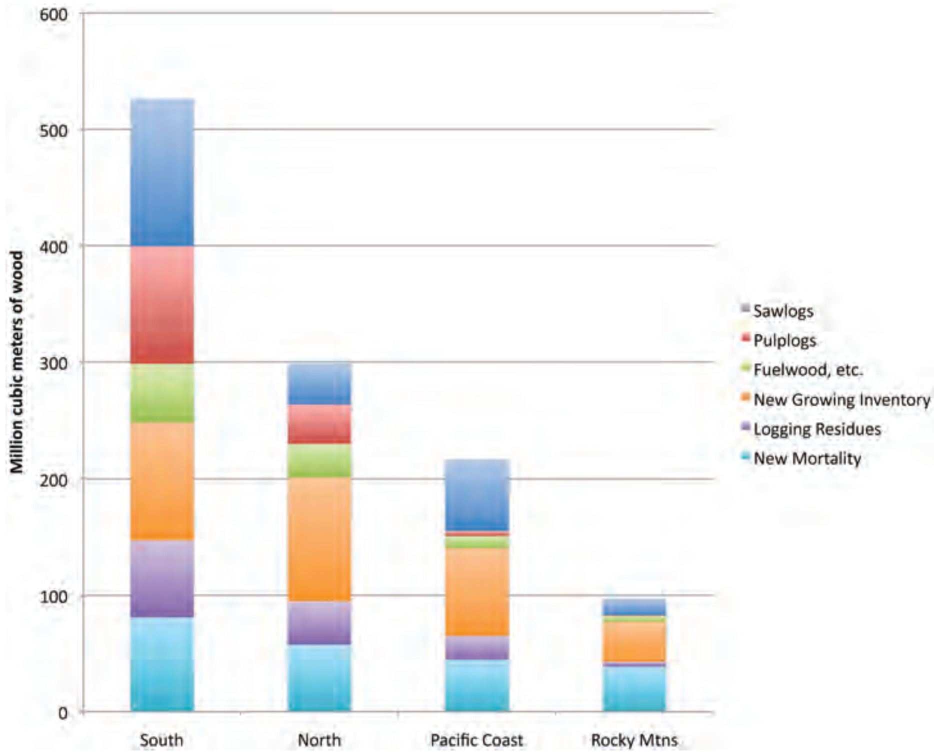

Figure 2-2. Annual flux on timberlands in 2006, by region (million cubic meters of woody biomass). (Source: Smith et al. (2009).)

Table 2-3. Total estimated annual biomass flux into products, new inventory, and mortality as a percentage of gross annual growth on US timberlands.

Out-of-mills flux and in-forest flux	South	North	Pacific Coast	Rocky Mountains	Total United States
Final products	30%	15%	24%	12%	23%
Energy	23	17	11	8	18
New growing inventory	19	36	35	36	28
Logging residues	13	13	10	4	11
Natural mortality	15	19	21	40	19

Source: Calculated from Smith et al. (2009).

United States as new global climate carbon sequestration benefits overstates the global benefits.

Figure 2-2 combines forest inventory and forest product data to illustrate the net flux in wood volume on US timberlands in 2006. The measurements include changes in both growing inventory and dead trees in the forest. Each flux has a very different carbon trajectory over the next 100 years. Sawlogs can be used to create long-lasting wood products but account for only about one-half of the wood products used by consumers. The conversion of harvested volume into consumer products is determined at the mills as they respond to market price and demand. About one-third of harvested volume goes into lumber products, with the remainder going into structural composite lumber, oriented strandboard, structural and nonstructural panels, paper products, and fuelwood (Smith et al. 2009). Traditional forest inventory statistics focus on the live-tree inventory and apply no value to logging residues and mortality left in the forest. From a GHG perspective, both natural mortality and logging residues will add to respiration-based carbon emissions even if they appear to be "storage" (in deadwood) in the year that a tree dies. At a smaller scale, near wood energy facilities, more of the net carbon flux commonly goes to fuelwood and other energy uses, and less of the carbon is left in the forest as logging residues or new mortality. Although the proportions vary across regions, nationally, a third of the total flux is taken out as products, a third adds to growing trees, and third goes into dead and down wood that will decompose over time. The annual flux from live trees into mortality from natural causes or logging is significant. In terms of new carbon storage, the deadwood is a "leaky bucket" because decomposition rates and eventual CO_2 release are high. Harmon et al. (2001) estimated decomposition rates for deadwood of 3%/year for coniferous forests and 8%/year for deciduous forests, based on a review of more than 20 published and unpublished studies from temperate forests.

Table 2-3 summarizes the total forest and forest product carbon flux by region after estimating the portion of harvested volume of sawlogs and pulpwood used as energy in mills and counting this as energy. Wood used for energy in the industrial sector accounts for 67% of the total energy wood category; residential (21%), electricity generation (8%), and commercial uses (3%) made up the rest (US EPA 2010).

Carbon fluxes from US forests vary by region and ownership. Forests in the South are more intensively managed and have the lowest level of emissions related to natural mortality, and more of their gross growth is converted into products and energy feedstocks. Along the North and Pacific Coasts, the proportions of forest biomass going into products and energy, new growing inventory, and mortality is approximately equal. Forests in the Rocky Mountains have a large ratio of new inventory to harvested products, because there is little harvest activity in that region, but also have high flux into natural mortality. Recognizing the regional variations in where forest carbon accumulates is the key to interpreting national and sector-specific accounting.

Climate–Forest Interactions

Because forests cover approximately 30% of the Earth's land surface and store about 45% of terrestrial carbon (Sabine et al. 2004), forests and global climate are closely linked. Recent empirical results (Baldocchi 2008) and climate models that now link the biosphere and atmosphere (Bonan 2008) indicate that the interactions between forests and the atmosphere are highly complex. Climatic changes can affect existing forests, for example, though incidence of drought, fire, and reproductive cycles of forest pests. Conversely, forests can affect climate in ways other than carbon storage. An overview of the three major forest biomes (tropical, temperate, and boreal) and the three major processes that connect forests with the climate (carbon, energy, and water fluxes) helps puts US forests in a global context.

Forest Biomes and Forest–Atmosphere Fluxes

The three major forest biomes have very different biophysical dynamics with significant consequences for the atmosphere (Table 3-1). The United States has all three types: 3.03 million km^2 of temperate forests, 0.46 million km^2 of boreal forests, and 0.02 million km^2 of tropical forests (Smith et al. 2009). Total carbon storage is similar for each biome, even though photosynthesis is highest in the tropics and declines toward the poles. Only a fraction of the carbon captured by photosynthesis is added to carbon storage. A global review of net ecosystem carbon exchange concluded that "in general, 77 gC m^{-2} year^{-1} of carbon is lost by ecosystem respiration for every 100 gC m^{-2} year^{-1} gained by gross photosynthesis when an ecosystem has not experienced recent and significant disturbance" (Baldocchi 2008). A synthesis of 10 carbon flux studies (Misson et al. 2007) concluded that forest floor and soil respiration made up around one-half of the total site respiration. The increase in forest floor and soil respiration is proportional to how much residue is left on site to decompose (Amiro 2006a). Although the carbon contained in logging residues and dead trees is not considered as part of the growing stock in forests, the deadwood has a significant effect on forest respiration and the net carbon flux at the forest level.

Carbon flux dynamics differ significantly among the three forest biomes. For instance, because most solar energy entering the atmosphere is absorbed by the land and then transferred to the atmosphere (McGuire and Chapin 2006), the role of forests in energy fluxes has considerable relevance. A significant energy flux is the drop in the albedo (and the reflection of solar energy back through the atmosphere) when dark-colored trees expand at the expense of snow-covered areas (Bonan 2008, Jackson et al. 2008, Anderson et al. 2011). A lower albedo decreases the fraction of solar energy that is immediately reflected. The expansion of boreal forests into areas that are currently tundra has been noted in many northern latitudes. The energy feedbacks related to decreased albedo from the natural movement of forests into tundra regions can have local as well as global impacts (Euskirchen et al. 2010).

Links between water and carbon flux are seen most strongly in the tropics. The most significant water flux linkage between forests and the atmosphere is the evaporative cooling from tropical forest canopies, which has a positive relationship with cloud formation and rainfall patterns (Fung et al. 2005). Other research has pointed to a tradeoff between increased carbon storage and reductions in streamflow from afforestation in semiarid locations (Jackson et al. 2005). In boreal forest regions, warming has also been associated with more fresh-water runoff into the Arctic Ocean and more area of wetlands and water bodies that can be a significant source of methane (Chapin et al. 2000). Some researchers have estimated that the climate implications of the biogeophysical effects related to energy and water fluxes are of a similar order of magnitude as aboveground carbon sequestration (Arneth et al. 2010).

Climate-Related Characteristics of Forest Biomes

New data on changes in tropical forest cover have lowered the estimates of net greenhouse gas emissions from tropical deforestation and suggest an emphasis on deforestation where carbon-rich peat soils are disturbed (van der Werf et al. 2009, Friedlingstein et al. 2010). Nevertheless, a review of numerous studies shows that when all feedbacks are considered, tropical forests are generally seen as the most effective forests for providing climate benefits per unit of area or biomass (Jackson et al. 2008).

Although temperate forests cover the least area of the three biomes, they are the source of most of the sustainably produced wood products. Temperate forests continue to increase as carbon sinks (Friedlingstein et al. 2010) even though large quantities of wood are removed annually. The current

Table 3-1. Area, storage, and gross photosynthesis of global forest biomes.

Biome	Forest area (million km^2)	Total carbon storage (kg C/m^2)	Gross primary productivity (photosynthesis; kg C/m^2 per yr)
Tropical forests	17.5	31.6	2.322
Temperate forests	10.4	28.1	0.954
Boreal forests	13.7	28.8	0.605

Note: Total carbon storage includes vegetation and soil organic matter.
Sources: Grace (2004), Anderson et al. (2011), and Beer et al. (2010).

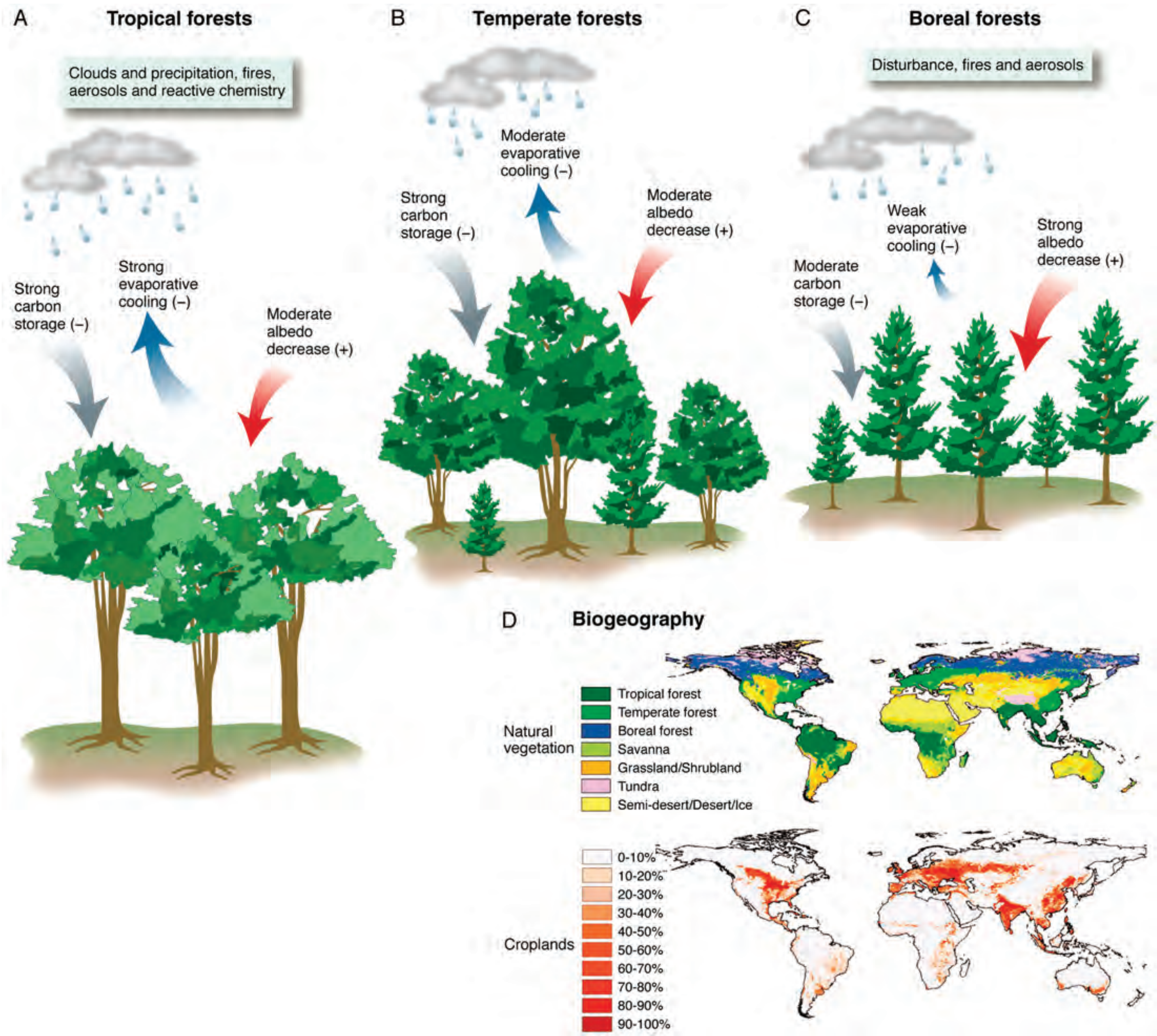

Figure 3-1. Forest biomes' atmospheric interactions and geographic distribution. (Source: Bonan (2008).)

rate of carbon accumulation may decline, however, if the average age of the trees in US forests continues to increase (Albani et al. 2006). Some researchers believe that management can enhance forest productivity even under changing climatic conditions. The key, they suggest, is matching seed sources and silvicultural methods to future rather than historical climatic conditions (Lindner and Karjalainen 2007, Nabuurs et al. 2007).

Boreal forests constitute 77% of Canadian forests (Natural Resources Canada 2005) and 13% of US forests (Smith et al. 2009). These forests have already experienced significant changes due to warming climates (Randerson 2006, Kurz et al. 2008b, Chapin et al. 2010). Outside the intensively managed boreal forests in Scandinavia, the natural forests in most other boreal regions may experience changes that are still only poorly understood (Amiro et al. 2006b, Euskirchen et al. 2009, Chapin et al. 2010). Such forests are believed to be less amenable to cost-effective management interventions than temperate forests.

Figure 3-1 highlights the relative magnitudes of the three major fluxes (carbon, water, and energy) for the three major forest biomes. Focusing on only one or two of these fluxes as guidance for forest climate policy may give a biased perspective.

Atmospheric models and forest cover and forest inventory models give very different estimates of the carbon, water, and energy balances of forests (Houghton 2003) and, therefore, policy inferences drawn from any single model type may be highly misleading. Our understanding of forest dynamics continues to improve with the development of more accurate models that couple the carbon in atmosphere with the carbon in vegetation (Bonan 2008, Tjoelker et al. 2008, Beer et al. 2010, Yuan et al. 2010), make use of better field-based measurements (Baldocchi 2008), and more effectively link process models and experimental field data (Vargas et al. 2010). Better understanding of the influence of nitrogen depositions on growth and soil respiration in temperate forests (Magnani et al. 2007) and global nitrogen fluxes (Thornton et al. 2009) is also clarifying the relevant feedbacks.

Climate Induces Disturbances and Mortality

Climate change will bring disturbances that affect tree mortality and forest regeneration. Drought and species range shifts are mentioned as critical processes associated with climate change, but in western North America two processes dominate the discussion: wildfire and bark beetle outbreaks.

Wildfire is the dominant natural disturbance regime in western forests (Agee 1993). Changes in wildfire behavior, extent, frequency, and impact in the past 10 years are notable (Calkin et al. 2005) and highly correlated with changing temperature patterns and drought (McKenzie et al. 2004, Gedalof et al. 2005, Westerling et al. 2006, Littell et al. 2009b). Although fuel buildup from fire suppression plays a role in increasing fire extent and intensity, Littell et al. (2009b) found that the predictors for large fire years are all related to climate. Researchers predict at least a doubling of the area burned annually for western forests (McKenzie et al. 2004, Gedalof et al. 2005, Westerling et al. 2006, Littell et al. 2009a) under moderate climate change scenarios.

Massive and ongoing mountain pine beetle (*Dendroctonus ponderosae*; MPB) outbreaks have affected the entire range of susceptible pine in the West from New Mexico to Alaska, and outbreaks of spruce bark beetles (*Dendroctonus rufipennis*) have been significant in northern British Columbia and Alaska. Bark beetle outbreaks are a natural part of the western forest ecosystem, but their severity and extent have dramatically increased in the past 10 years as a result of climate change (Logan and Powell 2001, Carroll et al. 2004, Logan et al. 2003, Gibson 2006, Oneil 2006). In more northerly regions, MPB outbreaks have been correlated with warmer winters (Carroll et al. 2004), whereas outbreaks to the South have been correlated with hotter, drier summers (Oneil 2006). In southern Alaska, spruce bark beetle outbreaks have been substantial (Berg et al. 2006), causing 90% or higher mortality in mature forest stands. These outbreaks are associated with warm summers that permit bark beetles to change from a 2-year to a 1-year life cycle. For the western United States, summer temperature extremes and/or extended droughts are predicted under regional climate change scenarios. Both conditions increase tree mortality, either directly through die-off (Adams et al. 2009, Breshears et al. 2009) or indirectly by increasing stress complexes (McKenzie et al. 2008) that collectively cause large-scale mortality. The most likely scenarios involve greater water deficits across drier areas of the West, leading to species die-offs (Littell et al. 2009a). These effects are not limited to western North America: Allen et al. (2010) found that climate change–related mortality driven by water stress affects forests globally.

Biomass Use and Feedstock Issues

The supply of biomass as feedstock for energy production depends not just on supply and demand but also on the physical amounts from different sources; delivered costs; and national, regional, state, and local laws, regulations, and policies. Regional variations influence the United States' potential biomass supply and ultimately the placement of bioenergy facilities. Whether biomass is removed and used for energy affects ecological systems and influences long-term climate change mitigation measures.

Availability of Biomass

Biomass feedstocks for bioenergy and biofuel include forest and agricultural resources, residuals from forest product mill operations, and municipal solid and urban waste wood (Perlack et al. 2005). Although each source is important, this article focuses on forest resources—residues from timber harvest, hazardous fuel reduction, forest health restoration projects, and energy wood plantations—based on forest growth, removals, and mortality (Figure 4-1).

The "Billion Ton Report" projected the potential amount of biomass to be as much as 1.2 billion tons of biomass availability annually in the United States (Perlack et al. 2005). It is now recognized, however, that the actual amount, given social, political, and market constraints, will be less (Sample et al. 2010, US DOE 2011).

Five types of biomass have been defined (White 2010):

- *Potentially available biomass* is all the woody biomass reported to be available.
- *Technically available biomass* is the amount of woody biomass that can actually be used, determined as a percentage of potentially available biomass and representing the amount expected to be recoverable using current or expected technology (e.g., Perlack et al. 2005). Updated estimates of these volumes are also provided as available supplies based on accessibility and operability for each US region (Greene et al. 2010).
- *Market price biomass* is the amount of woody biomass that could be available at a given market price (e.g., Biomass Research and Development Initiative [BRDI] 2008, Walsh et al. 2003).
- *Supply curve biomass* is the amount of woody biomass available over a range of biomass prices (White 2010).
- *Performance-based biomass* is the amount of woody biomass available via a field verification of a coordinated resource offering protocol (CROP). Developed for the US Forest Service, CROP is a tool for assessing biomass supply from land management agencies, based on "ability to perform" removal (versus potential to remove based primarily on inventory) (Mater and Gee 2011).

The use of energy fuels has changed slowly over time. Wood served as the main form of energy for about half of the United States' history. Coal surpassed wood in the late 19th century and was in turn overtaken by petroleum products in the mid-1900s. Natural gas consumption experienced rapid growth in the second half of the 20th century, and coal use also began to expand as the primary source of electric power generation (Energy Information Administration 2010). The majority of bioenergy produced from woody biomass is consumed currently by the industrial sector—mostly at pulp and paper mills that use heat and electricity produced on site from mill residues (White 2010). But that is changing. As of January 2011, there were 445 (nonpulp and paper mill) operating and announced wood-using bioenergy projects in the United States, ranging from wood pellet mills and wood-to-electricity plants to pilot projects for cellulosic ethanol (Forisk Consulting 2010).

Factors that Affect Feedstock Supply

Changes in feedstock supply are controversial and a point of contention for competing industries (paper and pulp versus bioenergy), environmental groups, private landowners, and public land managers. The controversy is amplified by uncertainties surrounding the effects of climate change on forests and the best mix of mitigation and adaptation strategies to use across forest types and landowner categories. Research

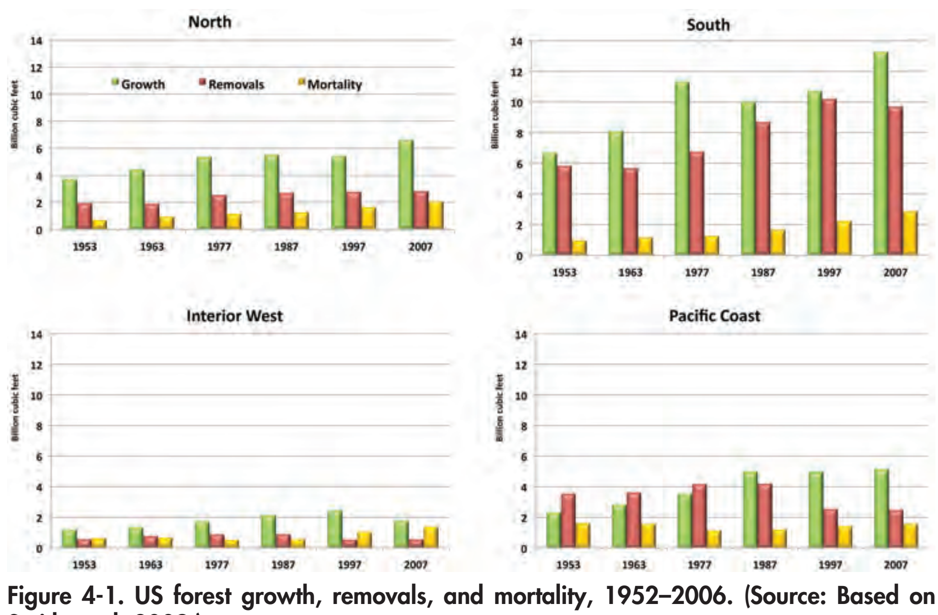

Figure 4-1. US forest growth, removals, and mortality, 1952–2006. (Source: Based on Smith et al. 2009.)

has begun to analyze the perceived competition conflicts between traditional consuming forest products mills and new wood energy plants. For example, Ince et al. (2011, 142) modeled US forest sector market and trade impacts of expansion in domestic wood energy consumption under hypothetical future US wood biomass energy policy scenarios. Bowyer (2011) also examined policy implications for bioenergy development, as well as the likely impact of global energy trends on biomass demand.

Environmental Consequences and Constraints

The ecological effects on soils, wildlife, fire regimes, and water quality of using biomass for bioenergy depends on the existing condition of the forest stand and the amount of biomass to be removed over a specific period. The results depend on such factors as the timing of removal and the nature of the biomass (e.g., logging residues or short-rotation woody crops; Pan et al. 2008, 2010, Hurteau et al. 2008).

There are concerns that if too many bioenergy and biofuel plants are established over time they will not be sustainable. However, sustainable forest management practices are well known and widely practiced and can protect forests' environmental and ecological values. States such as Minnesota, Wisconsin, and Pennsylvania, are developing woody biomass removal guidelines to ensure small-scale and sustainable bioenergy plants can meet long-term environmental, ecological, and economic needs. Use of forestry best management practices and certification systems such as the American Tree Farm System, Sustainable Forestry Initiative, and Forest Stewardship Council is also widespread.

There can be environmental tradeoffs involved in removing harvesting residuals where the residuals have value in maintaining site productivity and biodiversity. Site responses to residue removal and retention depend on site conditions and limiting factors. Scientific evidence from sites across North America suggests that the productivity of most sites is largely resilient to removing harvesting residuals (Powers et al. 2005). For instance, Westbrook et al. (2007) found that even with removal of all harvesting residues and all nonmerchantable woody biomass between 1- and 4-in. dbh, nutrient losses from a Georgia pine plantation were expected to be replaced by precipitation in 5 years. Overall, documentation of negative effects on site productivity due to biomass removal is rare.

Two recent meta-analyses of the scientific literature suggest that effects of biomass harvest on biodiversity can vary by forest harvesting practice and other factors. Studies of forest thinning have generally reported positive or neutral effects on diversity and abundance of terrestrial vertebrates and invertebrates across all taxa, although thinning intensity and the type of thinning may influence the magnitude of response (Verschuyl et al. 2011). Studies that document biodiversity response to harvest of coarse woody debris and/or standing snags report substantially and consistently lower diversity and abundance of cavity- and open-nesting birds and reduced invertebrate biomass in treatments with lower amounts 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). With scientific support lacking for significant project level impacts, harvesting guideline provisions should allow managers the flexibility to tailor prescriptions to site conditions and limiting factors and promote analysis of the impacts across a scale that includes numerous ownerships and projects.

Genetic Improvement and Woody Crops

Genetic tree improvement programs have focused on improving phenotypic characteristics, predominantly to increase volume for timber production. Today, mostly private companies are investing in poplar and willow to increase feedstocks through advanced genetics in tree selection. Mass control pollinated and varietal pine seedlings that exhibit genetic gains are now available (Dougherty 2007).

Poplar breeders in the United States have focused on increasing adaptability, growth rates, and pest and stress resistance. Significant increases have been achieved through traditional selection and breeding along with intensified cultural practices. Efficiencies have also been gained in harvesting and handling. Opportunities for manipulating feedstock quality have long been recognized but have gone largely unrealized because of uncertainties over which traits to modify for what process and because of some social resistance to genetic modification of trees. Quality changes can affect process efficiency in numerous ways, but reliable information concerning the effects is sparse (Dinus 2000, BRDI 2008, Sample et al. 2010, White 2010).

Short-rotation woody crops, such as shrub willow, hybrid poplar, southern pine, and eucalyptus, have the potential to increase biomass feedstocks, but large-scale production of these crops has yet to occur (Volk et al. in press). Hybrid poplars grown in the Midwest, South, and Pacific Northwest under intensive silviculture can provide biomass for energy as well as sawlogs, veneer logs, and fiber for the pulp and paper industry (Volk et al. in press). Coppice systems are still under development, but yields from commercial plantations range from 9 to 10 oven-dry tonnes (odt)/ha per year in the Midwest to 18 odt/ha per year in the Pacific Northwest (Netzer et al. 2002). With additional research, including breeding and genetic advances, sustainable yields of 16, 24, and 36 odt/ha per year are possible in the Midwest, South, and Pacific Northwest, respectively (Volk et al. in press).

Pine and eucalyptus grown in the South also have the potential to supply biomass as well as sawlogs and fiber. Loblolly pine's widespread cultivation and high growth rates make it a likely candidate for short-rotation culture (Dickmann 2006), but extensive development is required. Eucalyptus has been called an ideal species for biofuels and bioenergy (Volk et al. in press), and in the South, it can be produced and delivered at a cost competitive with grasses and other hardwoods. Under the right growing conditions, it can produce more than 29 odt/ha per year for either biomass feedstock or ethanol (Gonzalez et al. 2009, 2010, 2011a, 2011b).

Economics

Traditional forest products such as sawtimber and pulpwood are more or less complementary uses, because pulpwood can be managed to become sawtimber. Forest biomass, at least for energy generation, can come from pulpwood-size trees, which are easily substituted: established markets, silvicultural systems, and harvesting and logistics supply chains already exist. Although traditional pulpwood harvesting can accommodate small woody biomass and forest residue collection, there is a point at which production efficiency suffers (Westbrook et al. 2007). Price to the landowner will invariably be a determining factor of end use. The traditional forest products industry, particularly the pulp and paper sector, has already seen price competition for pulpwood to be turned into pellets (Greene et al. 2010).

Government Policy

The Biomass Research and Development Act of 2000 authorized an interagency board (representing USDA, Department of Energy, Department of the Interior, and the Environmental Protection Agency) to promote development of biofuels in the United States. The Board recently issued an eight-point strategic plan focused on this goal. Agency coordination was recognized as important given often conflicting agency initiatives and guidance from Congress. For instance, the Energy Policy Act of 2005 disallowed the use of federal woody biomass for the renewable energy credit. In contrast, Section 203 of the Healthy Forests Restoration Act of 2003 (PL 108-148, codified at 16 US Code Section 6531) provided authority for the Biomass Commercial Utilization Grants Program, which emphasizes the use of woody biomass especially from wildfire-affected areas in the wildland–urban interface. The Food, Conservation, and Energy Act of 2008 (PL 110-234; Farm Bill 2008), under Title IX, Section 9011-9013, promotes the use of woody biomass for research and development of biofuels, wood-to-energy programs for states and local communities, and includes the Biomass Crop Assistance Program (BCAP).

Differing and often conflicting definitions of *renewable biomass* in current federal energy policies hinders policy implementation and the development of biomass markets. A universal definition of renewable biomass that includes renewable, sustainable forest biomass—and does not confound this definition by attempting to address other policy goals—would promote the development of sustainable energy and environmental policies on appropriate lands.

A further problem is that policies designed to promote the use of forest biomass energy have focused on development of transportation fuels despite public concerns about this direction. As Caputo (2009) describes the situation:

> … federal incentives have largely focused on the production of renewable transportation fuels and co-products. Input from stakeholders indicates that future policies should focus on improving forest sustainability, increasing research capabilities, and improving the economics of biomass utilization. Additionally, many feel that the production of heat and power should be given similar attention to the production of liquid transportation fuels as an important use for woody biomass.

Landowner Preferences

The availability of biomass feedstocks will also depend on landowner preferences, which vary based on the type of ownership. Numerous studies have documented that for nonindustrial private forest landowners, harvesting is often a secondary objective (e.g., Butler 2008). Even industrial and those nonindustrial private forest landowners interested in harvesting forest biomass are often reluctant to engage in the long-term contracts necessary to participate in forest carbon offset projects.

Nonindustrial forest landowners who seek maximum revenue, may plant short-rotation woody crops, such as hybrid popular or willow, in response to the incentives created by BCAP. For example, Gan et al. (in press) found that without financial incentives and technical assistance, fewer than 6% of landowners would be willing to thin forest stands for energy production even if it reduced fire hazard, but with government cost sharing and technical assistance for growing biomass, two-thirds of timberland landowners would consider producing biomass for bioenergy purposes. The most reasonable expectation about biomass production by private landowners is that they will be guided by economic reality and sustainability. High transaction costs can prevent interested nonindustrial landowners with small acreage from participating in biomass projects.

Wood–Fossil Fuel Substitution Effects

When trees are harvested, carbon is removed from the forest. It is tempting to conclude that forest harvesting should be avoided to reduce carbon emissions and maximize carbon storage. However, careful consideration of carbon flows reveals that conversion of wood to useful products can significantly reduce overall societal carbon emissions. Major considerations are the low carbon emissions associated with wood products manufacture, carbon storage in long-lasting wood products, avoided emissions that result when wood is used in place of energy-intensive materials and products, and the efficient use of wood residues for energy.

To arrive at a cogent picture of the forest sector's overall effects on atmospheric carbon, we need to understand the material and energy flows as inputs and outputs within well-defined system boundaries. Analysis using attributional life-cycle assessment (LCA) methods that measure inputs and outputs within a system boundary explains the interactions at that scale. We then need to integrate these effects across system boundaries to see how substitution of harvested wood products for fossil fuels and fossil fuel–intensive products can offset the flow of carbon dioxide from fossil fuel reserves to the atmosphere.

Product Flows of Harvested Wood

Carbon makes up a considerable proportion of wood volume, amounting to about 50% of the moisture-free weight. Within forests, significant quantities of carbon are stored (or sequestered) in the twigs, branches, boles, and roots of trees. Additional carbon is stored in forest litter and forest soils. In 2005–2009, some 24–25 billion tonnes of carbon was stored in standing trees, forest litter, and other woody debris in US forests, and another 20–21 billion tonnes was in forest soils and roots (US Environmental Protection Agency [EPA] 2010). Carbon is also found within harvested wood products. The carbon in wood products in use and in landfills during 2005–2007 was estimated at 2.3–2.4 billion tonnes—equivalent to 5.2–5.7% of forest carbon pools.

Carbon was sequestered in US forests during 2005–2007 at a rate of 192 million tonnes/year. The annual rate of carbon accumulation within wood products in use and in landfills was estimated at about 28–29 million tonnes—14.8% of the rate of sequestration within forests and 22–23% of the annual additions to nonsoil forest carbon stocks (US EPA 2010). 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.

Much of the carbon in wood products resides in the nation's housing, as well as in commercial, industrial, public, and other structures. Wood-framed buildings make up about 90% of homes in the United States, and in all homes, whether wood framed or not, wood furniture, cabinets, flooring, and trim are dominant.

Emissions from Wood Products Manufacture

The carbon dioxide that is removed from the air as a tree grows is combined with water and converted to simple sugars within the leaves, conveyed downward through the branches and bole in the form of sap, and then converted into complex polymers that combine to form an intricately structured polymeric material that has a higher strength-to-weight ratio than structural steel. That this natural process uses freely available solar energy largely explains why the energy embodied in wood products is lower than for any other construction material (Glover et al. 2002, Perez-Garcia et al. 2005, Gustavsson and Sathre 2006, Lippke et al. 2010). "Embodied energy" refers to the quantity of energy required by all the activities associated with a production process, including gathering, transporting, and primary processing of raw materials. Lumber, in particular, requires little energy to produce, because only minimal processing is needed to convert the naturally produced wood to desired shapes (Milota et al. 2005, Puettmann et al. 2010). Wood products, such as furniture, require more steps in processing and therefore more energy (e.g., Puettmann and Wilson 2005, Wilson 2010) but still significantly less energy than nonwood materials (Lippke et al. 2010).

Not only does production of lumber and wood products require relatively little additional energy beyond the solar energy used in tree growth and wood production, but very little of that additional energy comes from fossil fuels. In the United States in 2008, renewable energy produced from tree bark, sawdust, manufacturing and harvest residuals, and byproducts of pulping in papermaking processes provided 65% of the energy used in manufacturing paper products and more than 73% of the energy used in manufacturing wood products (American Forest and Paper Association 2010). In the same year, the wood and paper industries of the United States accounted for 94% of the manufacturing sector's derived renewable fuel use, and they generated 37% of the total energy produced by cogeneration-capable systems within all manufacturing sectors.

Because wood is produced using solar energy, the manufacture of lumber and other wood products requires little additional energy. Moreover, only one-quarter to one-third of the energy consumed is fossil energy. The result is that total emissions from wood products manufacture, including emissions of carbon dioxide, are typically lower than for potential wood substitutes on a weight or mass basis (Table 5-1). For example, carbon emissions for the manufacture of a tonne of lumber are markedly less than for a tonne of steel, plastic, or aluminum.

Product Substitution

For every use of wood there are substitutes: wood studs can be replaced by steel studs, wood joists by steel I-joists, wood walls by concrete walls, wood floors by con-

Table 5-1. Net carbon emissions in manufacture per tonnes.

Material	Net emissions (tCe)
Framing lumber	0.033
Concrete	0.034
Concrete block	0.038
Medium-density fiberboard (virgin fiber)	0.088
Brick	0.088
Glass	0.154
Recycled steel (100% from scrap)	0.220
Cement (Portland, masonry)	0.265
Recycled aluminum (100% recycled content)	0.309
Steel (virgin)	0.694
Molded plastic	2.502
Aluminum (virgin)	4.529

Notes: Values are based on life-cycle assessment and include gathering and processing of raw materials, primary and secondary processing, and transportation; a 10% increase in energy consumption is assumed for the production of concrete block. tC, tonnes of carbon equivalent.
Sources: Based on US EPA (2006, Exhibit 2–3); data for concrete is from Flower and Sanjayan (2007).

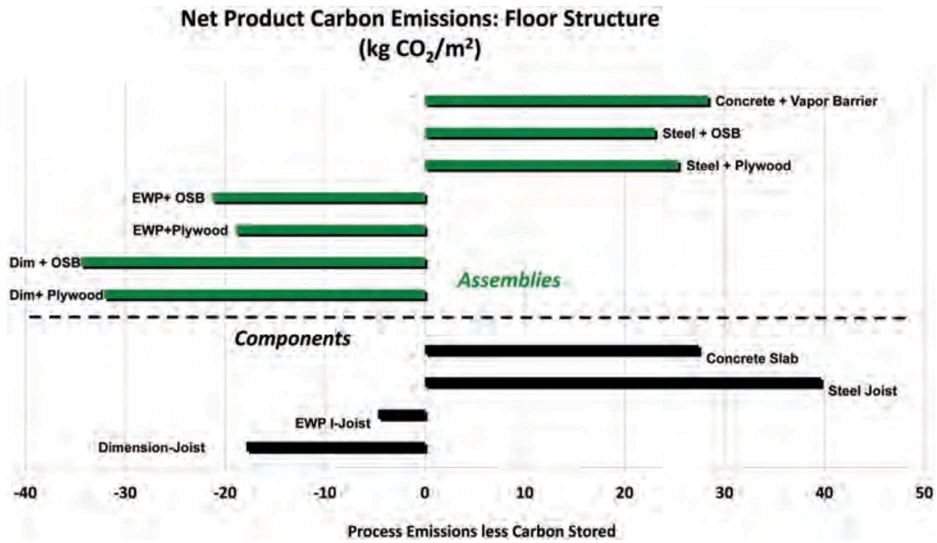

Figure 5-1. Process emissions less carbon stored in floor structure components and assemblies. Notes: EWP = engineered wood product, OSB = oriented-strand board, Dim = dimension lumber. (Source: Adapted from Lippke and Edmonds (2009).)

crete slab floors, and biofuel by fossil fuel. Every product use has its own life-cycle carbon footprint (Perez-Garcia et al. 2005, Lippke and Edmonds 2009). Using life-cycle inventory (LCIs), which include the carbon stored in wood as well as the processing emissions to harvest, transport, and make the product, one can compare the net carbon consequences of substituting one product for another.

Life-cycle analyses have shown marked differences in energy requirements and carbon emissions associated with different building materials and the structures made from them (Glover et al. 2002, Gustavsson and Sathre 2006, 2011, Perez-Garcia et al. 2005, Buchanan 2007, Gerilla et al. 2007, Salazar and Meil 2009, Lippke et al. 2010). Comparisons of structures having comparable heating and cooling requirements show that wood products and structures require the least energy to produce and consequently have the lowest greenhouse gas (GHG) emissions profile. Thus, substituting wood for more energy-intensive, nonrenewable materials produces a substantial net reduction in carbon emissions, called the substitution effect. In addition, wood stores carbon for the useful life of the product, enhancing the benefits of wood relative to other building materials.

The comparisons in Table 5-1 are per tonne of product. More appropriate comparisons, which reflect the functions that products perform, have been made between wood and nonwood assemblies for walls, floors, and sheathing. Wood fares well in such comparisons because of its high strength relative to weight, its low embodied energy, and carbon stored in the product itself. Lippke and Edmonds (2009) show the relative process emissions and stored carbon per functional unit for wood and nonwood products (Figure 5-1). In Figure 5-1 the vertical zero line is where process emissions equal carbon stored. A component (black bars) or assembly (green bars) to the right of the zero line produces more emissions than it stores, and one to the left of the line stores more carbon than it takes to produce (i.e., is a carbon sink) as long as the product remains in use. Longer useful life, recycling, and reuse extend the period of this offset. Similar charts for wall assemblies (not shown) show the same patterns, with wood products storing more carbon than is emitted during their harvest and manufacturing.

Another study compared wood and steel houses built to Minneapolis code standards and wood and concrete houses built to Atlanta code standards (Meil et al. 2010). The two designs shared many of the same structural assemblies (i.e., foundation footings and basement block wall, support beams and jack posts, and roof), and therefore the differences in the environmental effects can be traced to their respective wall and floor assemblies. For the Minneapolis house, the steel design was found to embody 66% more energy (measured in megajoules per square foot of assembly) and generated 49% more global warming potential than the wood design. Focusing on only the assembly groups affected by changes in material use (i.e., walls, floors, and roofs) revealed more pronounced differences. For instance, compared with the wood design, the steel design's floors and roof were found to embody 245% more energy and produce a corresponding increase in global warming potential. In the Atlanta comparison, increases in embodied energy and global warming potential were determined to be 41% and 65% higher for concrete construction than for wood houses, respectively. Comparisons of building components made to specified codes using wood, steel, and concrete options show that wood designs produce not only the lowest global warming potential, but also provide the lowest emissions to air and water. (See, for example, Table 3-1, Malmsheimer et al. 2008). Only in the solid waste category does wood fare worse than steel, a result that arises because steel is precut and wood is cut on site during construction (Lippke and Edmonds 2006). Further examination of fossil fuel consumption and associated carbon emissions, linked to construction of entire structures, reveals that differences in global warming potential for the various designs are in nearly direct proportion to the differences in fossil fuel consumption (Tables 5-2 and 5-3).

An analysis of carbon storage and avoided emissions for wood versus steel construction in a large wood structure also illustrates the carbon-related advantages of wood (Table 5-4). The completed structure, in Anaheim, California, comprises five sto-

Table 5-2. Consumption of fossil fuels associated with exterior wall designs in warm climate home.

	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 gypsum for both designs.
[d] Includes subtotals from structural, insulation, and cladding categories.
Source: Edmonds and Lippke (2004).

Table 5-3. Consumption of fossil fuels associated with floor designs (excluding insulation).

	Fossil fuel energy (MJ/ft^2)
Dimension wood joist floor	9.93
Concrete slab floor	24.75
Steel joist floor	48.32

Source: Edmonds and Lippke (2004).

Table 5-4. Carbon storage and avoided emissions from wood versus steel commercial/residential complex.

Carbon sequestered and stored (CO_2e)	3,970 tonnes
Avoided greenhouse gases (CO_2e)	8,440 tonnes
Total potential carbon benefit (CO_2e)	12,410 tonnes

Source: This case study is based on use of the Forintek Wood Carbon Calculator for Buildings based on research by Sathre and O'Connor (2010) and is described by WoodWorks (2011).

ries of wood frame construction over a concrete parking garage and first level and includes 251 luxury apartment units and 13,000 ft^2 (1,208 m^2) of retail space. The structure incorporates 5,201 m^3 of wood, with resulting long-term storage of 3,970 tonnes of equivalent carbon (CO_2e), with twice that level of avoided GHG emissions resulting from selection of wood rather than traditional steel construction.

The effect of substitution on a per hectare basis is illustrated in Figure 5-2, which compares substitution of wood for concrete in construction and its carbon implications over a timeline of two rotations of a forest initially planted on bare land. Carbon stored in products (designated as "products carbon") is significant relative to the carbon stored in the live- and dead-tree biomass (designated as "forest carbon"). Furthermore, well before the end of two rotations, overall sequestration of carbon (forest carbon plus products carbon plus substitution carbon) far exceeds carbon sequestration in an unmanaged forest (i.e., a forest managed without timber extraction, shown as the dotted line designated as "no-harvest carbon"). The figure includes the carbon emissions associated with generation of bioenergy from short-lived product pools, taking into account that the efficiency of the conversion of wood to energy is lower than for gas- or coal-fired boilers. A net benefit in this case appears about 30 years after stand establishment, with benefits increasing over time. The managed and no-harvest forest scenarios both use growth trends in Douglas-fir, a species that is known to maintain growth well into advanced years (Curtis and Marshall 1993). Other species with growth rates that peak sooner show even larger differences in the relative carbon sequestration between managed and unmanaged forests. These trajectories show the relative carbon consequences assuming a change in management intent at the point when the first thinning was implemented. In practice, a no-harvest forest scenario would more often than not have a lower forest growth trajectory because the investment in regenerating the forest from bare land would not have occurred without the expectation of a return on the investment in later years.

As the examples illustrate, substitution values vary with the wood product or assembly in question and its alternative. Sathre and O'Connor (2010) conducted a meta-analysis to estimate average substitution rates for common building products. They arrived at a value of 2.1 tonnes of carbon displaced per tonne of wood carbon used. This is a more general characterization of substitution across all wood uses than the specific examples shown in Figures 5-1 and 5-2 and Tables 5-3 and 5-4.

End-of-Life Considerations

Based on census data, the half-life of the US housing stock is approximately 80 years (Table 5-5; Winistorfer et al. 2005). First-order decay functions have often been used to estimate losses of wood in use over time (e.g., Intergovernment Panel on Climate Change [IPCC] 2007b), but they greatly overestimate early losses because they assume the highest decay (loss) rate when there is the most stock, with a declining rate thereafter. Because houses are rarely demolished in their first 10 years, first-order decay func-

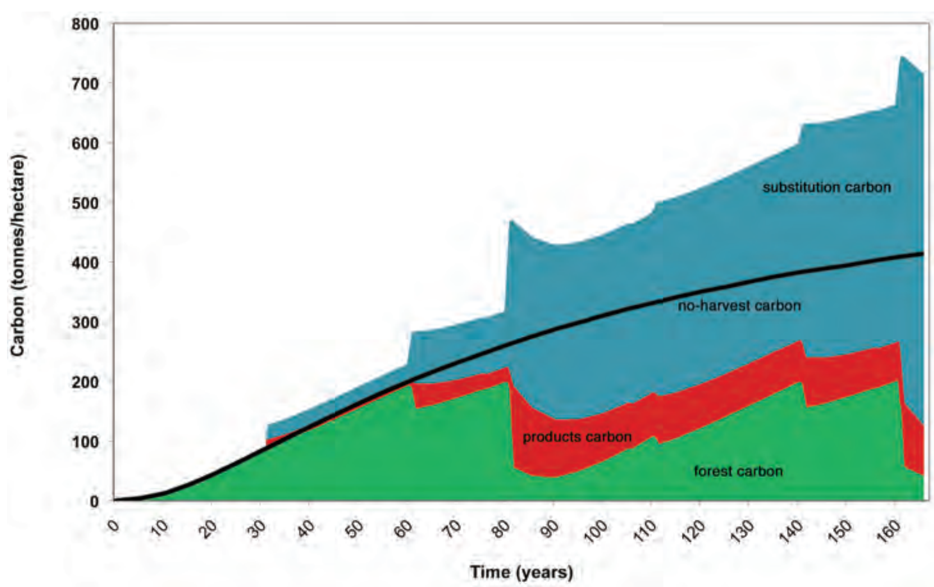

Figure 5-2. Carbon (tonnes per hectare) stored in forests (designated as "forest carbon") in products (designated as "products carbon"), and retained in the lithosphere because of substitution for concrete and fossil fuel energy (designated as "substitution carbon"), compared with carbon stored in an unmanaged forest (dotted line designated as "no-harvest carbon"), per hectare of forest. Notes: Douglas-fir forest, 80-year rotation, with intermediate thinnings at years 30 and 60; portion of wood harvested at rotation age used for long-lived construction products; dotted line indicates unmanaged forest. (Sources: Perez-Garcia et al. (2005), Wilson (2006).)

Table 5-5. Projected half-lives for end uses of wood.

Use	Half-life (yr)
Single-family home (1920 and before)	78.0
Single-family home (1921–1939)	78.8
Single-family home (1939–)	85.0[a]
Multifamily home (as fraction of half-life for single-family home)	52.3[b]
Housing alteration and repair (as fraction of half-life for single-family home)	25.7[c]
All other uses for solidwood products	38.0
Paper	2.5

[a] Based on half-life increase per 20 yr for post-1939 period.
[b] Based on half-life of multifamily home that is 0.61 of single-family home.
[c] Based on half-life of repair and remodel that is 0.30 of single-family home.
Source: Based on Skog (2008).

Table 5-6. Fate of material in solid waste disposal sites.

	Fraction permanently sequestered	Fraction that decays	Half-life of decaying portion
Solid wood	77%	23%	29.0 yr
Paper	44%	56%	14.5 yr

Source: Based on Skog (2008).

tions fail to capture the carbon storage potential of long-lived materials. An alternative approach has been proposed by Marland et al. (2010), who applied gamma functions to distributed product pools so that short-lived products, such as paper, decay quickly but long-lived products, such as oriented strandboard and lumber, decay more slowly. Refinement of the parameters used by Marland et al. (2010) to reflect actual decay rates on a regional, national, or wood basket basis is needed, but the functional form improves on previous estimates of decay rates.

The collection efficiencies of landfilling have carbon storage implications (Skog 2008). Of the wood products that enter solid waste disposal sites, more than three-quarters of the carbon in solid wood and almost one-half of the carbon in paper is never released to the atmosphere (Table 5-6). The carbon that is released during decay takes many years to reach the atmosphere. For example, the 23% of the solid wood that does decay has a half-life of 29 years. Skog (2008) found that when paper is landfilled, the nonlignin component (56%) decays, leaving the lignin component (44%) as a long-term store in the landfill (Table 5-6). This nondegradable fraction varies by grade, from approximately 10% for bleached chemical pulp fibers to 85% for mechanical pulp fibers (US EPA 2006).

Methane emissions from wood degradation in a landfill can offset any benefits of carbon stored there. Heath et al. (2010) found that with current landfill design and operating practices, US landfills appear to be a net long-term sink for carbon in wood products but a long-term source of GHG emissions from paper products, particularly paper that contains a large fraction of carbon that is degradable under anaerobic conditions. This suggests that incentives should be high to reuse paper and wood, recycle it, or burn it to recover its heating value, and that landfills should be managed to recapture the energy value of methane emissions. Collection systems are evolving rapidly. For example, US EPA (2007b) reported that the recovery or oxidization of methane increased from 20 to 50% between 1990 and 2006. Methane capture from landfills is one of the most cost-effective investments for atmospheric GHG reduction because of the dual benefit stream of reducing methane release (methane has 25 times the global warming potential of CO_2; Forster et al. 2007) and converting the methane into usable energy that offsets fossil fuel emissions.

Wood Energy

The US Department of Energy (DOE) estimates that in 2009, about 8% (7.75 quadrillion Btu) of the energy consumed in the United States came from renewable sources (excluding ethanol; US DOE 2010). For 2004–2008, about 30% (2.1 quadrillion Btu) of this renewable energy was supplied from woody biomass, equivalent to about 2% of annual energy consumption from all sources and the largest source of renewable energy after hydropower (US DOE 2009). Renewable energy consumption (excluding ethanol) is projected to increase to 8.4 quadrillion Btu by 2015 and to 9.7 quadrillion Btu by 2030. Assuming the current share of renewable energy coming from woody biomass remains static, woody biomass would be the source of about 2.5 quadrillion Btu of energy in 2015 and 2.9 quadrillion Btu of energy in 2030. At present, wood energy consumption requires about 111 million oven-dry tonnes (odt) of woody material annually (assuming 17.2 million Btu/odt of wood). Under DOE's reference projection, approximately 132 million odt of wood will be used for energy in 2015 and 152 million odt will be used in 2030 (White 2010).

Using biomass instead of fossil fuels for meeting energy needs has several advantages. Specific benefits depend on the source of the wood (and its alternative fate if not used for energy) and the intended use. Benefits can include reduction of GHG emissions (particularly CO_2) and other air pollutants, energy cost savings, local economic development, reduction in waste sent to landfills, and the security of a domestic fuel supply. In comparison with other renewable energy sources, such as wind and solar power, biomass is more flexible (e.g., can generate both power and heat) and reliable, because it is a nonintermittent energy source whereas the alternatives rely on the weather.

In the United States, the potential role of forest bioenergy is readily accepted by private parties in regions where relatively low value pulp is the major output (Galik et al. 2009a). It is more controversial in the context of public forests. As in Europe, the pursuit of aggressive bioenergy targets in the United States could affect traditional users of industrial roundwood, especially pulp producers in the southeast region of the country (Abt et al. 2010), but in other areas of the country it could create opportunities for synergy. Increasing the use of managed forests for biomass could enhance forest resiliency and productivity without using scarce high-quality agricultural land or irrigation water.

Heat and Power (Combustion and Gasification)

Of the 9,709 megawatts (MW) of biomass electric capacity in the United States in 2004, about 5,891 MW (61%) was generated from wood and wood wastes. Another 3,319 MW of generating capacity was from municipal solid waste and landfill gas, and 499 MW of capacity was attributable to other biomass, such as agricultural residues, sludge, and anaerobic digester gas (US EPA 2007a).

Much of the biomass used for energy, especially the biomass burned in pulp mills, is burned in combined heat and power (CHP) systems. CHP is not a single technology but an integrated energy system that can be modified depending on the needs of the energy end user. The hallmark of all well-designed CHP systems is an increase in the efficiency of fuel use. By using waste heat recovery technology to capture a significant proportion of heat created as a byproduct in electricity generation, CHP typically achieves total system efficiencies of 60–80%

for producing electricity and thermal energy. These efficiency gains improve the economics of using biomass fuels, as well as produce other environmental benefits. More than 60% of all biomass-powered electricity generation in the United States is in the form of CHP (US EPA 2007a).

Energy Balance and Benefits of Biomass Energy

A small amount of fossil fuel is used to produce bioenergy—approximately 1 U of fossil fuel for every 25–50 U of bioenergy (Börjesson 1996, Boman and Turnbull 1997, McLaughlin and Walsh 1998, Matthews and Mortimer 2000, Malkki and Virtanen 2003, Matthews and Robertson 2005). Biofuels (transportation fuels) typically require more input energy, so the energy balance for producing biofuels is less favorable, as well as more variable—approximately 1 U of fossil energy for every 4–5 U of bioenergy (Gustavsson et al. 1995). Net carbon emissions from generation of a unit of electricity from bioenergy can be 10–30+ times lower than emissions from fossil-based electricity generation, depending on the systems and fuel types being compared (Boman and Turnbull 1997, Matthews and Mortimer 2000, Spath and Mann 2000, Mann and Spath 2001, Matthews and Robertson 2005, Cherubini et al. 2009).

Although energy self-sufficiency is one reason for pursuing the development of woody biomass-to-energy initiatives (Energy Independence and Security Act 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. Reducing fire risk while maintaining other forest values often entails removing low-value material while retaining higher-value trees for other purposes. Without a viable economic return for woody biomass that is removed, the costs are prohibitive and the likelihood of action is low.

Wildfire emissions are equal to 5% of total GHG emissions in the continental United States (Wiedinmyer et al. 2006). Avoiding wildfire emissions by thinning susceptible forests and using the harvested material as a woody biomass feedstock is a potentially valuable side benefit that is often ignored in the assessment of the carbon consequences of bioenergy. Oneil and Lippke (2010) calculated the GHG forcing per tonne of biomass burned during wildfires using default emission and consumption values from Wiedinmyer et al. (2006) to compare the implications of thinning to reduce fire risk versus stand-replacing wildfires. Because open burning generates methane and nitrous oxides, two potent GHGs, burning a tonne of biomass in a wildfire generates more emissions in CO_2e than the carbon content of the wood burned. Burning the same wood under controlled conditions in a boiler reduces non-CO_2 emissions by up to 98% while generating energy. The substitution of woody biomass for fossil fuel energy provides a GHG offset because the fossil fuel remains underground and the flow of fossil carbon to the atmosphere is reduced.

Thus, harvesting woody biomass to reduce wildfire risk, damage, and, ultimately, emissions delivers an additional atmospheric benefit beyond the substitution of fossil fuel (Mason et al. 2006, Hurteau et al. 2008, Stephens et al. 2009, Reinhardt and Holsinger 2010). That additional benefit is constrained, however, by the number of treatments and their spatial extent: limited treatments may not be sufficient at the landscape scale (Reinhardt and Holsinger 2010). The effectiveness of the benefit is also constrained by the ecology of the forests in question. For example, in a detailed analysis of fire risk reduction treatments for Pacific Northwest coastal western hemlock–Douglas-fir and western hemlock–sitka spruce forests with 500-year fire return intervals, Mitchell et al. (2009) found that the treatments would be ineffective at reducing carbon dioxide emissions and that leaving the forests untreated would be a better option. This result is not unexpected in a region where fire is rare and fire risk reduction treatments are highly unlikely.

Energy Substitution

The substitution effect noted in conjunction with production and use of wood products rather than metals, plastics, or concrete also applies to use of wood in production of energy. Using wood to produce electricity, heat, liquid fuels, or other forms of energy avoids the flow of fossil carbon to the atmosphere, provided that energy offsets the use of fossil fuels. Although a CO_2 molecule is a CO_2 molecule, regardless of source, crediting biofuel use as a fossil fuel offset recognizes the reduction of the flow of fossil carbon. Consistent carbon accounting counts the emissions *and* takes credit for the offset value (i.e., the amount of fossil fuel carbon that was not emitted, net of the fossil fuel used to produce the biomass energy). Current protocols and policies generally do not allow this credit (see Section 6).

Potential biofuel feedstock that burns or decays in the woods is a net decrease in the carbon stock—the equivalent of an emission. The loss of carbon from the forest is already accounted for in the forest carbon stock change, but care must be taken when extrapolating the results from a single stand to a wider context (Figure 5-3). For a single stand under sustainable management, the forest carbon cycles around some average value that is contingent on inherent site productivity, rotation age, and species mix, and there is a time interval between uptake and release of carbon (Figure 5-3a). However, no processing facility relies on a single stand to provide feedstock, so extrapolating the time-dependent dimension of a single stand analysis to the emissions profile of a facility is inappropriate and leads to incorrect conclusions (O'Laughlin 2010).

A more correct characterization of the effects of harvesting biofuel uses a landscape-level analysis to determine whether the harvest needed to sustain processing facilities within an economic haul distance increases or decreases average carbon stores on the land. If harvesting results in a stable average of carbon across the total forest through time (Figure 5-3b), the forest itself is carbon-cycle neutral. If forest carbon stocks are unaffected by the choice between forest biomass and fossil fuels, the products removed from the forest provide a carbon benefit to the atmosphere equal to the avoided emissions from fossil fuels less any fossil energy it took to produce energy from the biomass feedstock. To meet this condition, it is necessary to ensure that harvests and mortality do not exceed net growth across the forest and that soil conditions and carbon sequestration potential are maintained.

An analysis using publicly available data from the US LCI database (National Renewable Energy Lab 2011) and the EPA TRACI Impact method found that the global warming potential for a cradle-to-grave analysis was greater for coal than for woody biomass (Figure 5-4; Lippke et al. 2011). The comparison in Figure 5-4 is for the cleanest coal type (bituminous); other coal types produce more emissions and therefore produce an even larger differential between the fuel types. Results show that if the uptake of CO_2 in the forest is ignored, disregarding the fundamental difference between renewable and nonrenewable fuels, emissions from using biomass as a feedstock

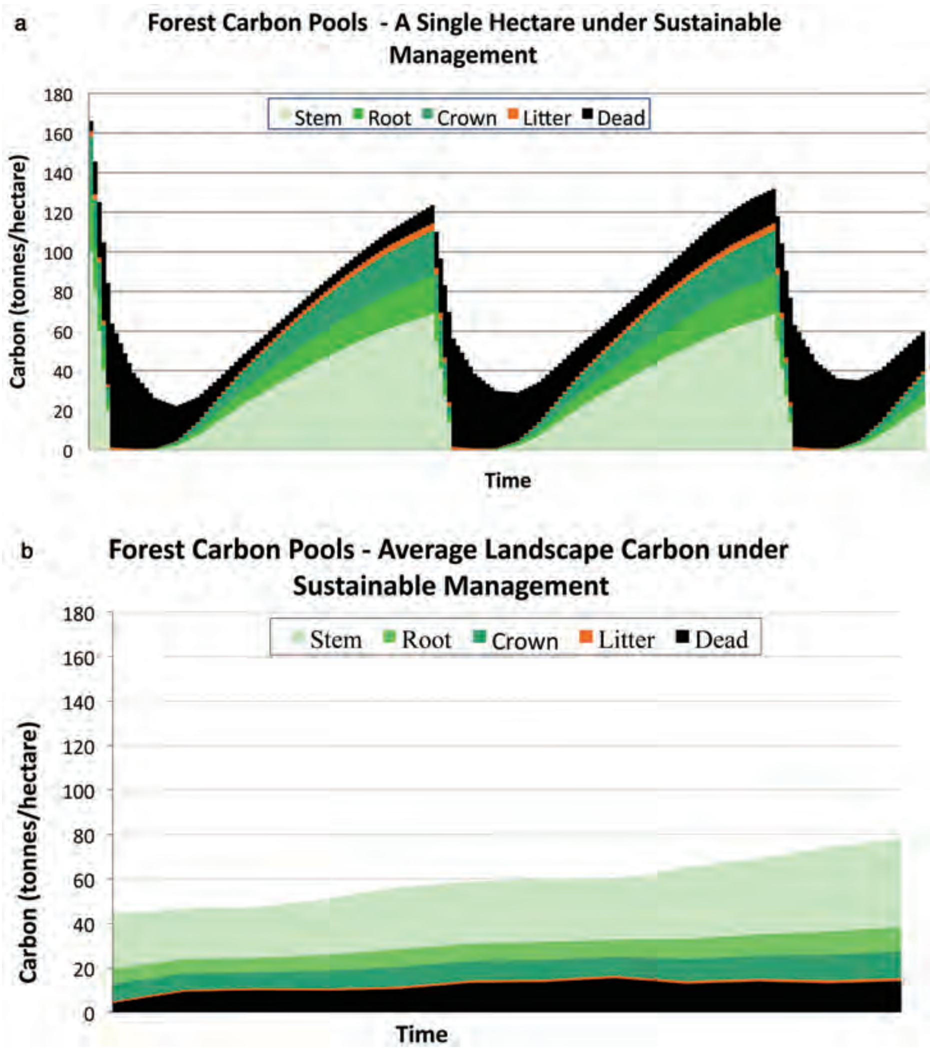

Figure 5-3. Forest carbon under sustainable management, by (a) single hectare and (b) landscape. (Source: Oneil et al. 2011.)

are 82% of coal-fired emissions per megajoule of electricity produced. If biomass is considered a renewable resource such that emissions represent prior uptake, burning biomass to generate electricity produces 4% of the emissions of a coal-fired power plant.

The net biomass bar in Figure 5-4 assumes that the biomass was produced in an area where forest carbon stocks remain stable over the long term. Some assume that harvesting causes a reduction in forest carbon stocks, and particularly soil carbon, relative to a scenario where the biomass is not used for energy, creating a carbon debt that must be overcome before the forest biomass–based system yields net benefits (e.g., Schlamadinger et al. 1995, Searchinger et al. 2009). Such thinking is based on initiation of measurement and comparison at the point of harvest.

Whether and how biomass is included in emissions accounting affects policies aimed at reducing overall GHG emissions. Accounting should (1) accurately characterize atmospheric consequences of reducing the flow of fossil fuel emissions by using biofuels and (2) measure the effects on the forestland base in terms of growing stock and soil carbon. The assumptions and boundaries for analyzing the GHG emissions of bioenergy are critical to the resulting conclusions and must be clearly understood when studies are used to justify policies or regulations.

Determination of Carbon Neutrality

Analyses of the benefits of forest-based products and systems should incorporate spatial and temporal boundaries appropriate for forestry and forest products. Forest management practices may be applied at the individual stand or project level, but wood supply systems involve large areas managed for long periods of time. Using a single stand or project to model a wood supply system can severely distort systemwide outcomes (Lucier 2010).

At the scale of a wood supply area, sustained-yield forestry and sustainable management systems keep growth and removals in balance, and the loss of carbon from harvests in any given year is equal to gains in carbon elsewhere in the area. The net change in carbon stocks in all years is then zero; i.e., net removals of carbon from the atmosphere equal the amount of carbon in wood removed from the forest, and the system is carbon neutral. The variation in definitions of carbon neutral (Table 5-7), however, suggests the need for elaboration when using the term.

Even if forestland is maintained as forestland, deviations from carbon-cycle neutrality can occur in both directions. Climate change, more frequent insect and disease outbreaks, exotic and/or invasive disturbance agents, failure to regenerate, and severe wildfires that reduce soil productivity can affect long-term carbon storage potential. Ensuring continued carbon benefits from the forest sector requires maintaining long-term site productivity. Given adequate nitrogen supplies to maintain carbon stores in dynamic equilibrium, average forest carbon stores can increase concurrent with ecological protections, such as riparian buffers and habitat requirements. Incorporating most ecological sustainability criteria into this forest management framework does not affect a forest's carbon-cycle neutrality, but overall carbon benefits will be underestimated if harvested wood products and their substitution effects are not taken into account. LCI and LCA occur within defined system boundaries. Substitution occurs when one product is replaced by another product and the comparison is between the LCIs within each boundary. An example would be the comparison between steel joists and engineered I-joists that are functionally equivalent. There are also displacement factors when biofuel is used instead of fossil fuel for manufacturing that occurs inside the system boundary. The displacement occurs inside the system boundary of a particular product and forms part of its LCI.

Figure 5-5 integrates harvested wood products and substitution benefits for the forest management regime in Figure 5-3b to provide the landscape context. It is based on current patterns of wood use from harvested

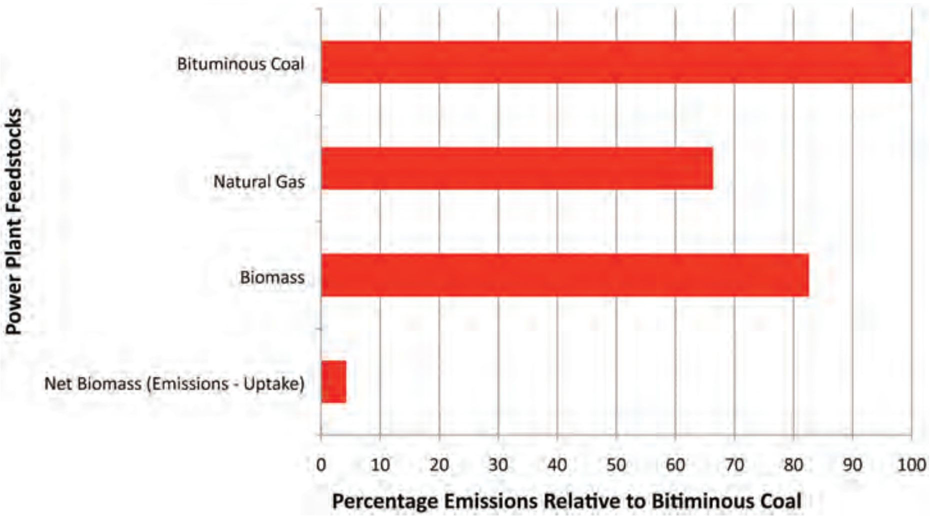

Figure 5-4. Comparison of GHG emissions from electric power plants. (Source: Adapted from Lippke et al. 2011.)

Table 5-7. Definitions of carbon neutrality.

Type	Definition	Example
Inherent carbon neutrality	Biomass carbon was only recently removed from the atmosphere; returning it to the atmosphere merely closes the cycle	All biomass is "inherently carbon neutral"
Carbon-cycle neutrality	If uptake of carbon (in CO_2) by plants over a given area and time is equal to emissions of biogenic carbon attributable to that area, biomass removed from that area is carbon-cycle neutral	Biomass harvested from regions where forest carbon stocks are stable is "carbon-cycle neutral"
Life-cycle neutrality	If emissions of all greenhouse gases from the life cycle of a product system are equal to transfers of CO_2 from the atmosphere into that product system, the product system is life-cycle neutral	Wood products that store atmospheric carbon in long-term and permanent storage equal to (or greater than) life-cycle emissions associated with products are (at least) "life-cycle neutral"
Offset neutrality	If emissions of greenhouse gases are compensated for by using offsets representing removals that occur outside of a product system, that product or product system is offset neutral	Airline travel by passengers who purchase offset credits equal to emissions associated with their travels is "offset neutral"
Substitution neutrality	If emissions associated with the life cycle of a product are equal to (or less than) those associated with likely substitute products, that product or product system is (at least) substitution neutral	Forest-based biomass energy systems with life-cycle emissions equal to (or less than) those associated with likely substitute systems are (at least) "substitution neutral"
Accounting neutrality	If emissions of biogenic CO_2 are assigned an emissions factor of zero because net emissions of biogenic carbon are determined by calculating changes in stocks of stored carbon, that biogenic CO_2 is accounting neutral	The US government calculates transfers of biogenic carbon to the atmosphere by calculating annual changes in stocks of carbon stored in forests and forest products; emissions of CO_2 from biomass combustion are not counted as emissions from the energy sector nor are emissions from decay of dead trees in the forest counted as emissions in the forest sector

Source: NCASI (2011).

sites across a landscape that support a viable forest industry. It does not include increased recovery of forest residuals for bioenergy use, which would offset more fossil fuel and increase the slope of the graph. In Figure 5-5 the displacement is the amount of carbon benefit that accrues from using biofuel in place of natural gas for drying of the long-lived products produced in the Inland Northwest. Displacement can be larger in other regions where fossil fuels comprise a greater share of the energy used to generate electricity or where more wood waste is used for energy. In this case from the Inland Northwest, the analysis incorporates LCI data on mill drying and the high percentage of nonfossil electricity generation in the region caused by extensive hydroelectric resources. Note that the total emissions (including biofuel emissions) resulting from production of these products shows up as a negative benefit in Figure 5-5, depicting the emissions associated with generating the total positive carbon benefits shown in this figure. The displacement factor above the line is the amount of equivalent fossil fuel emissions that were avoided by using biomass in place of natural gas for drying. The displacement factor takes into account the differential in burning efficiency between natural gas and biomass.

As this example shows, where forest operations do not exceed the forest's ability to regenerate, the gains from forest management are seen in carbon pools and offsets outside the forest, without a decline in forest carbon storage. The forest is carbon-cycle neutral in its own right; all products removed from it are additional carbon sinks as long as they are in use, and the substitution benefits of using wood in place of comparable building products or energy sources also accrue. If a change in forest operations (e.g., shorter rotations, high natural mortality without salvage, and reduced stocking because of climate shifts) causes a decline in forest carbon storage, the slope of the graph changes and the forest itself is no longer carbon-cycle neutral. Maintaining or enhancing forest productivity so that a continuous flow of products can come from the forest provides the greatest carbon mitigation benefit.

The forest is only the first tier. Making products that displace fossil fuel–intensive products provides a cumulative offset by reducing fossil fuel emissions and delivers the largest carbon benefit (Eriksson et al. 2007, Lippke et al. 2010). Discussions about base-

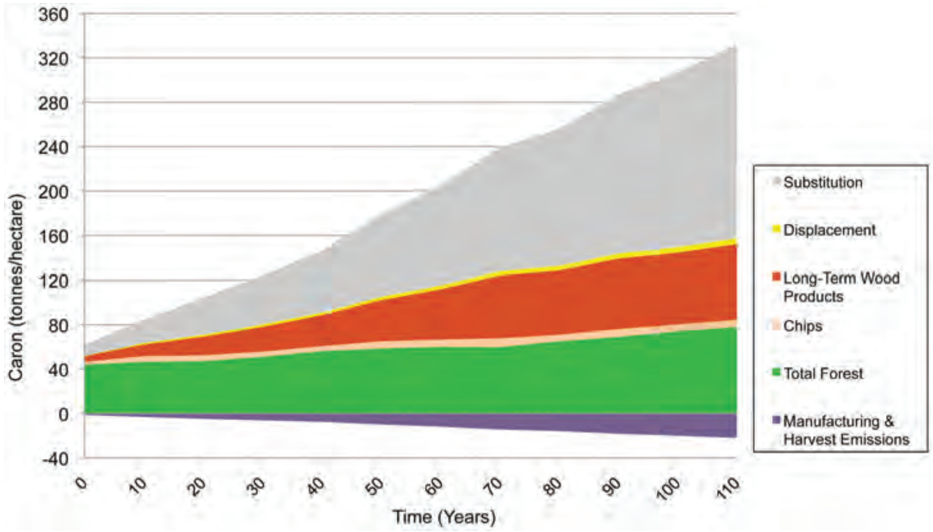

Figure 5-5. Carbon trajectories under sustainable management of a forested landscape (as shown in Figure 5-3b). (Source: Oneil and Lippke 2010.)

lines and additionality are about who gets the credit. Likewise, discussions about leakage are about where it occurs in the global economy. These concepts are relevant in the marketplace but irrelevant for climate change mitigation because if, for example, a construction company does not use wood, it will likely use a competing product with a higher carbon footprint. These market factors are explored in Section 6.

Even where growth and removals are in long-term balance, carbon stocks can fluctuate across the wood supply area. Although the timing of year-to-year carbon fluxes can affect the radiative forcing of the atmospheric system, focusing on these transient conditions instead of the long-term balance between growth and removals can lead to different conclusions about the costs and benefits of harvested biomass and wood products.

The temporal scale of an analysis can be important in several other ways, especially as it affects biomass carbon accounting. The time period for accounting may be expanded to include flows of CO_2 into trees; CO_2 emissions from decomposing biomass in the forest; and emissions associated with establishing, growing, or regenerating the forest (including land-use change and other activities that alter long-term average carbon stocks). The end point for the accounting may extend through the end of life of the product (World Resources Institute/World Business Council for Sustainable Development 2011).

Life-cycle studies often combine all flows of GHGs to and from the atmosphere into a single number reflecting the total effects over a product's life cycle. It may be important, however, to understand the timing of removals and emissions, particularly if comparing forest-based and substitute products or comparing alternative uses for land. Such comparisons may show short-term benefits attributable to delayed harvesting, but over time, these benefits diminish and eventually cease as forests age and natural emissions approach uptake. The benefits associated with using products from forest-based systems, however, often continue to accumulate (Schlmadinger and Marland 1996, Lippke et al. 2010, 2011). Extending the period of analysis through multiple rotations can be critical to understanding the short-term and long-term implications of using forest-based products.

Temporal considerations can also be important when discounting is used to reflect the time value of emissions and reductions (Levasseur et al. 2010). Such studies are the norm in the physical models used in climate modeling but are relatively uncommon in life-cycle studies and policy-related work.

Forest Carbon Policies

Policies to increase the benefits of forest carbon can use a range of strategies. At the national level, the quantity of greenhouse gases (GHG) emitted can be reduced by:

- increasing net carbon sequestration rates in forests,
- using wood products rather than energy- and emissions-intensive building products, and
- converting forest residues into energy.

Voluntary carbon management programs for individuals and groups of landowners have been promoted in the United States, and countries that ratified the Kyoto Protocol have introduced their own programs. Although the Chicago Climate Exchange (CCX) suspended activity in November 2010 and no federal cap-and-trade legislation that would include forest carbon projects was enacted in 2010, there are voluntary systems, regional programs (Northeast Regional Greenhouse Gas Initiative and Western Climate Initiative), and a state program (in California) that could evolve into more significant schemes. In other countries with temperate forests, increased demand and prices for woody biomass used for energy across Europe (European Union 2009) and the creation of carbon property rights for post-1990 plantations in New Zealand (New Zealand Government 2011) could inspire US incentive programs for landowners to manage for forest-based climate benefits.

Forest Carbon Offset Projects

Forest carbon offset projects started as a way to finance projects to reduce tropical deforestation with voluntary investments from electric utilities (Dixon et al. 1993). Many US consumers interested in mitigating climate change also preferred forest-based projects offered by voluntary offset schemes (Niemeier and Rowan 2009). The concept of offsets is that individual emitters can compensate for their carbon emissions with carbon sequestered by qualifying projects. The protocols for forestry carbon offset projects vary; most offset sales have been for projects where the value was based on measurable increases in forest carbon stocks compared with a no-project scenario.

Forestry offset projects generally can be classified into one of the following five categories based on adaptations of Helms's (1998) and the Florida Department of Environmental Protection's (Stevens et al. 2010) definitions. Not all categories are recognized by the various protocols governing forestry offset projects, and in some cases the definitions overlap.

- Afforestation—establishing forests where the preceding vegetation or land use was not forests.
- Reforestation—the reestablishment of forest cover after the previous forest was removed.
- Forest management—management of existing forests to meet specified goals and objectives while maintaining forest productivity.
- Forest conservation—management and protection of existing forests to avoid conversion to nonforested land uses.
- Forest preservation—management and protection of existing forests to avoid degradation into less productive conditions.

Protocols for those project types typically include the following elements, but the requirements may differ significantly (Pearson et al. 2008):

- Eligibility—for forestry offset projects, many of the eligibility criteria (e.g., landownership, commercial harvesting, and use of pesticides) are not directly related to climate benefits.
- Carbon sequestration calculation procedures—methods to determine the number and timing of carbon credits earned throughout the life of an offset project include volume equations, growth-and-yield tables, and direct measurements of standing forest biomass.
- Baseline requirements—carbon credits are earned for carbon sequestered above and beyond a baseline, which may be fixed to a certain year, based on the national trend, or defined as the "without project" scenario or business-as-usual (BAU) case.
- Carbon pools—protocols typically credit carbon sequestered in one or more carbon pools. The definitions and required measurement method of these carbon pools differ greatly among protocols. Typical carbon pools include measurable aboveground biomass, estimated belowground biomass and soil carbon, and some harvested wood products. Most project protocols do not credit wood biomass initially used for energy or the future storage of woody biomass in landfills, even though these uses are calculated as climate benefits in national emissions reports.
- Crediting period—the crediting period specifies the time frame within which credits for sequestered carbon may be issued from a specific project.
- Leakage—a project's carbon benefits can be canceled out by activities elsewhere. Internal leakage occurs if an owner increases harvests on portions of its lands to replace timber restricted from harvest under the offset project. External leakage occurs outside the firm's sphere of operations and occurs at a regional, national, or global scale.
- Permanence and reversals—carbon sequestered by an offset project, particularly if credits are issued, should remain sequestered long enough to equal the atmospheric effect of an emission. Based on IPCC definitions (Forster et al. 2007), 100 years of new terrestrial carbon storage is considered a permanent offset for an emission of an equal quantity of carbon dioxide. A reversal occurs if carbon sequestered and credited during a project's lifetime is lost, typically to natural disasters such as wildfires or storms but also to deliberate acts such as timber theft.

Forestry offset protocols (see Box next page) have been created to serve several different purposes. Some are part of cap-and-trade programs, whether mandatory or voluntary. Others are part of emissions reduction schemes. Still others were developed independently but have been adopted by one or more programs:

- Mandatory GHG reduction programs—caps are imposed on GHG emissions. If emissions are tradable, polluters can

Examples of Offset Programs

Mandatory cap-and-trade systems
- Clean Development Mechanism (CDM), www.cdm.unfccc.int
- New South Wales Greenhouse Gas Reduction Scheme, www.greenhousegas.nsw.gov.au/default.asp
- New Zealand Emission Trading Scheme, www.climatechange.govt.nz/emissions-trading-scheme/
- Regional Greenhouse Gas Initiative (RGGI), www.rggi.org.
- California AB 32 Scoping Plan's Cap-and-Trade Program (2012 start date)

Voluntary cap-and-trade systems
- Chicago Climate Exchange (CCX), www.chicagoclimatex.com (suspended in 2010)

Voluntary emissions offset protocols
- American Carbon Registry (ACR), www.americancarbonregistry.org
- Climate Action Reserve (CAR), www.climateactionreserve.org
- The GHG Protocol for Project Ac counting and the Land Use, Land-Use Change, and Forestry Guidance for GHG Project Accounting, www.ghgprotocol.org
- Voluntary Carbon Standard (VCS) Program, www.v-c-s.org

purchase benefits from certified projects or other polluters that have reduced their emissions more than required. Among countries that ratified the Kyoto Protocol, New Zealand and New South Wales (Australia) have credits generated from plantation forestry, and some developing countries host Clean Development Mechanism afforestation projects.

• Voluntary cap-and-trade systems—participation is voluntary; however, participants are obligated to reduce their GHG emissions. As in mandatory cap-and-trade systems, unused quotas or credits from offset projects can be purchased to meet the cap. The demise of the CCX means that as of 2011, there are no voluntary systems in operation.

• Voluntary emissions offset protocols—various organizations have developed rigorous standards for offset projects. These protocols are usually independent of any requirement to reduce GHGs.

Variation among Protocols

The amount of carbon credits generated under protocols used in the United States can differ dramatically for the same project (Galik et al. 2009c), depending on the sets of carbon pools allowed by the protocol and its baseline approach. Differences can be further compounded by leakage, permanence, and buffer requirements. The substantial ranges in creditable carbon generated have a dramatic effect on the financial viability of carbon offset projects compared with BAU timber management scenarios. When six different protocols were applied to the same southern pine plantation in a study by Galik et al. (2009c), break-even carbon prices ($/t$CO_2$e) had a 20-fold range depending on the protocol's rules about baseline values, reversals, leakage, and uncertainty. Most of the break-even prices were far above the best 2010 value for voluntary carbon offsets, $10/tonne of CO_2 (equivalent to $8/green tonne of stumpage).

The costs associated with establishing and maintaining forestry offset projects also vary depending on verification requirements, carbon measurement procedures, monitoring frequencies, and third-party certification. Per hectare, costs for the high-cost protocol may be five times greater than for the low-cost protocol (Galik et al. 2009b). Transaction costs for small ownerships (less than 100 ha) were 10–20 times more costly per offset credit than for larger ownerships. Differences in transaction costs for large ownerships (greater than 10,000 ha) are still large but are minor in absolute terms (less than $1.20/ha) because of economies of scale.

Under regional and state programs, the number of voluntary projects exceeds the number of projects with sales. As of the end of 2010, no afforestation or reforestation forestry projects had been registered with the Northeast Regional Greenhouse Gas Initiative (RGGI), Inc. (RGGI 2011), and just three conservation-based forest management and improved forest management projects had offset sales following protocols approved by the California Air Resources Board (Climate Action Reserve [CAR] 2011). Since less than 20% of credits in California have been retired after offsetting an emission (CAR 2010), it would appear that many purchasers are assuming that some of the credits will be grandfathered in future mandatory systems. This pattern has also been noted in international carbon markets (United Nations Economic Commission for Europe/Food and Agriculture Organization 2010). As of 2011, uncertainty about acceptable methodologies for measuring forest carbon and related climate benefits has significantly limited interest in developing forest carbon projects that involve large upfront costs (Waage and Hamilton 2011).

Accounting Issues

Additionality and Baseline Settings. With reduction in GHG emissions to the atmosphere as the goal, the net amount of carbon sequestered must be additional to what would have occurred without the offset project. For forest projects, additionality is relatively easy to establish when new trees are planted and maintained but considerably more difficult to establish when based on a counterfactual assertion (e.g., "I was going to harvest in 10 years but instead will wait 30 years"). This is further complicated when project guidelines are designed by the project proponent, and the underlying documentation is not audited by any official regulator, as would be required for a real estate or stock transaction. A carbon baseline must be established against which the net change in carbon stocks is measured so that emissions reduction credits can be quantified, verified, and registered. Baseline carbon values of forest inventories are determined through standard forestry biometric methods that include direct and statistically designed and modeled measurement techniques, but projections into the future may require numerous assumptions. The baseline carbon value of wood products and wood energy that are used outside the project are typically based on a study by Smith et al. (2006). However, the Smith et al. (2006) estimates of the amount of wood still in use are considerably lower than the sawmill efficiency estimates of Smith et al. (2009) and the product lifetime estimates of Skog (2008). The practical effect of using the Smith et al. (2006) estimates is to increase the apparent carbon benefits of reducing current harvests. The potential to exaggerate the net climate benefits of a forest offset project will be increased if it is assumed that wood used for energy results in a direct loss of carbon without any fossil fuel substitution benefit.

Additionality can be controversial because new activities earn credits whereas identical activities initiated in the past do not. Thus, additionality sometimes rewards late entrants while appearing to punish those who have historically engaged in the desired behavior. Additionality is also controversial because determining the counterfactual often requires judgments regarding motivation.

US registries and programs use BAU and base-year approaches. The BAU baseline is the emission that would have happened without any new technologies or actions. This scenario works well for comparing existing and improved technologies but is often less useful for land-based sequestration practices, where natural ecosystem dynamics and future market-based actions increase the uncertainty of any projection. Changing forest management objectives, markets for alternative land uses, timber prices, and ecosystem service prices (e.g., the price of sequestered carbon, wildlife habitat acres, and water yields) all contribute to a high level of inherent uncertainty when a BAU baseline is defined. Unlike the baseline emissions of a direct emitter of CO_2 (e.g., a coal-fired power plant), which can be precisely measured and operationally controlled, forest BAU baselines are difficult to establish at the project level.

In the base-year approach, an inventory is taken at the beginning of the project period, and a second inventory is conducted some years later, using the same inventory design. The net change in carbon stocks (of all allowable carbon pools within the forest offset project) represents the carbon sequestration related to the forest for that period and is the basis for the number of carbon credits issued. In a sustainably managed forest, this net change in carbon stocks will reflect forest management actions, such as harvesting, treeplanting, and fertilizing. It will also reflect effects of natural events such as weather, wildfire, insects, and disease.

Reversals and Permanence. If forest carbon credits are used to permanently offset industrial emissions, the forest project must establish permanence by ensuring an equivalent amount of new carbon storage over time. Because of the unpredictability of wildfires, insect infestations, and weather, permanence is typically achieved through insurance mechanisms to guarantee that any losses will be compensated. Some registries and programs require that any released carbon be included in the net change calculations so that credits previously issued can be paid back; no additional credits can then be issued until the net change in carbon stocks is again positive. Various mechanisms are typically used to address permanence for land use, including deed restrictions on land use, long-term or permanent conservation easements, buffers, and reserve pools (whereby portions of the carbon sequestered are held in reserve to offset potential losses). Insurance is another approach to guaranteeing that the promised climate benefits materialize.

Market Leakage. In the forest climate project literature, meeting consumer demand with new purchases from outside the project boundary is referred to as market leakage. Market leakage is often underestimated at the project or regional level in the United States because alternative wood supplies may come from other regions or nations. As noted in Section 2, domestic production has fluctuated around 300 million m^3 of wood products since 1980 while consumption continued to increase (Smith et al. 2009). When Murray et al. (2004) modeled the large reduction in timber harvests from public lands in the Pacific Northwest in the 1990s, they estimated a market leakage rate of more than 80% as timber demand was met through harvests elsewhere in North America. Underestimating market leakage rates will proportionally overestimate the global climate benefits of forest offset projects. However, most project-based forest offset protocols ignore market leakage altogether, allow the project proponent to choose the leakage rate, or set a maximum market leakage rate of 20%.

Temporal and Spatial Boundaries. The spatial and temporal boundaries for carbon accounting in offset programs are very program-specific. In offset programs, selection of these boundaries is closely related to the leakage and permanence issues discussed previously and based on a combination of scientific and policy considerations. Because programs have different policy priorities, these boundaries vary considerably, even for seemingly similar project types.

Spatial boundaries are usually determined based on the scale of the offset project, the jurisdiction of the program authority, and, to some extent, the need to prevent leakage. Accordingly, spatial boundaries vary considerably. In principle, the boundaries of the accounting should extend to all areas potentially affected by the offset project activity, but as a practical matter, spatial boundaries are usually extended only to those areas directly affected by the project. Under normal circumstances, therefore, boundaries extend only as far as needed to address direct benefits and internal leakage. Limiting the boundaries in this manner risks missing important indirect benefits and large-scale leakage.

Temporal boundaries in offset programs also vary significantly. For forest-based projects, however, the temporal boundaries are especially significant, e.g., in selecting and modeling baseline conditions; as noted previously, the baseline can have dramatic effects on the estimated benefits of offset projects. Temporal boundaries are also critical in addressing concerns about reversals and permanence.

Estimates of Forest Carbon Flux. Carbon stocks in the forest sector do not directly affect atmospheric GHG levels; rather, carbon flux, typically assessed as a change in carbon stocks, is what matters in evaluating the contribution of forests. The change in carbon flux, relative to a baseline or BAU scenario, is therefore the relevant metric. For tracking flux at broad (state and regional) scales and for generating baseline reference values, comprehensive forest inventories based on remeasured, permanent, sample plots provide the most accurate and precise estimates. However, such inventories do not measure woody carbon, biomass, or even volume. Instead, they assess forest area, enumerate and track live and dead trees, and measure tree circumference and assess tree height. Some inventories also sample down wood, litter, soils, and understory vegetation.

Getting from those data to estimated carbon stock involves several sources of error: measurement, sampling, model, and model selection. Commitment to quality assurance—as practiced, for example, by the Forest Inventory Analysis Program (Pollard 2005)—can control measurement error. Sampling error can be controlled by increasing sample size, which typically does not introduce bias as long as the sample is representative. Model error, the uncertainty not explained by the variables included in a model, can be accounted for when modeling error propagation (e.g., Phillips et al. 2000) as long as model authors report error information. However, model selection error can introduce substantial bias and cannot be resolved without investing in improved inventory technology and/or models on a scale not previously contemplated.

Model selection error arises from the need to estimate carbon stores for each live tree by selecting from thousands of arguably plausible, analytically defensible computation pathways generated from different combinations of published biomass, volume, and density equations for whole trees, boles, branches, and bark, based on dbh alone or dbh and height. Under the most optimistic scenario of a sensitivity analysis of live-tree carbon stores in northwest Oregon, model selection error (half the prediction range expressed as a percentage of the prediction envelope midpoint) was $\pm 37\%$ (Melson et al. 2011). Given that sampling error for the same analysis implied a 95%

confidence interval of 6%, model selection accounts for most uncertainty in carbon stores.

In most cases, carbon flux is a small fraction of carbon stocks and can be far smaller than the error of estimated carbon stocks. When flux is calculated as a difference in carbon stocks, the error of the difference can exceed the estimate of flux. An analysis of Canada's managed forests estimated annual net forest carbon fluxes of -2 ± 20 teragrams (Tg) of C/year from 1990 to 2008 (Stinson et al. 2011). A study of carbon balance in European forests that used estimates based on ecological site studies, national forest inventories, and vegetation models calculated standard errors, not accounting for model selection error, ranging from 21 to 133% of estimated flux (Luyssaert et al. 2010). The current "systems" in place for estimating forest carbon flux are grossly inadequate and do not fully use the data that is available. The error estimates are generated via an entirely ad hoc approach that omits what is likely the greatest component of error (model selection). For example, a US EPA (2010) report found uncertainty of $\pm 20\%$ in estimates of forest ecosystem carbon flux and $\pm 25\%$ in estimates of harvested wood products carbon flux. However, the Monte Carlo–based error simulation used to predict uncertainty accounted primarily for sampling and model error and did not address model selection error (Smith and Heath 2000).

Especially under disturbance regimes, it can be important to understand carbon flux from pools other than live trees, because these other pools contain 65–100% (for a nonstocked stand) of total ecosystem carbon (Van Miegroet et al. 2007). Obtaining accurate estimates of nonlive tree pools, however, can be especially challenging. For instance tracking down wood over long time intervals in an extensive forest inventory still is not feasible because no system of accounting for components of change, analogous to growth, removals, and mortality of standing trees, has been developed; the few studies, to date, have involved only small areas and short time intervals and required substantial effort (e.g., Vanderwel et al. 2008). Moreover, the density of standing and down wood is unpredictable, and questions remain about the ability to develop estimates of flux from estimates of deadwood for the same plot at two points in time (Woodall and Monleon 2008). The difficulties are illustrated by Westfall and Woodall (2007) who found that measurements of fine wood pieces taken by two inventory crews even in the same season agreed only 26–57% of the time, and the lengths of coarse wood pieces agreed only 72% of the time; in both cases, "agreement" was defined as within a $\pm 20\%$ tolerance. Estimating carbon flux from soil can be problematic due to sampling and measurement costs as well as horizontal and vertical variability, even at the plot scale; accurate flux is not possible because the soil sample is removed from the ground and therefore cannot be remeasured the way a tree can be remeasured.

These challenges to obtaining accurate estimates of forest carbon flux at broad scale apply equally to obtaining estimates at the stand or project scale, e.g., to establish a project baseline or show a change in carbon stores or flux. Additional challenges include ensuring a representative sample, obtaining sufficient sample size to control sampling error, and the need to model the carbon impacts of prospective management alternatives (e.g., BAU versus an offset project). Unless vigorous effort is invested in avoiding subjectivity in plot placement (both in terms of which stands are selected for sampling and where the samples are collected from sampled stands) and in assuring that stand edges are sampled with appropriate probability, inventories built on stand or compartment "exams" often exhibit sample location bias that compromises representativeness. This is especially true when the stakes in the outcome of the inventory are high (such as refunding carbon offset payments if promised sequestration cannot be proven): sampling results could easily be manipulated by plot placement or, conversely, by management activity being different at plot locations than elsewhere. Given the large number of plausibly valid carbon calculation pathways, there is ample opportunity for "equation shopping" to generate the greatest offset value.

The considerable cost of implementing a comprehensive, systematic inventory design at project scale has driven some to propose relying instead on remotely sensed estimates of forest carbon flux for monitoring (e.g., Ahern et al. 1998, Running et al. 1999). Carbon storage has been estimated via spectral imagery (Law et al. 2006, Blackard et al. 2008, Powell et al. 2010) and synthetic aperture RADAR (SAR) (Bergen and Dobson 1999) from satellite and airborne platforms. These approaches have relied on "ground truth" of the same carbon estimates modeled from vegetation assessed on field plots as described previously. Sampling error is not a factor, because remote sensing takes a census rather than a sample of the forested landscape. Nevertheless, modeling carbon stores directly from spectral imagery or SAR has limitations: (1) saturation of the response signal in stands with dense canopies and high biomass (Lefsky et al. 2002); (2) little if any direct response signal from tree boles, the vegetation component containing the most biomass; and (3) inability to consistently detect changes in understory trees, down wood, and herbaceous cover under dense canopy. These deficiencies partly explain recent enthusiasm over using LiDAR (Light Detection and Ranging systems) (e.g., Wulder et al. 2010); unfortunately, LiDAR acquisition at a coverage density suitable for characterizing forest carbon is prohibitively costly.

Remote-sensing estimates of carbon stocks remains attractive because of its apparently low cost, spatially comprehensive coverage, and perhaps the deterministic result—uncertainty information is essentially never carried along with pixel-level or aggregated estimates (for example, as standard errors incorporating measurement, model, and model selection errors); indeed, it would be hard to know how to do so in a meaningful way, but this does not mean that the uncertainty does not exist. When no uncertainty is recognized, however, it is easy to assume that stock change can be legitimately computed by comparing modeled stocks at different times. In fact, even seemingly large differences may not be real, and even the best validation results (typically for overstory trees) show models explaining barely 70% of the variation; for subcanopy carbon components, such as down deadwood and snags, there is virtually no relationship between model predictions and field-observed values (e.g., Wimberly et al. 2003).

Clearly, numerous challenges exist in developing suitably accurate estimates of carbon flux in forest-based carbon offset projects for supporting investment decisions (e.g., McKinley et al. in press). Offset programs must recognize these limitations, providing mechanisms that protect against claims of benefits or assignments of liabilities that are artifacts of uncertainties in estimates of carbon stocks and flux.

Improvements in measurement and sampling methods are needed. Although measurement and sampling error are relatively manageable for generating estimates of live-tree carbon stocks and fluxes at broad scale, there are important opportunities to improve the models that transform inventory measurements into estimates of carbon flux. Existing allometric equations (volume and biomass of all tree components) need to be evaluated for their validity for different populations of trees (e.g., across geography, species, site classes, and diameter ranges) and, undoubtedly, many more need to be developed. The transportability of models and model forms across forest types also needs evaluating, because a poor match between models and actual trends could overpredict the level of benefits and promote dubious projects (Bottcher et al. 2008). A critical question will be whether it is possible to achieve these and other improvements in measurement and sampling methods and quantitative risk assessments at a sufficiently low cost to avoid the situation where achieving levels of accuracy comparable with those required for regulated financial transactions exceeds the total financial value of forest management projects. Policy alternatives to offsets that avoid the expensive imperative for high accuracy measurement of flux while still achieving climate benefits include, for example, "bonus payments" for treeplanting or carrying higher tree stocking or permit waivers for sanitation/salvage prescriptions aimed at capturing carbon benefits from mortality via substitution.

Policy Alternatives to Offsets

Science-based forest carbon policies should be part of a comprehensive energy policy to achieve energy independence and deliver carbon benefits while providing environmental and social benefits, including clean water, wildlife habitat, and recreation. Economic incentives—in the form of tax credits, subsidies on required reforestation inputs, or direct payments for easily measurable attributes (e.g., forest cover)—can encourage forest landowners to retain their forests as forests and manage their forests for carbon benefits. Markets and economic incentives are powerful tools; however, two other effective policy mechanisms have promise.

• Information disclosure—The Toxic Release Inventory, Green Energy purchasing programs, and the Safe Drinking Water Act have shown that information disclosure, whether required by government or by private entities, can motivate firms to change their behavior. Easily understood programs requiring companies to disclose their GHG emissions for processes or products could encourage the use of forest products, especially if these disclosures differentiate between emissions that recirculate atmospheric carbon and emissions that add to atmospheric carbon. Importantly, information disclosure requirements are often politically and socially more acceptable than regulatory programs that mandate behavior modifications.

• Building codes and procurement policies—substituting wood products for steel, aluminum, concrete, plastic, and other materials permanently reduces GHG emissions (see Section 5). Local government policies, such as building codes and procurement policies, which encourage or require the use of life-cycle assessments on the carbon consequences of material choices, can have significant climate change and energy benefits.

Those alternative policy approaches do not require the precision in forest carbon accounting needed in offset programs. Using life-cycle analyses, numerous scientific studies have already determined the relative carbon benefits of various products and processes, including forest biomass–based products; thus there is no need to quantify the carbon benefits in each application of those products.

Managing Forest Carbon Benefits and Risks

The capacity of US forests to sequester carbon over the next 100 years is subject to powerful, disruptive forces: climate change; development pressure; conversion of forestland to nonforest uses; and likely expansion of exotic plants, insects, and pathogens. At the same time, political imperatives for clean energy will drive production of energy from biomass, including forest biomass. We can expect concerted efforts to mitigate climate change by increasing the carbon in US forests and using wood-based energy and products. All this will occur against a backdrop of intense international competition among companies that make traditional and nontraditional forest products.

That presents several challenges for the forestry sector. First, we cannot simply extrapolate past forest and wood use trends to forecast likely futures or even apply models without accounting for the many uncertainties. For instance, carbon accumulation rates will likely change with a different climate and species mix, and mortality relationships could be quite different than in the past. Second, a rational management response entails adaptation to and mitigation of these effects (Malmsheimer et al. 2008). Changes in planted species selection, silvicultural treatments, fire regimes, and insect damage must be accounted for when projecting forest carbon dynamics. Third, the uncertainties present risk management problems. A central question is how to strike a smart balance between in-forest sequestration by managing for increased carbon density across all forest carbon pools, and use for bioenergy that offsets fossil fuel use and the removal of carbon to long-term sequestration in harvested wood products and landfill storage (Matthews and Robertson 2005). The near certainty of eventual disturbance makes dependence on in situ carbon storage sinks a high-risk alternative in many areas (Galik and Jackson 2009).

The most effective management strategies to satisfy multiple economic, environmental, and societal objectives will vary from site to site. There is substantial literature developing around management and mitigation practices that maximize landscape-level ecosystem carbon stocks while considering uncontrollable disturbances and sustain or increase carbon sequestration in wood and bioenergy products that achieve fossil fuel substitution benefits (Hines et al. 2010). Other approaches could maximize product and energy benefits while putting less emphasis on the levels of ecosystem carbon stocks. A major challenge for the future will be ensuring policy and market environments that promote the application of strategies best suited to specific circumstances.

If bioenergy is to contribute to climate mitigation, the bioenergy sector will need to expand. How this changes demand for forest products depends on renewable energy policies, the treatment of bioenergy in climate policies, and the relative cost of producing energy from forest biomass versus other renewable energy sources and fossil fuels. Developing more efficient forms of bioenergy, such as combined heat and power, will also be important. Emissions reduction benefits of wood energy use will vary by wood source, forest condition, the extent of forest disturbance, and geographic region. Markets and policies will determine how much new forest biomass is purpose grown to meet energy goals and whether harvest residues can be redirected to produce energy that offsets fossil fuel use (Morris 2008).

Integrating Forests into a Rational Policy Framework

Forests are an integral component of the global carbon cycle and may change in response to climate change. US forest policies can foster changes in forest management that will provide measurable reductions in carbon emissions over time while maintaining forests for environmental and societal benefits, such as timber and nontimber forest products, vibrant rural communities, clean water, and wildlife habitat. Policies founded on three tenets reflecting the stocks and flows of woody biomass in US forests can ensure that our forests will produce sustainable carbon, environmental, and societal benefits.

1. Keep Forests as Forests and Manage Appropriate Forests for Carbon

For more than 70 years, US forest cover has increased and net growth has exceeded removals and mortality. Therefore, carbon storage is increasing in the United States. In some forests (e.g., old-growth), other considerations and other benefits will usually outweigh carbon benefits. However, forests will 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. Net primary productivity declines and the 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. Substantial volumes of wood go into construction products and structures: even during the midst of the recent "Great Recession" (2007–2009), US housing starts exceeded 440,000 annually. Additional wood is used for furniture and other products, which at the end of their useful lives may be converted to energy. Paper may go into long-term use (e.g., books) or be recovered from the waste stream for energy production. Other wood—construction debris, yard waste, unrecycled paper—winds up in landfills, where it often deteriorates more slowly than is generally assumed. In total, the rate of carbon accumulation from wood products in use and in landfills was about 88 million tonnes of carbon dioxide equivalents (CO_2e) in 2008, about 12% of the rate of sequestration in forests.

3. The Substitution Effect Is Real, Irreversible, and Cumulative

Compared with steel, aluminum, concrete, or plastic products, considerably less energy, and vastly less fossil fuel–derived energy, is required to make wood products. The low embodied energy of wood building products, structures, furniture, cabinets, and other products has been well documented through life-cycle assessments. Not only is the quantity of energy used in manufacturing wood products low compared with other materials, but the quantity of fossil energy is comparatively very low: one-half to two-thirds of the energy used by the North American wood products industry is bioenergy. For instance, compared with steel framing with an average recycled content, the manufacture of wood framing requires one-half or less the total energy, and one-fourth to one-fifth the fossil energy.

Conserving forests for recreational, aesthetic, and wildlife habitat goals has been a strong policy driver in the United States over the past few decades, especially in the Pacific Coast and Northeast regions. Evidence of increasing losses to disturbances that are not captured in forest growth modeling and decreasing rates of carbon accumulation in maturing forests suggests that a strong conservation-oriented strategy may not always produce significant global climate benefits. The climate benefits of active forest management are most apparent when substitution benefits that occur in the consumer sector are included. As we move forward with policy discussions regarding the many positive roles of US forests at local, national, and global scales, it will be imperative that objective, science-based analysis and interpretations are used, and that particularly close attention is paid to assumptions underlying the analyses.

US policymakers should take to heart the finding of the Intergovernmental Panel on Climate Change in its Fourth Assessment Report when it concluded that "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" (IPCC 2007a, 543). An integrated 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. Forest carbon policy that builds on the scientific information summarized in this article can be an important part of a comprehensive energy policy that promotes energy independence and delivers real carbon benefits while providing essential environmental and social benefits, including clean water, wildlife habitat, and recreation.

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Malmsheimer, a professor at SUNY ESF since 1999, teaches courses in natural resources policy and environmental and natural resources law. His research focuses on how laws and the legal system affect forest and natural resources management, including how climate change and carbon sequestration policies affect forest and natural resources. Before becoming a professor, Malmsheimer practiced law for 6 years. He has a PhD in forest policy from SUNY ESF, a JD from Albany Law School, and a BLA from SUNY ESF. He is a SAF Fellow and the chair of the SAF Committee on Forest Policy. He cochaired the 2007–2008 SAF Task Force on Climate Change and Carbon Sequestration, and he has chaired and served on numerous national and state SAF committees and task forces.

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Fried has been with the PNW Research Station's Forest Inventory and Analysis unit since 1999, serving as California FIA analyst since 2000 and as team leader from 1999 to 2009. His research focus is interdisciplinary application of systems analysis and geographic information science to contemporary natural resource management issues. Current and recent examples include economic feasibility of landscape-scale fuel treatments, forest carbon accounting, initial attack simulation and optimization, impacts of climate change on wildland fire, and building inventory-based models of fire effects. Before joining the PNW Research Station, he served on the forestry faculties at Michigan State and Helsinki universities. He has a PhD in forest management and economics from the University of California–Berkeley and an MS in forest ecology and soils from Oregon State University. Fried served as the resource measurements subject area representative on SAF's Forest Science and Technology Board and as an officer (secretary, chair-elect, and chair) of both the Management Science/Operations Research and GIS working groups.

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Gee is the past chair of the Interagency Woody Biomass Utilization Group. He was one of the coauthors of the SAF task force report, "Forest Management Solutions in Mitigating Climate Change in the United States." He has a BS in natural resource management from the University of California–Berkeley and an MBA in international business from the University of Phoenix; he also completed graduate work in silviculture and fire ecology at the University of Washington. He has more than 35 years of diverse experience as a line and staff officer with the US Forest Service in the Washington Office, two regions, six national forests, and international programs.

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Izlar has been director of the University of Georgia Center for Forest Business since 1998, and he teaches courses on renewable natural resources policy and consulting. He has 26 years' experience in private forest industry, including stints as head of the Georgia and Mississippi forestry associations. He has a bachelor's and a master's in forest resources from the University of Georgia and an MBA from Georgia Southern University. He served as SAF Georgia Division chair in 1995 and Oconee Chapter chair in 2010, and was elected a Fellow in 2003. He is a fellow of the Royal Swedish Academy of Agriculture and Forestry and is a SAF Certified Forester and a Registered Forester in Georgia.

Reid A. Miner
Vice President for Sustainable Manufacturing, National Council for Air and Stream Improvement (NCASI), Research Triangle Park, North Carolina

Miner has worked for National Council for Air and Stream Improvement since 1974. For the past 15 years, he has focused on sustainability topics, including the connections between the forest products industry and the global carbon cycle. His work has involved collaborations with a range of organizations, including the United Nations Food and Agriculture Organization, the International Finance Corporation of the World Bank Group, the Intergovernmental Panel on Climate Change (IPCC), the US Forest Service, the Environmental Defense Fund, the Council for Sustainable Biomass Production, the World Resources Institute, and the World Business Council for Sustainable Development. He was a contributing author to IPCC's Fourth Assessment Report and is on US EPA's and IPCC's lists of expert reviewers on carbon accounting. Miner has BS and MS degrees in chemical engineering from the University of Michigan.

Ian A. Munn

Professor of Forestry Economics and Management, Mississippi State University, Mississippi

Munn has been a professor in the Department of Forestry at Mississippi State University since 1993. He teaches the department's capstone course in professional practices, as well as a course in advanced forest management. He also coordinates student internships for academic credit. His research focuses on nonindustrial private forest landowner issues, including landowners' willingness to provide ecosystem services, recreational opportunities, and logging residues and short-rotation woody crops for biofuels. Before pursuing his PhD degree, Munn was a timberland manager for a forest products firm for 10 years. He has a PhD in forestry and economics from North Carolina State University, an MBA from Louisiana Tech University, an MS in resource management from SUNY ESF, and an AB in biology from the University of North Carolina. He is a SAF Fellow, a councilman from District 11, editor of the *Southern Journal of Applied Forestry*, and has served as a chair of the Mississippi state society and local SAF chapter. Munn is a SAF Certified Forester and a Mississippi Registered Forester.

Elaine Oneil

Research Scientist, University of Washington, and Executive Director, Consortium for Research on Renewable Industrial Materials (CORRIM), Seattle

Oneil is a research scientist at the University of Washington and the executive director of the Consortium for Research on Renewable Industrial Materials, a 17-university research consortium that conducts life-cycle inventory and life-cycle assessments on wood products from cradle to grave. She has a BS in forestry from the University of British Columbia and MSc and PhD degrees from the University of Washington. Her focus is on forest management operational research: the effects of harvesting on bald eagle nesting, management of Douglas-fir at the edge of its climatic range, climate change impacts on forest health in Inland West forests, integration of forest carbon accounting into a forest management framework, ecological and economic constraints to biomass feedstock availability, life-cycle analysis, and timber supply analysis. Before her midcareer return to academia, she worked as a Registered Professional Forester in both consulting and government forestry positions in several central British Columbia areas devastated by the mountain pine beetle epidemic.

William C. Stewart

Forestry Specialist, Environmental Science, Policy and Management Department, University of California–Berkeley

Stewart is a Cooperative Extension forestry specialist who has been based at UC Berkeley since 2007. He is also the director of the Center for Forestry and co-director for the Center for Fire Research and Outreach at UC Berkeley. His current areas of research and extension focus on the linkages between managed forests and climate change, the economic aspects of fire-adapted silviculture in California, and succession planning with family forest owners. He has an MS and PhD in forest economics and policy from the University of California–Berkeley and a BS in environmental earth sciences from Stanford University. He is active on technical committees of the Northern California SAF and has served on numerous national and state scientific review task forces.

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