Life Cycle Impacts of Forest Management and Bioenergy Production

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Introduction

The wood provided by forest management has the potential to provide many important energy products. Wood can provide replacements for gasoline and other liquid transportation fuels, heating products, plastics, and a wide range of industrial chemicals. There is great interest today in expanding the use of wood. However, the growing interest in wood energy has resulted in concerns about long-term forest sustainability and the role of forests in carbon mitigation and climate change.

This article provides an overview of forest bioenergy evaluations and a brief summary of the recent report *Life Cycle Impacts of Forest Management and Wood Utilization on Carbon Mitigation: Knowns and Unknowns* (Lippke et al. 2011). This recent report by Lippke et al. is the first to apply systematic life cycle analysis to forest bioenergy development and resulted in a number of key findings, including the following.

- **Managed forests continually accumulate carbon and maintain stable carbon stocks.** Photosynthesis turns carbon dioxide into solid wood in growing forests. Managed forests with healthy, growing trees maximize the rate of carbon capture, serve as a stable repository for carbon, and provide useful materials that store carbon outside of the forest.
- **Sustainably managed forests are "better than carbon neutral"**
  Forests managed for sustainability balance timber outputs with ecosystem needs and social values. Managed forests are considered sustainable if the outputs do not exceed growth and management results in a steady forest inventory over time. Forests absorb carbon dioxide from the atmosphere as they grow and carbon is stored in the wood produced. Wood products from the managed forest result in continued storage of carbon in useful materials outside of the forest. The carbon storage benefits of carbon pools outside of the forest combined with ongoing carbon absorption within the forest produces net carbon benefits that continue to accumulate over time.
- **Carbon dioxide emissions from biomass power are 4% of emissions from coal power**
  Life cycle assessment comparing electricity production from biomass versus coal shows an overwhelming emission reduction per unit of electricity produced.

Wood from managed forests is already a widely used and important material. One of the reasons wood is so widely used is because it is renewable and, through responsible management, wood is produced while protecting other forest values. The growing interest in forest bioenergy creates new questions about forest management, and the findings of the recent report by Lippke et al. provide helpful information for evaluating the potential for sustainable bioenergy development.

Forest Bioenergy Considerations

The evaluation of forest bioenergy opportunities occurs in the context of balancing life cycle benefits of using a renewable material with responsible management of diverse forest resources. The following considerations directly relate to the potential life cycle impacts of bioenergy development and the influence on carbon cycles.

◆ **Forests, trees, and the wood they produce are renewable**
Trees are renewable resources. Over 847 billion cubic feet of timber have been harvested from U.S. forests in the past sixty years. This harvest volume is equivalent to a pile of wood measuring 2 miles x 2 miles x 7,600 feet high. Put another way, this is enough wood to create a square foot stack that would reach to the moon and back 334 times![1] During this same time period, the volume of wood within America's forests *increased* by more than 50 percent. Living tree volumes have increased through forest management, tree growth and renewal.

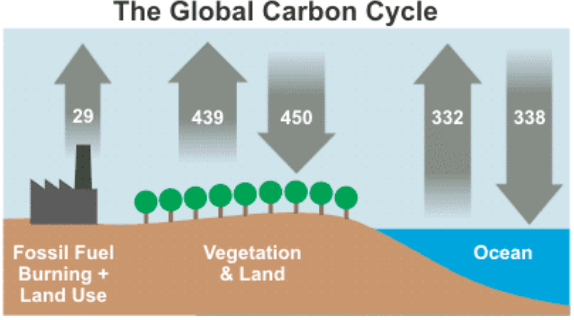
◆ **Forest management can impact climate mitigation in three ways**
Trees and wood are one-half carbon by weight. Forest management maintains within-forest carbon storage while contributing to new carbon pools in wood products in use. America's forests have built more than 90 million homes. Using forest products also reduces greenhouse gas (GHG) emissions through avoided use of fossil fuel.

◆ **Sustainable forest management balances diverse and critical services**
Forest management provides for water resources, wildlife habitat, recreation, jobs, wood and fiber products and the potential for bioenergy development. Wood is an important construction material in the United States and it is used in making furniture, paper, energy and chemicals. Biomass is also our largest source of renewable energy, accounting for 4% of total energy and 50% of renewable energy[2].

The Global Carbon Cycle

On a global scale, carbon is stored in various pools (stocks) with dynamic flows (fluxes) between the pools (Figure 1). The largest pools are the atmosphere, the oceans, and the land and plants (including forests and forest products). Substantial movement of carbon between the atmosphere, oceans and land is ongoing in the form of carbon dioxide and methane. These gases are part of the group of compounds known collectively as greenhouse gases (GHGs).[3] A much smaller, but one-way, flow of carbon is traceable to the burning of fossil fuels. The GHG releases traceable to fossil fuel combustion shift the carbon cycle balance to one of net emissions. As a result, levels of atmospheric carbon are steadily rising.

Figure 1.



(Source: Figure 7.3, IPCC AR4).

Proposed strategies for bringing the global carbon cycle back into balance include establishing new carbon sinks and reducing fossil fuels consumption. Systematic assessment

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[1] The moon is estimated to average 240,000 miles from the earth. 847 billion cubic feet would form a stack of wood 160,416,667 miles high.

[2] U.S. Energy Information Administration. 2010. *Annual Energy Review, 2009* Table 1.3 US Energy Consumption by Energy Source, 2009.

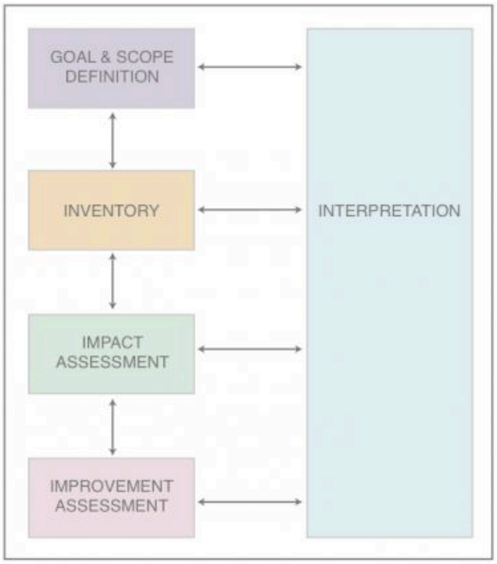
[3] GHGs (greenhouse gases) are compounds that absorb and emit radiation within the thermal infrared range. These gases, many of which occur naturally in the Earth's atmosphere, blanket the earth and maintain surface temperatures of about 60º F warmer than they otherwise would be. In other words, these gases in proper concentration protect the surface of the earth from the extreme cold of space, but also moderate temperature rise from solar radiation; in short, they enable life as we know it on earth.

shows the potential for forests to play a role in both areas. Increasing the area of forests increases the rate of forest growth and increases the use of wood in long-lived products, resulting in new carbon sinks. Using wood as a source of energy avoids consumption of fossil fuels and associated carbon emissions. Understanding the direct and indirect substitution connections between fossil fuels and forests and the timing of impacts is essential to insure that policy decisions optimize the role of forests in balancing the global carbon cycle.

Life Cycle Analysis

Life cycle analysis, or LCA, provides a mechanism for systematically evaluating the environmental impacts linked to a product or process and in guiding improvement efforts (Figure 2). LCA-based information provides insights into the environmental impacts of raw material and product choices, and maintenance and end-of-product-life strategies. An LCA includes a careful accounting of all the measurable raw material inputs (including energy), product and co-product outputs, and emissions to air, water, and land; this part of an LCA is called a Life Cycle Inventory (LCI). An LCI may deal with product manufacture only or may also include product use, maintenance, and disposal.

Figure 2. Phases of LCA



Source: Garman, J. (2011) based on ISO 14040.

Life cycle analysis can also be used to evaluate the consequences of product selection decisions. For example, in considering the impact of choosing wood in a building project, a systematic assessment would examine not only the direct impacts to forests and environmental impacts of wood products manufacturing, but also the indirect effects of using wood products instead of a functionally equivalent volume of alternative materials. Life cycle data for many primary materials are publicly available. In the United States a peer-reviewed source of primary product life cycle data, including GHG emissions, is available through the US Life Cycle Inventory Database.[4]

Forest Management and Carbon Stocks

In many developing nations, deforestation, driven primarily by expansion of agriculture, is a serious concern. In contrast, in most developed nations where agricultural expansion peaked many decades ago, the total forest area is either steady or expanding. The forests in most developed countries are managed such that growth exceeds harvest removals. In the United States, net annual forest growth has for many decades exceeded removals, with the result that timber volume and forest carbon stocks have steadily increased over time. Net forest growth includes accounting for forest loss due to natural disturbance mortality and decay. The relationship between net forest growth and changes in carbon stocks is direct; about one-half the dry weight of wood is carbon.

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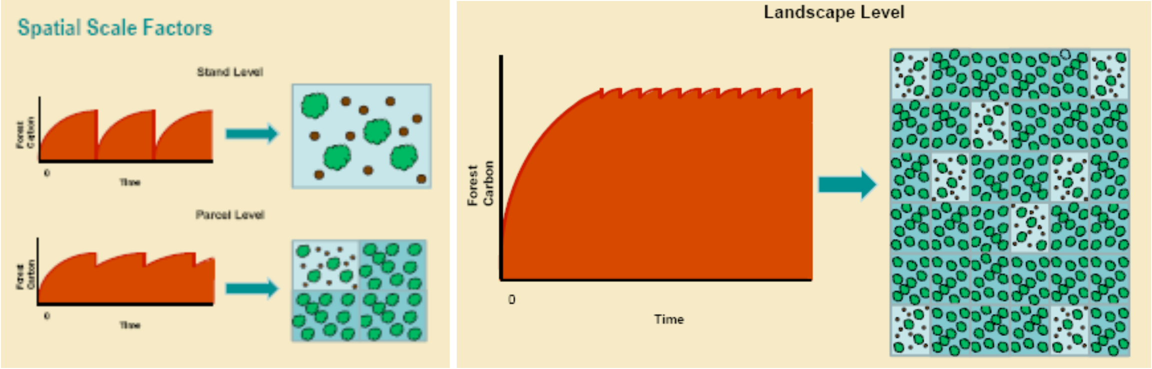
[4] National Renewable Energy Laboratory. 2011. U.S. Life Cycle Inventory Database. U.S. Department of Energy. (http://www.nrel.gov/lci/)

Figure 3

A Depiction of Forest Carbon in a Sustainably Managed Forest at Stand, Parcel, and Landscape Levels



Source: Colnes (2011)

As at the national level, individual forests or forest management units are typically managed such that removals do not exceed net growth and the result is that a carbon storage equilibrium is maintained over time (Figure 3). Management activities and natural disturbances (e.g., wildfire) may result in forest carbon storage being reduced for a period of time as the forest grows and the carbon equilibrium is reestablished. The same cycle is true at all spatial scales, including the scale of the forest stand level. Forest carbon stocks periodically rise with periods of regeneration and growth, and fall with periodic harvests or disturbance (Figure 3, upper left). In a managed forest the carbon dynamics of a forest are defined by similar treatments progressively applied over a period of time to individual stands across a forested parcel (Figure 3, lower left). Forest management results in a stable average of carbon within any given stand over the long run, and also across the total forest at any point in time. Through forest management there tends to be little change in forest inputs or outputs from year to year at the forest level even though there are periodic changes for an individual stand. As a result, forest carbon in a managed forest tends to be essentially stable, with carbon inputs from growth equaling carbon outputs resulting from harvest, natural mortality, and decay (Figure 3, right). This cycle provides the foundation for the concept of "carbon neutrality," meaning that carbon is being balanced on an appropriate temporal scale and no additional carbon is being added to the atmosphere.

In all forests, competition between trees, combined with natural aging processes translates to changing dynamics that must be considered in management. Growth rates in young trees and newly established forests tend to be rapid. As trees grow in size and crown closure occurs, competition between trees intensifies, leading to the death of some and enhanced prospects for others. The rates of growth and carbon capture slow as a result of aging, and may even decline at advanced ages due to increasing natural mortality. The reduction in net growth with age is substantial. For instance, in west-side forests in the Pacific Northwest the rate of carbon capture typically falls from as much as 4 tons of carbon per hectare per year (1.6 tons per acre per year) at age 50 to -1 ton per hectare by age 150. Therefore, while older forests can store more carbon (e.g., in large standing trees), the rate at which they remove additional carbon from the atmosphere is substantially lower, will eventually plateau, and can become negative if mortality increases to the point that it exceeds growth (i.e., net growth becomes negative). Research has also found that older forests are often more susceptible to catastrophic disturbance, and unscheduled loss of stored carbon.

In recent years questions have been raised about how carbon stocks in forest soils are impacted by harvesting. Though further research is needed on this topic, studies to date have found that harvesting activity generally has little impact on soil carbon. The studies suggest that carbon-to-nitrogen ratios in the soil, forest floor, and litter remain relatively constant through time. Soil organic carbon on some sites can be increased by fertilization, and soil carbon can be negatively affected when a site is burned through a prescribed fire or due to wildfire. Although there is uncertainty due to variability in soil types and responses, a growing body of literature is indicating that forest management generally can maintain and in some cases enhance soil carbon.

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A relevant question regarding forest management and its impact on carbon stocks is what happens to carbon contained within trees when they are harvested. U.S. mill survey data gathered in accordance with LCA protocols shows that approximately 50-70 percent of the aboveground biomass in a sustainably managed forest is utilized in manufacturing processes to make solid wood products (lumber, engineered wood products, panels), paper, and energy or energy products. The remaining 30-50 percent, in the form of the tree crown, leaves and needles, dead and broken stems, and forest litter is left to decay along with the roots. Much of the wood converted to products winds up in long-term use, such as in buildings, where the carbon within the wood is stored for as long as a building is in service, and longer if the wood is reused or recycled. The production of paper and other products shifts carbon into shorter-lived carbon pools, with longevity influenced by the degree of recycling and/or landfilling. What this means is that production and use of wood products results in creation of new carbon pools outside the forest.

Commercial forest management involves relatively short rotations (e.g., 30-35 years is common in the southeastern United States and 80-85 years elsewhere) because forest growth slows with age, reducing economic returns. When rotations are extended beyond the period of rapid growth, the volume and value of wood production (and wood product carbon pools) is reduced, and the rate of absorption of carbon from the atmosphere is reduced as well. Viewed from a different perspective, a singular focus on maximizing the quantity of carbon stored in forests often results in minimization of the quantity of carbon moved from the forest for use in products. This strategy reduces the volume of products that can be used to substitute for energy intensive products and similarly reduce long-term storage of carbon within wood products.

Carbon Stocks and Natural Disturbance

Any strategy aimed at storing carbon in forests over long time periods must take into account the reality of aging and increasing natural mortality. Such a strategy also needs to consider the increasing risk of natural disturbance with the passage of time.

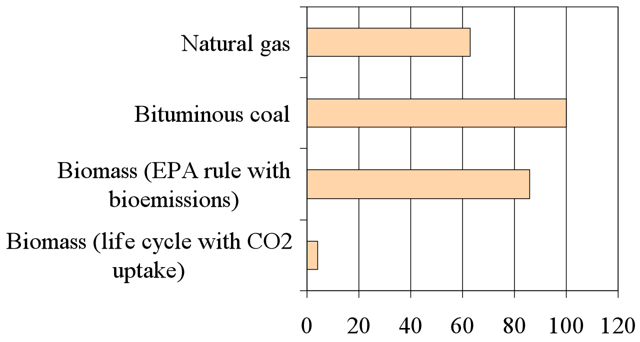
Unmanaged forests, including regulated set asides and public forests left for non-timber values, can store considerable quantities of carbon in the absence of natural disturbance (Figure 5). However, at the carrying capacity of the land there is no positive contribution to carbon mitigation. Moreover, there are higher risks of carbon loss due to natural disturbance than in management forests. Forests are susceptible to a range of disturbances including wind, fire, and disease or insect infestations that are often more severe in untended forests typified by crowding and significant quantities of dead and dying trees. Catastrophic disturbance in such forests can generate very large carbon emissions.

An example of the risks posed by fire comes from the drier interior forested regions of the western U.S. Here, increasing rates of fire are projected due to warmer, drier weather linked to climate change and the presence of extremely dense forests resulting from a century of fire suppression. A recent study suggests that since 2002 higher levels of carbon have been emitted from the national forests in this region than have been removed from the atmosphere by new growth (Oneil and Lippke 2010). It is projected that without more aggressive fire risk reduction treatments, such as thinning to reduce forest stand density and reforestation of previously burned sites, many more forests in this region will become emission sources rather than carbon storage sinks.

The Substitution Effect

Using wood-derived energy instead of fossil energy results in *avoidance* of non-renewable fossil fuel consumption and associated emissions of GHGs and other compounds. When wood from a sustainably managed forest[5] is used to generate energy, the only fossil fuel carbon emitted is that used in managing and harvesting forests and transporting the harvested wood. The emissions from fossil fuels used in harvesting amount to about 1-2 percent of the carbon stored in the forest prior to harvest. Carbon emitted in combustion of wood for energy production is offset by ongoing forest growth.

Figure 4
Electric Power Plant GHG Emissions Comparisons



Source: Consortium for Research on Renewable Industrial Materials, unpublished data. (2011)

Each type of wood use involves a different impact on carbon stores and displacement of fossil emissions from substitute products. Life cycle information collected in wood processing mills suggests a reduction of approximately 1.2 tons of CO_2 for every 1.0 ton of wood biofuel consumed in place of the typical mix of fossil fuels used in manufacturing. Using data from the US Life Cycle Inventory database and the US EPA TRACI impact method, a comparison of wood-fired electric generation to coal and natural gas shows that each megajoule of electricity that a woody biomass plant produces generates only 4 percent of the emissions generated by a bituminous coal plant (Figure 4). This finding shows a larger difference in emissions than the results obtained using the EPA rule with bioemissions, a method wherein CO_2 uptake in the wood from the atmosphere is treated the same as if it were mined like a non-renewable resource. This EPA accounting method shows that electricity generation from

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[5] Forests managed for sustainability balance timber outputs with ecosystem needs and social values. Managed forests are considered sustainable if the outputs are planned to not exceed growth and management results in a steady forest inventory over time.

biomass would result in 86 percent of the GHG emissions of a coal-fired plant, and 35 percent greater GHG emissions than a natural gas-fueled plant.

There is also a substitution effect when wood products are used in place of products that require more fossil fuel energy to manufacture. Wood is a material produced by trees using solar energy (via photosynthesis) and relatively little additional energy is required to convert wood into useful products. The use of fossil fuels is further avoided as 60-70 percent of the energy used in wood product manufacturing is biomass energy.

Considerable research focused on life cycle impacts of various materials and products has documented the benefits of substituting wood for more energy and fossil fuel intensive products in construction. For instance wood studs can be compared to steel studs, wood joists to steel I-beams, wood walls to concrete walls, and wood floors to concrete slab floors. Using life cycle inventory data to compare a steel floor joist to an engineered wood I-beam shows that, in this case, the use of wood reduces the carbon footprint by almost 10 tons of CO_2 for every ton of wood used (Lippke and Edmonds 2010). The same analysis found that substituting a lumber stud for a steel stud (a less structurally demanding application) reduced the carbon footprint by 2 tons of CO_2 for every ton of wood used. A ton of wood stores approximately 0.4 tons of carbon, equivalent to 1.5 tons of CO_2 over the life of the product, net of processing emissions. A similar analysis shows that replacing a concrete slab with a wood floor reduces the carbon footprint by approximately 3.5 tons of CO_2 for every 1 ton of wood used. A number of studies of such substitutions reveal a meta-average value for wood of 3.9 tons of CO_2 emissions reduction for every dry-ton of wood used to displace other structural materials.

Using life cycle analysis to examine all carbon pools, including substitution, demonstrates that generating energy from biofuels rather than fossil fuels produces a sustainable reduction in atmospheric carbon, a reduction that is cumulative over time. The same is true when using wood from responsibly managed forests to displace fossil-intensive products such as steel and concrete.

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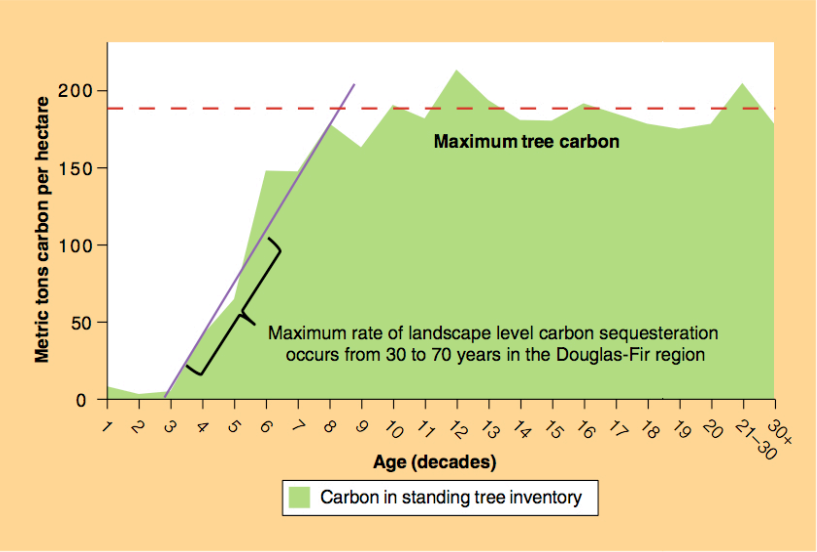
Unintended Consequences of No Harvest

The goal of climate mitigation policy is to address overall greenhouse gas emission rates and quantities. Emissions displacement pools resulting from product substitution are as important to climate change as carbon storage pools, and hence both must be measured and considered in crafting climate mitigation policies.

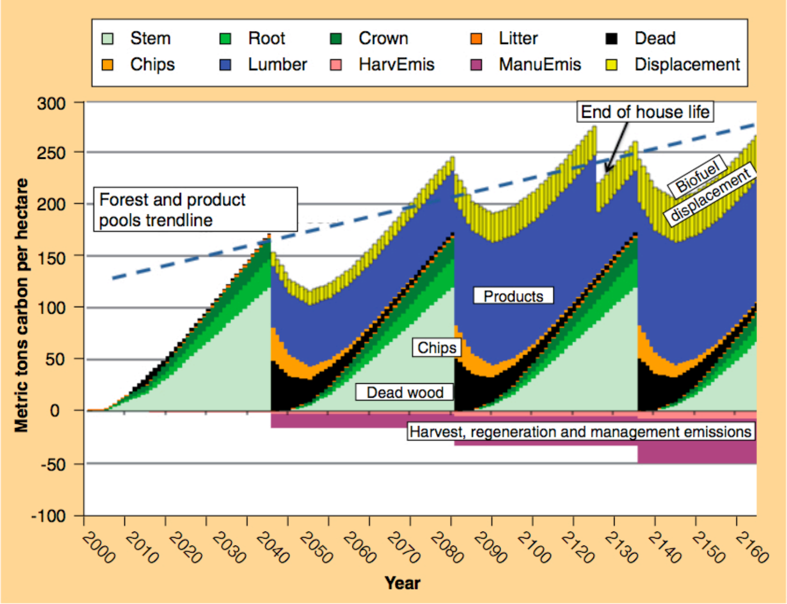
Figures 5 and 6 provide a graphic comparison of the carbon dynamics in forests with and without periodic harvest for products. Both figures are based on data from Douglas-fir forests of the Pacific Northwest. All product related data in Figure 6, including those related to substitution effects, are obtained from life cycle inventory studies for the same region.

Figure 5
Forest-Carbon Growth Rate Decreases with Age in Western Washington



Source: Derived from Bolsinger et al. (1997)

Figure 6
Forest Plus Product-Carbon Pools and Process Energy Emissions



Source: Perez-Garcia et al. (2005)

The data show that carbon storage is lower within managed forests with periodic harvests (Figure 6) than within forests maintained without harvesting (Figure 5). However, the data also show that over time the total carbon pools associated with the managed forest will exceed carbon accumulation in a forest maintained without harvesting. In Figure 6, the various layered segments that appear following the harvesting cycles represent carbon stores in various pools (roots, crowns, litter, dead wood, chips, lumber), with accounting for harvest and manufacturing emissions, and displacement of emissions due to substitution effects. Carbon stored in long-term wood products (blue), and avoidance of carbon emissions by using wood as a substitute for fossil-fuel intensive products like steel or cement (orange), distinguishes managed forests from un-managed forests. Illustrated in Figure 6 is carbon that remains in the forest (green and black) and carbon emitted from fossil fuel use in the course of harvesting and processing of wood (cranberry). These emissions are partly counterbalanced by the burning of mill residues for energy, a practice that results in avoided emissions (yellow). These evaluations include assumptions of equal soil carbon and rates of decomposition of dead material. In the "forest-plus" scenario (Figure 6) emissions are partially offset by internally generated biofuels and results in a *better* than carbon neutral outcome, producing a sustainable trend *increase* in the integrated forest-plus-product-carbon pools. This "better than carbon neutral trend increase" occurs without including the substitution benefit of using solid wood to displace the use of fossil intensive construction materials.

Forest carbon neutrality (or better than neutrality) is not limited to a regulated, even-aged forest condition. Managing for multi-storied forests or using partial cutting methodologies that set harvest removals equal to growth will provide the same carbon neutral status on a landscape basis or across cutting cycles for individual stands.

Carbon mitigation strategies focused on maximum accumulation of carbon within forests are not realistic when they have been designed with an assumption that carbon stocks will continuously increase over time. The reality is that projections of future forest carbon stocks need to account for the effects of natural aging and the risks of natural disturbance. To provide a truly accurate analysis on which to base decision making, these projections should also include consideration of the opportunity to optimize the rate of forest carbon capture and the creation of forest product carbon pools as a component of a carbon mitigation strategy. In addition, the substitution effect needs to be taken into account as it represents an even larger opportunity to avoid depletion of non-renewable fossil fuels and emissions of fossil carbon.

Projections should include consideration of the opportunity to optimize the rate of forest carbon capture and the creation of forest product carbon pools.

Consider, for example, the findings of a Canadian study that examined the quantity of carbon stored in Ontario's managed forests and wood products, and the potential for increased storage over a 100 year period (2000-2100) (Colombo et al. 2007). The carbon pool within the forest was projected to increase by almost 7 percent across all forests, with stocks increasing in all types of managed forest as a result of management activities and forest growth. By far the greatest increase in carbon storage, however, was identified as that within wood products flowing from the forest. The study found that the wood products carbon pool opportunity was about five times the amount in forests, a value that does not include avoided emissions.

Policies that focus solely on forest carbon, ignoring carbon storage in harvested wood products and the very real effects of products and materials substitution, risk the unintended consequence of capturing far less carbon than would be possible through implementation of systematic life-cycle science-based solutions.

Controversy Regarding Carbon Pools and Bioenergy

A recent study (Manomet 2010) created a stir when the Boston Globe published an article under the byline "Wood Power Worse Polluter Than Coal." The report indicated that use of wood in producing energy can result in an initial "carbon debt" because burning wood releases more CO_2 into the atmosphere per unit of energy than burning fossil fuels (oil, natural gas or coal). However, the report goes on to say that "unlike fossil fuels, forests can grow back and recapture (or sequester) CO_2 from the atmosphere." As the forest grows back the carbon debt is "paid off," and thereafter a "carbon dividend" is realized as a forest continues to grow, resulting in increasing greenhouse gas mitigation. In addition, the report acknowledges an immediate carbon benefit when using mill residues to generate power.

Beyond the attention grabbing headline, two aspects of what is known as the *Manomet Report* continue to generate debate: 1) the notion that there is no difference between the carbon released from fossil fuel combustion and the carbon from burning biomass, and 2) claims of an initial carbon debt. Regarding the latter, Lippke et al. weighed in relative to use of forest residuals in electricity generation vs. power generation from natural gas. They point out that equating biomass carbon and fossil carbon can lead to concerns about the immediate release of carbon from burning biomass as opposed to slower releases that occur if biomass is left in the forest and allowed to decompose. On this point they note that "While much has been made about this time sensitivity – that burning wood is worse than letting it decay – the longer term benefits of sustainable wood production displacing fossil fuel emissions rotation after rotation far outweighs any short-term impact." They also observe that because there is no change in forest carbon over the entire area managed in the course of a harvest rotation, time preferences (and therefore the notion of an initial carbon debt) are not relevant to carbon measures at the forest landscape level. This view is reinforced by another recent study (Strauss 2011) that challenges the debt notion altogether, concluding that what was considered by Manomet as a debt should instead be properly viewed as harvesting a credit of previously accumulated carbon. Strauss found that there is no debt if the forest system from which the biomass is removed has been in growth-to-harvest equilibrium, or has a growth-to-harvest ratio greater than one, and is managed sustainably so that the net stock of biomass does not deplete.

Energy as Only One Product of Sustainable Forest Management

Life cycle research over the last decade has demonstrated the carbon benefits of sustainable forest management. This research demonstrates that forest carbon removals and emissions from wood bioenergy are being offset by sustained capture of carbon in growing forests, and ongoing additions to forest product carbon pools. There is also the substantial benefit of avoidance of carbon emissions through substitution effects.

Removal of wood from forests for bioenergy production must be done carefully and within the boundaries of responsible, sustainable forest management. Sustainable management is the key to realizing carbon benefits over both the short and long term. Constraining the operation of timber markets may reduce economic incentives for maintaining and managing forests as well as creating negative impacts to carbon cycles. The potential for increased energy production from forest biomass is but one piece of a larger picture involving a full range of products and services from sustainably managed forests.

The potential for increased energy production from forest biomass is but one piece of a larger picture involving a full range of products and services from sustainably managed forests.

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