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Review

Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns

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This review on research on life cycle carbon accounting examines the complexities in accounting for carbon emissions given the many different ways that wood is used. Recent objectives to increase the use of renewable fuels have raised policy questions, with respect to the sustainability of managing our forests as well as the impacts of how best to use wood from our forests. There has been general support for the benefits of sustainably managing forests for carbon mitigation as expressed by the Intergovernmental Panel on Climate Change in 2007. However, there are many integrated carbon pools involved, which have led to conflicting implications for best practices and policy. In particular, sustainable management of forests for products produces substantially different impacts than a focus on a single stand or on specific carbon pools with each contributing to different policy implications. In this article, we review many recent research findings on carbon impacts across all stages of processing from cradle-to-grave, based on life cycle accounting, which is necessary to understand the carbon interactions across many different carbon pools. The focus is on where findings are robust and where uncertainties may be large enough to question key assumptions that impact carbon in the forest and its many uses. Many opportunities for reducing carbon emissions are identified along with unintended consequences of proposed policies.

Recent objectives to increase the use of renewable fuels in order to reduce fossil carbon emissions and increase energy independence have raised policy questions with respect to the sustainability of managing our forests and how best to use wood from our forests. There has been general support for the benefits of sustainably managing forests for carbon mitigation, such as that expressed by the IPCC, "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, fiber, or energy from the forest, will generate the largest **sustained mitigation benefit**" [1]. However, there are many integrated **carbon pools** involved that have led to conflicting implications for best practices and policy including concerns that rising carbon values may reduce other **ecosystem services**. The objective of this review is to show the extent to which recent research findings on life cycle carbon accounting across all stages of processing, from cradle-to-grave, can identify opportunities for carbon mitigation improvement, which can contribute to global carbon objectives and national energy independence objectives. Focus is given to measurement systems that can infer where findings are robust as well as determine if and where uncertainties are large enough to question key assumptions that impact forest-management practices, and the many different ways wood is used. Many opportunities for reducing carbon emissions are identified, some with very high leverage to reduce emissions relative to the amount of wood used. Also identified are

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Key terms

Sustainable forest management: Forests managed for timber production are considered sustainable if the harvests are planned to not remove more wood than is grown (i.e., the forest inventory is not declining over time). Forests managed for sustainable multiple ecosystem values would attempt to include a sustainable balance between timber outputs, ecosystem values and economic or social values; acknowledging that not all forests can produce all values. Unmanaged forests may result in regeneration after natural disturbances, but are subject to mortality risks that complicate restoration. Unmanaged forests do not support sustainable timber production; however, they may contribute critical ecosystem values not found in timber producing forests.

Sustained mitigation benefit: Working Group III to the Fourth Assessment Report of the IPCC in regard to the impact of forests stated: "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, fiber, or energy from the forest, will generate the largest sustained mitigation benefit."

Carbon pools: Processing products produces emissions from the use of energy, a negative carbon store. Absorbing atmospheric carbon in growing trees produces a positive carbon store. Since increases in carbon stores and decreases in atmospheric carbon are equally important to carbon mitigation, they are generally all referred to as carbon pools not drawing the distinction whether a store, a reduced emission or an offset.

Ecosystem services: Public values on many forest attributes that are not traded in the market such as clean air, water, habitat, biodiversity and aesthetics may be complementary or competitive with strategies to maximize carbon mitigation. An increasing focus on carbon mitigation as an important ecosystem service can be expected to compete with some non-carbon ecosystem values.

Global carbon cycle: Carbon is stored in various pools (stocks) with dynamic flows between the pools (fluxes). The forest, oceans and land can absorb carbon from the atmosphere or emit carbon in a two-way flow, whereas in any meaningful time frame the fossil fuel reserves provide a one-way flow to the atmosphere from ancient reserves.

potential unintended consequences of proposed policies that fail to consider the full life cycle of carbon from the atmosphere to products and fuels, and their displacement of fossil fuel emissions.

The review begins with a brief summary of the **global carbon cycle** and the major interactions between forest products and fossil fuel reserves. Thereafter is an examination of boundary conditions for tracking carbon and the importance of life cycle databases that have been developed in recent years. We then track the impact of carbon across forest pools, first for sustainably managed stands and later for unmanaged stands, accumulating the impacts from management, and products including their integrated impacts on processing energy carbon. We follow this by considering the alternatives (i.e., if wood is not used, what else?), resulting in integrated carbon tracking pools for the forest, wood products, emissions, energy displacement and product **substitution**. We examine the impacts of alternative forest management treatments and the different ways wood is used contrasted with no management where the total carbon impact is limited by what can be stored in the forest. We consider the additional impact that may be generated by using forest residuals and other waste for biofuel even though this may currently be uneconomic, until higher carbon values are internalized into the market.

We note that the life cycle data for the forest and product carbon pools as well as for product substitutes have relatively high certainty associated with their measurement. However, there are areas of high uncertainty that can affect overall carbon accounting. The impact of end-of-life strategies for products and buildings, landfill emissions and methane capture from landfills, and soil carbon changes under forest management regime changes are most prominent among them. While the main focus is on managed forests producing wood products, there are high uncertainties in unmanaged forests, particularly the increasing rates of fire and consequent impact on both forest and product-carbon pools. The analysis can be described as the science behind the status quo based on current and fixed technologies. Forests are dynamic and carbon-mitigation objectives will produce dynamic changes requiring changes in technology, hence updated reviews will be needed as processes and technologies change.

A review of current carbon policies indicates that many consider only the impacts on a limited set of carbon pools and frequently produce unintended consequences on other impacted carbon pools. We consider the difficulty in looking more deeply at large scale dynamic change such as covered by 'consequential life cycle assessments' driven by behavioral economic relationships that could incentivize forest management and product substitution. We compare 'consequential' methods focusing on, understanding at what level of detail can the markets economic affect on outputs be modeled versus 'attributional' life cycle analysis (ALCA) with its detailed tradeoffs between product, process and design alternatives that can be implemented. We note that carbon mitigation impacts on ecosystem services affecting their non-market values can be significant. This may justify greater efforts to protect certain habitat that might be at risk if focusing only on carbon mitigation and that tradeoffs between ecosystem metrics and carbon are more critical for unmanaged than sustainably managed commercial forests. While we focus mainly on North American research, in order to gain insights on whether these findings can be generalized across other developed or underdeveloped economies, we note similar research findings in Europe using examples from Sweden. While the methods are believed to be quite general, the variability of forests across regions are substantial, requiring further data to support similar conclusions for regions such as the tropics and developing economies lacking in product manufacturing capacity. Life cycle data tend to be costly to collect, thus placing boundaries on where it can be used effectively. However, the lessons learned identify many opportunities for environmental improvements affecting carbon emissions and energy independence that have not yet been given much consideration in policy discussions. Finally we draw conclusions and summarize what has been learned.

The global carbon cycle

On a global scale, carbon is stored in various pools (stocks) with dynamic flows between the pools (fluxes) (Figure 1). The forest, oceans and land can absorb carbon from the atmosphere or emit carbon in a two-way

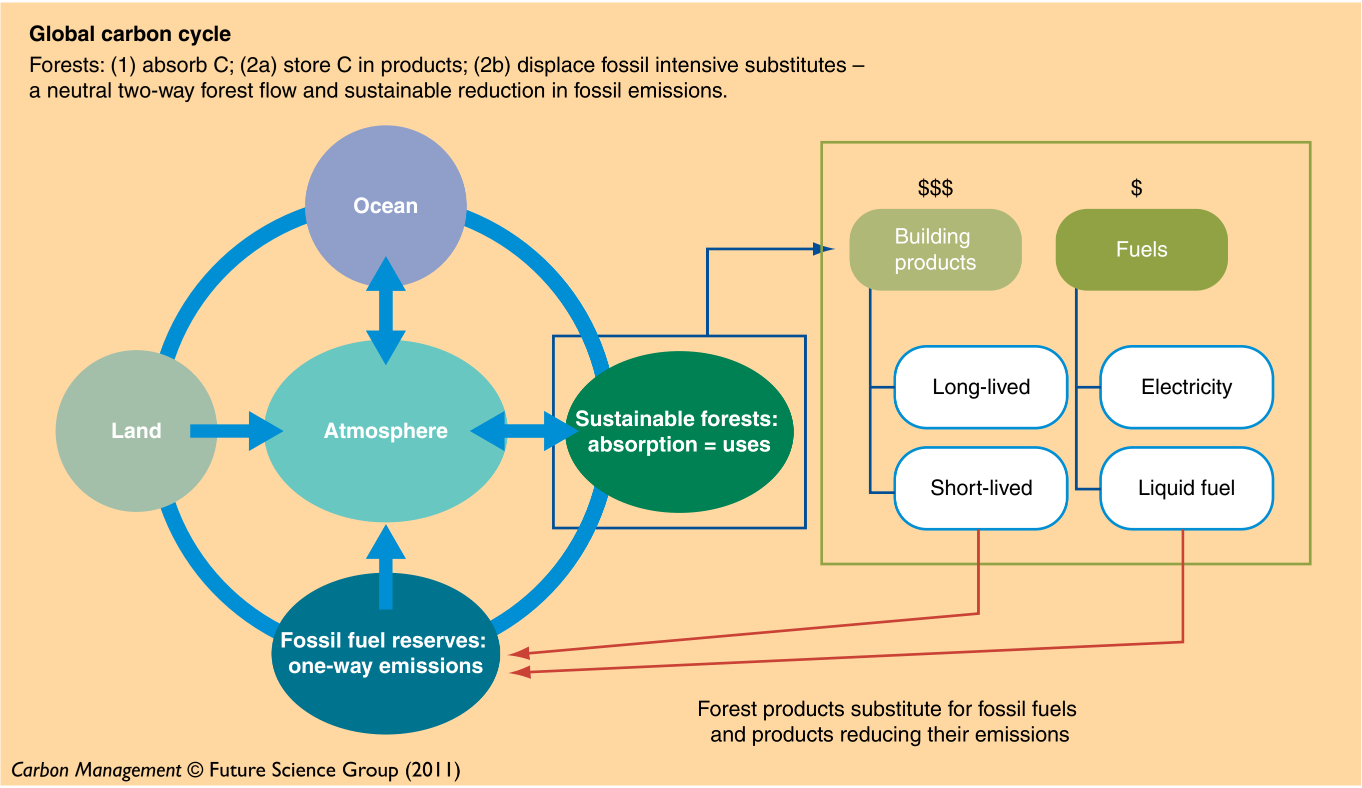

Figure 1. Major global carbon pools and their interactions. Fossil fuel emissions flow one way from deep reserves to the atmosphere, whereas, as forests grow, they absorb atmospheric carbon that is transferred to long-lived product pools, while also displacing fossil fuel emission-intensive products and fuels.

flow, whereas in any meaningful time frame, the fossil fuel reserves provide a one-way flow to the atmosphere as we continue to use fossil fuel [101]. While there are many uncertainties in measuring carbon stocks and flows globally, the objective of reducing GHGs suggests increasing carbon stores in non-atmospheric pools such as growing forests and using forest products that substitute for the use of fossil fuels and fossil fuel-intensive products. Displacing carbon emissions such as that produced by burning fossil fuels are as important in reducing atmospheric carbon, as increasing carbon stores by absorption of carbon in the atmosphere. Hence displacement pools that are negative emissions are also considered to be carbon pools. Understanding the direct and indirect substitution impacts between fossil fuels and forests and the timing of impacts is essential to insure that policy decisions do not result in unintended consequences such as reducing forest growth or failing to use forest products and biofuels where they substitute for fossil-intensive products and fuels. Many of these forest-related flows and stocks can be measured with reasonable certainty, at least on a regional basis, reducing some of the concerns in characterizing the impact of forest practices and product uses on carbon emissions.

Understanding where the biggest gains/losses/unknowns are in the relationship between fossil fuel use and forest management, and the timing of such gains or losses requires the use of **life cycle accounting**, which tracks the carbon through forest regeneration and management over time and each successive processing stage through product use and ultimate disposal. Comparing the inputs and outputs over time for each stage of processing provides a dynamic life cycle inventory (LCI) footprint of environmental impacts (burdens) for the technology evaluated. Developing a life cycle assessment (LCA) by comparing human or ecosystem risks imposed across alternative cases such as using more fossil fuels in products, thereby producing more emissions, provides a blueprint for life cycle carbon accounting across all carbon pools, as well as insight into alternatives that can improve environmental performance. The Consortium for Research on Renewable Industrial

Key term

Substitution: Substitution refers to replacing product A with product B, such as substituting wood for cement or biofuel for fossil fuel. Substitution replaces the LCI footprint of A for B and may cause additional indirect impacts as output volumes adjust. Each LCI has a system boundary. Substitution is differentiated from displacement in that substitution occurs outside of comparable system boundaries. Therefore, though using internally generated biofuel from waste in place of fossil fuel displaces the fossil fuel attributes, the biofuel is inside the product processing boundary and is considered direct internal displacement rather than substitution.

Key terms

Life cycle accounting: Life cycle inventories (LCI) measure every input (energy, materials etc.) and every output (emissions, waste, product and co-products) for every stage of processing from extraction or regeneration through processing, ultimate use, maintenance and disposal. Life cycle assessments (LCA) reduce the many LCI measures into risk indexes affecting human or ecosystem health with the objective of making comparisons between alternatives that reveal opportunities for improvement.

Attributional LCI: The inputs and outputs to produce a given product define its environmental attributes per unit of product referred to as attributional LCI (ALCI), a footprint of environmental burdens. No information is provided on how the output products might change or what might be necessary to change them, which may induce indirect impacts.

Global warming potential: Global warming potential (GWP) is an LCA index measuring climate change potential by the increase in greenhouse gases in CO_2 equivalent units.

Consequential LCI: Considers indirect impacts related to changing outputs such as increased production or land-use changes affecting production through economic motivational changes.

Materials, a 15 research institution consortium (CORRIM) was formed in 1996 to develop a research plan and a life cycle database for wood and its many uses [2]. Over the last decade, CORRIM has developed nationally and internationally peer reviewed LCIs for wood used in US construction and for processing energy. CORRIM has also developed LCAs comparing the uses of wood to other materials. Such comparisons provide insights into how to achieve improved environmental performance and we refer frequently to CORRIM's data sources and findings [3].

Boundary conditions

Concerns over the degree to which and over what time period wood products and biofuel feedstock derived from forest growth provide substantial reductions in carbon emissions can only be answered by tracking carbon across its life cycle. Life cycle accounting tracks all the inputs and outputs over time across every stage of processing from forest regeneration and management, harvesting, product processing, product use, maintenance and final disposal. To determine the impact of a change in forest management or a change in wood use, the carbon emissions between different product and management alternatives are compared. Estimation of carbon storage and emissions associated with each alternative is termed an LCI or LCA based on measures of all the inputs and emission outputs in producing the product under guidelines developed by the International Organization for Standardization [102]. An **attributional LCI** (ALCI) provides information about the impacts of processes to produce, consume and dispose of an average single unit of a product, but does not include induced effects from changes in outputs such as shifts in production and emissions from other products that are displaced by the product being assessed; for example, an ALCI would identify emissions from fossil and biomass fuels, but not the amount of emissions from fossil fuel emissions that are inferred to be avoided by use of those products or co-products outside of the production boundary. Many different ALCIs can be compared across differing technologies or different co-products of a process. **Global warming potential** provides an LCA risk index by aggregating the solar radiation impacts from LCI measures for not only carbon but methane and other GHGs that are contributing to global warming.

Estimation of the change in carbon storage and emissions with a change in a system is termed a **'consequential' LCA** (CLCA) including indirect effects that may be associated with changes in output [4]. CLCAs provide information about the consequences of changes in the level of production of a product and will include effects both inside (direct) and outside (indirect) the life cycle boundary of the product. Market forces generate the indirect effects; for example, the change in consumption of softwood lumber for construction would influence demand and production of non-wood substitutes for construction. Consequential LCAs may include, within their system boundary, a number of industrial sectors, including producers and users of wood plus producers and users of direct wood substitutes (e.g., fossil fuels and steel), or they may include all sectors that may have changes deriving from changes in production within the wood sector. They may focus on indirect impacts such as converting more land to sustainable forest management as prices rise thus, altering the land available for other uses whether for habitat, food production or altering cross country trade. CLCAs may be used to determine the effect of a decision or policy that would change production; for example, a softwood lumber CLCA that estimates the change in GHG flux with the atmosphere due to a decrease in production would include the change in GHG flux in forests if they were not harvested due to the lower level of production, and would include the change in GHG emissions from the higher production of non-wood products that replace wood products. In addition, a CLCA may include impacts in secondary products, which may have a change in production caused by the change in the production of wood products. Estimation of indirect impacts, can be simulated using economic models that show how demand and consumption of non-wood products change as production of softwood lumber changes or by sensitivity analysis that assume alternative levels of non-wood product change.

Attributional LCIs can be developed with greater detail based on current mill processing data, such that comparisons across attributional LCIs or LCAs are useful in identifying obvious opportunities to reduce environmental burdens even though it may be difficult to assess CLCA impacts on changes in outputs at the same level of detail. Some evaluations use features of both ALCAs and CLCAs. The evaluation identifies the direct effects of producing a product (ALCA) and considers some of the obvious indirect effects that would result from a change in production (CLCA) such as product substitution comparisons. In order to use these measures to suggest guidance for policy that would change the production of a product, it is important to identify the degree to which all major indirect effects have been included and the assumptions about how the indirect effects are attained.

Since the ALCIs for two products or treatments that produce directly substitutable outputs are entirely based on LCI information and not affected by uncertainties in indirect affects, the impact of direct product substitution by comparison of two ALCIs is of particular interest. For example, what is the impact of directly substituting product A (e.g., a wood stud resulting from increased production) for product B (e.g., a steel stud from decreased production) as well as co-product C (e.g., biofuel) versus product D (e.g., natural gas)? While this involves a product change (a CLCA by definition) it does not consider the indirect effects that may result from the supply and demand changes since it is based only on the more precise attributional LCI measurements used in each of two different LCIs. Considering direct substitution (the difference between two or more LCIs) identifies the direct effects of substitution but none of the indirect effects.

For both ALCAs and CLCAs, emissions and emission changes may occur over long time intervals. Interpretation of the desirability of a certain time path of emissions may need to consider the time preference to be placed on near term versus more distant emissions or emission changes, such as economic discounting of a changed valuation over time. Under sustained rotational forest management within a forest boundary, the time path across all stands in a rotation may eliminate any time impact for the aggregate; for example, every year a stand is treated such that there is no difference in inputs or outputs across the managed forest from one year to the next.

The life cycle data

Peer reviewed life cycle data for many primary materials now exists and for the USA, is publicly available, managed by the National Renewable Energy Lab (NREL) [103]. Comparable data is also available as a part of LCI/LCA software analysis systems. For wood products, primary mill surveys have been conducted to measure every input and output for every stage of wood processing, covering many different material and energy inputs and potentially hundreds of emission outputs for each product [5,6]. Surveys were segregated to measure data from mills in four wood-producing regions covering a range of products including; lumber, plywood, laminated veneer lumber, oriented strand board, glulam beams, trusses, medium density fiberboard, particleboard and the resins, used in manufacturing, while also tracking biofuel feedstock from internally generated wood wastes. These products and biofuels are almost exclusively produced from commercially managed forests producing sustainable harvests for the wood materials used in housing and light commercial construction as well as much of the energy used in the production of products and biofuels. While mill surveys typically include more than a 20% sample of a regions production, mill differences within a single product and supply region are not large as smaller mills with older technology are becoming uncompetitive and do not have a large impact on a sample survey.

For inputs and outputs to the forest, representative samples were generated by selecting the US Forest Service Forest Inventory Analysis (FIA) forest census data most representative of plots for a region [104], measuring all inputs to the seedling and through each subsequent forest-management activity, including timber removal activities [7,8]. LCIs produced from these samples measure the environmental burdens, including tracking carbon, from forest regeneration through the growth of trees, and the removal of logs, as well as measuring the decomposition or burning of dead wood left in the forest after harvest.

For the carbon life cycle, each stage of processing produces a change to the carbon pools to which it is linked. This includes changes in each of the forest carbon pools (e.g., stem wood, branches, dead and dying litter, and roots) and processing steps in the manufacture of products such as lumber (i.e., sorting, sawing, drying, energy generation, merchandising and transportation). The volume of lumber provides an output measure of the wood used that also functions as a measure of alternative/substitute materials that may be displaced as does the biofuel produced provide a measure of alternative fuels that may be displaced, primarily fossil fuels.

Some carbon pool impacts are not so easily measured, however, their impact can be imputed and described based on other research. For example, changes in soil carbon and the share of carbon that will remain in landfills at the end of useful product life when products are not recycled or burnt are more difficult to sample and less well described than CORRIM's product LCIs. These impacts are characterized by establishing a range for a sensitivity analysis around baseline or conservative estimates of carbon emissions from the other stages of processing. While forest carbon pools as well as product carbon pools are carbon sinks (storage pools), when wood is burnt for a fuel, or products displace fossil intensive materials such as steel and concrete, fossil emissions are displaced. Emission displacement pools or **carbon offsets** are as important to climate change as carbon storage pools hence both represent important carbon pools that must be measured.

Key terms

Carbon offsets: When wood is burnt for fuel displacing the emissions from a fossil fuel, the reduction in emissions is technically not a carbon store (unless the deep fossil reserves are included) but does measure a change in atmospheric carbon of equal importance to increasing a carbon store.

In life cycle analysis, displacement of energy sources is calculated based on the mix of fuels actually used. However, interest in carbon mitigation is often best characterized by displacement of the most common fuel with the worst environmental impact that would most likely be displaced, if there were a market value from the carbon emissions, such as a fossil fuel carbon tax. Such assumptions are consequential going beyond what can be attributed to current LCI measures. When wood waste within a mill is used to displace the purchase of natural gas, which is the most efficient energy form for drying, only the emissions from not using natural gas are considered since only natural gas would be displaced; however, if forest residuals are collected they would more likely displace coal as the highest carbon-emitting alternative to biofuel. This simple change deviates from an attributional measure to consequential assumptions affecting outputs. Even this convention may change as new technologies are developed that can competitively extract and store the carbon emissions from fossil energy sources.

While we have good data on the impact of management treatments and product selection on carbon impacts across the boundaries for all stages of processing, the results do not fit neatly into a policy setting or forecasting framework given the complex array of decisions made by a variety of decision makers and massive number of different, yet interacting, carbon pools affecting total carbon in the atmosphere. Nevertheless, unintended consequences of frequently advocated policies are evident, supporting a discussion on what is known and not known about consequential impacts affecting other sectors after focusing on the life cycle of carbon across many stages of processing.

Carbon in the forest & impacts from many different uses of wood

Forest management

In many developing nations, deforestation is a substantial concern and must be considered as part of a global carbon perspective. Forest management to produce timber outputs dominated by private forest-management regimes for all US regions and many developed countries is characterized as sustainable management, meaning that wood that is removed for product uses does not exceed net forest growth. By not removing more wood than is grown on a forest landscape basis, the forest carbon alone does not change and becomes of minor importance to the way the wood is used to reduce fossil emissions. In practice changes in treatment intensity or natural disturbance may result in more or less carbon stored in the forest after which a new equilibrium sustainable forest carbon balance is attained.

The carbon in an individual forest stand for any given treatment regime will cycle periodically, rising with periods of regeneration and growth, and falling with periodic harvest removals such as the example for the US Pacific Northwest (PNW) (Figure 2; [105]). Under sustainable management however, the individual stand is dependent upon similar treatments across a sustainable forest unit. This repeatable carbon cycle for any single stand results not only in a stable average of carbon across many rotations over the long run, but also across the total forest at any point in time since the harvests

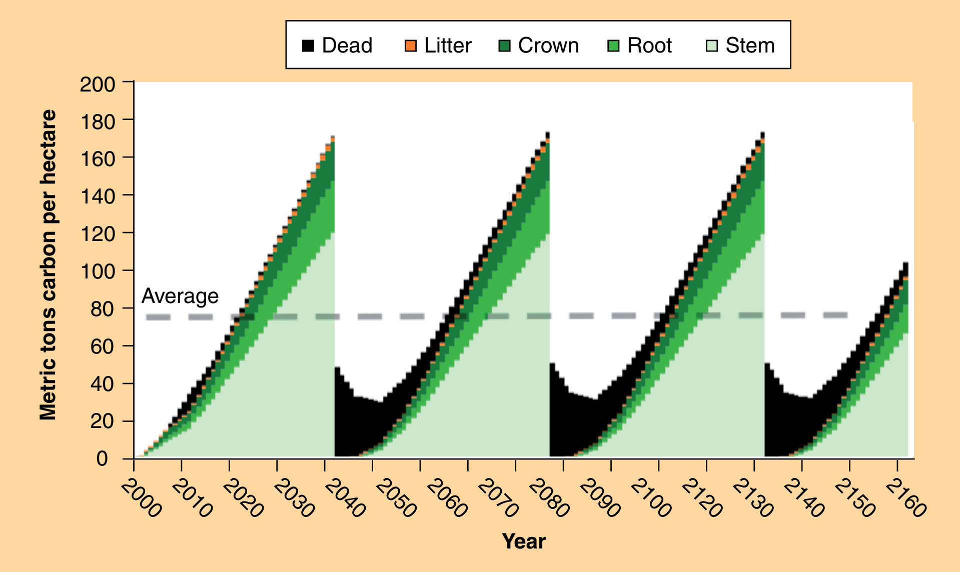

Figure 2. Forest carbon pools for sustainable 45-year rotations in the US Pacific Northwest. Forest-carbon pools include: (1) dead-wood carbon increases at harvest by leaving residuals when the cost of collection exceeds the market value to remove them. The dead-wood pool generally decomposes or is burnt before the next rotation. (2) Litter decomposes more rapidly. (3) The crown (branches and small diameter top) grows along with the stem, but becomes part of the dead-wood pool at harvest, unless the fuel value exceeds the cost of collection. (4) Roots grow proportional to the stem and become another dead-wood pool at harvest. (5) The removed stem makes up 50–70% of the aboveground biomass removed, leaving a substantial amount of dead wood for ecosystem functions or the potential for biofuels.
Reproduced with permission to publish from CORRIM [105].

are maintained at the sustainable rate by harvesting from a near uniform age distribution across all hectares. For a given treatment plan, there is no change in forest inputs or outputs from year to year even though these impacts are periodic for an individual stand. The forest carbon is essentially stable or carbon neutral with carbon input equaling carbon outputs through harvest or decay.

Forest carbon 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 the individual stands.

A singular change in sustainable management treatments may result in a singular change in the average carbon remaining in the forest across a cycle, such as the difference between burning forest residuals upon harvest versus letting them decay naturally, which will increase the average carbon in dead wood for some period of time, a one time impact on carbon from the change. We defer inclusion of soil carbon to a later discussion since most research has found little correlation with forest treatments that are considered sustainable management [9–12]. While natural disturbances may temporarily deviate from this cycle, either natural or managed forest regeneration will ultimately restore a level of forest carbon for a given treatment regime.

Unmanaged forests, including regulated set asides and public forests left for non-timber values can also show a long-term equilibrium level of forest carbon, such as shown for Federal Forests in Western Washington where adequate samples of old forests are available (Figure 3; [13]). However, these unmanaged forests are often susceptible to disturbances including insect and disease outbreaks and generate a much greater carbon debt if they are combusted during a wildfire, rather than a managed forest with lower carbon storage and much less dead and dying fuel wood. Carbon can be tracked across many carbon pools in unmanaged forests, but the uncertainty in disturbance impacts deviates substantially from sustainably managed forests. Under sustainable management, there are few measurable long-term impacts in the above- and belowground carbon stocks that would deviate from forest carbon neutrality in contrast to unnatural wild fires or infestations that are more prevalent in unmanaged forests.

There exists large natural variation in growth and timber volume across forest types with some forests peaking in stored carbon later than others, and some even showing declines from increasing mortality at advanced ages. The reduction in growth with age is substantial, falling from as much as 4 tons C/hectare/year (tC/h/y) at the age of 50 years (Figure 2), to 0–1 tC/h/y by the age of 150 years (Figure 3) for Westside Pacific Northwest forests. Therefore, while older forests can store more carbon, the rate at which they remove additional carbon from the atmosphere will be substantially lower and can become negative as mortality increases and exceeds new growth. A 20-year remeasurement program for old-growth permanent plots in British Columbia showed no change in volume for the well-stocked stands over the period even as the dominant trees grew larger, but many old-growth plots were more poorly stocked with much lower volumes [14]. Commercial forest management will inherently involve relatively short rotations, precisely because forest growth begins to slow with age reducing economic returns. Extending rotations beyond the period of fast growth reduces the volume and value of sustainable

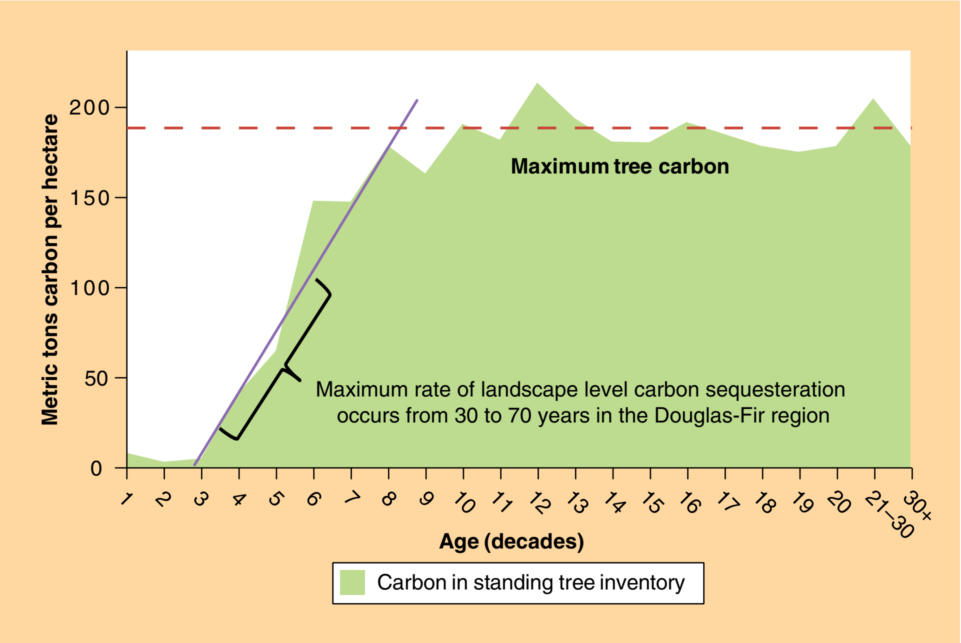

Figure 3. Forest-carbon growth rate decreases with age in western Washington. From US Forest Service – Forest Inventory and Analysis inventory plot data. Forest carbon growth rates begin to slow before the age of 100 years with little to no growth beyond the age of 100 years.
Data from US Forest Service Forest Inventory [13].

production that can be used for commercial purposes while also reducing absorption of carbon from the atmosphere (Figure 3).

The forest growth cycle characterizes a range of potential carbon storage options including:

- Storing carbon in the forest, knowing that ultimately the rate that carbon is removed from the atmosphere through net new growth will slow down, and in the event of a disturbance may emit more carbon than if harvested;
- Sustainably harvesting wood from the forest before growth slows down and storing the carbon in wood products that also displace fossil fuel consumption.

The examples presented can be calibrated to many regions even those with different natural disturbance regimes and hence provide useful descriptions for understanding the role of forest management and wood uses in carbon mitigation. Important exceptions would include forests in which dead and dying biomass is maintained in anaerobic conditions that prevent decay, such as forests growing in a peat bog. The lack of decay produces a cumulative increase in soil carbon pools similar to increased carbon stored in product pools [15,106].

Maximizing carbon stored in the forest essentially minimizes carbon moved from the forest for use in products that also substitute for fossil intensive products and their emission. The maximum sustainable rate of removals to support product uses does not minimize forest carbon, but will reduce the average carbon across the rotation to less than half that of an unharvested forest depending upon region, forest type and management treatment.

Important questions raised from harvesting the forest include: how much of the carbon can be stored in products; what happens with the stored carbon at end of product life; what happens with the wood processing residues; how much wood residue is left in the forest and; what are the opportunities to collect this biomass to offset the need for fossil fuels?

The US LCI mill survey data shows that approximately 50–70% of the aboveground biomass in a sustainably managed forest is currently utilized in product processing mills to make solid wood products along with paper and biofuel co-products. The remaining 30–50% (e.g., crown, litter and dead/breakage) is currently left to decay along with the roots to augment soil processes, be burnt, or provide protection for habitat.

There is a significant regional variation caused by different species, site productivity, and decay impacts. Johnson *et al.* [7] and Oneil *et al.* [8] provided estimates for carbon in the live stem, and branches (the crown), as the forest carbon pools having the greatest impact on emissions for different regions in the USA: Pacific Northwest (PNW), Southeast (SE), Northeast/North central (NE/NC) and Inland Northwest (INW) regions. Based on weighted averages of site productivity classes and associated best management intensity regimes, the PNW region provided the most biomass per hectare with larger pieces producing more structural products, whereas the shorter rotations in the SE provided a greater potential for whole tree removal of smaller trees for pulp and paper fibers and bioenergy production.

In each region, harvest on a specific stand produces a temporary reduction in forest carbon, but supports an increase in the rate of carbon uptake over time. When the regenerated crop is mature and ready to harvest, wood not removed at harvest is essentially left to decompose (Figure 2). Decomposition rates vary depending upon species, climatic conditions and post-harvest management options such as burning slash piles. While some stumps and other dead wood may take longer to decompose than a rotation period, they eventually do decompose, producing a stable dead wood pool that may be larger or smaller than shown in the PNW example [16]. Wood that is currently economic to remove provides feedstock for both processed wood products and processing energy. Dead wood that is not removed from the forest provides a potential biomass pool that could be used as an energy source with better economics to cover the cost of collection. Recovery and use is more prevalent in some countries, such as the case in Sweden compared with the USA [16].

Soil-carbon research does show increases in soil carbon with increases in site productivity, such as may be possible through fertilization in nutrient deficient stands [17,18], but does not show a direct link to forest cover or changes in rotation [11] and hence this is discussed separately as an area of greater uncertainty.

Life cycle forest, product & integrated processing energy carbon pools

The wood processed in manufacturing facilities extends the forest-carbon stores to short- and long-lived products (Figure 4; [19,20]), and produces emissions from those processing activities [3]. The emissions from management, harvesting, log transport and wood processing reduce the preharvest carbon storage by approximately 6% (negative carbon pool shown below the zero line). Approximately half of these emissions are currently offset by using internally generated mill residuals, such as bark, sawdust and trim as biofuel, displacing the need for fossil fuel. Some of the mill residuals that are generated internally may be sold directly and used in applications such as landscaping bark, while higher grades of mills residuals or low-grade logs are used for chips and composite panel products.

In **Figure 4**, short-lived products (e.g., chips for pulp and paper) are assumed to decompose within the rotation. In this example, no credit is taken for pulp chips displacing alternative products that may be fossil fuel-intensive or reductions in fossil fuels needed for such products. Long-lived products are largely related to housing [21] or similar light construction commercial buildings that have a useful life estimated at 80 years in the USA based on historic housing data. This finite lifespan for housing is illustrated by the sharp decline in long-lived product carbon after 80 years for tutorial clarity in **Figure 4**, although in reality the variation in life would smooth through this transition. Skog *et al.* noted that the useful life of housing is growing longer for newer construction, suggesting a housing life of more than 80 years [22]. **Figure 4** also assumes end-of-life products are incinerated without energy recovery, recycling or landfill, another conservative estimate given the amount of wood recycling and land filling that is currently occurring and the fact that there are expectations for more in the future. Landfill emissions are complex and are considered more directly later as a waste management problem than a forest or product management alternative.

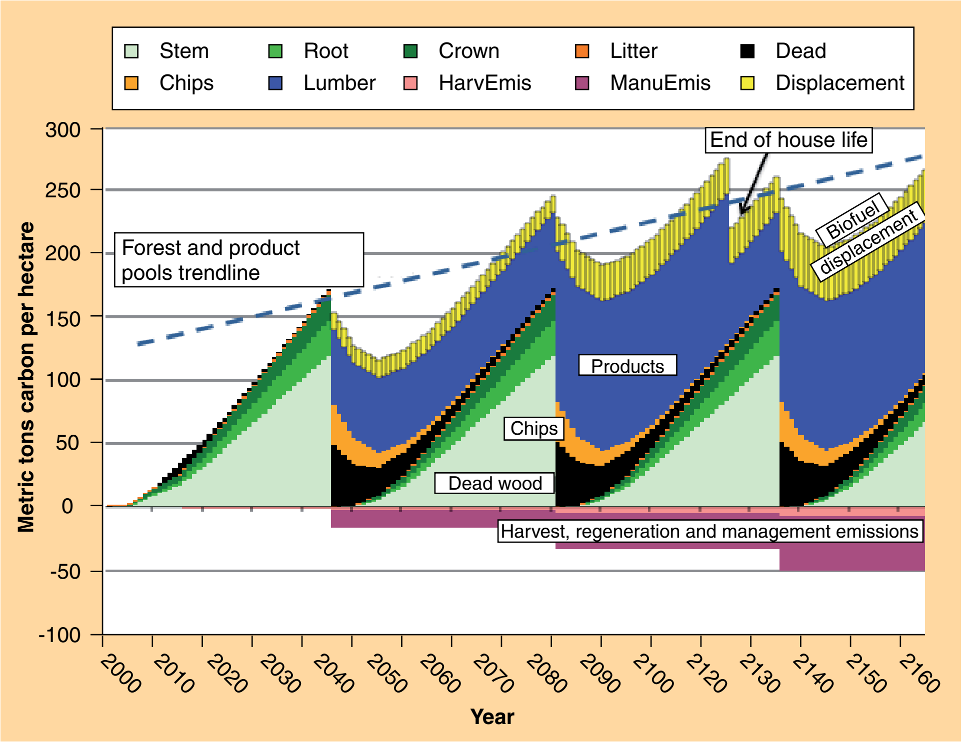

Figure 4. Forest plus product-carbon pools and process-energy emissions. In addition to the forest carbon, harvested products pools are shown based on life cycle inventory data for the Pacific Northwest along with the total harvesting and manufacturing emissions needed to produce them. While most products have long-lives, short-lived products are assumed to decompose rapidly. Mill residuals are used as a biofuel to offset some of the total energy for processing. The displacement value accounts for the amount of the total manufacturing energy that is displaced by the use of biofuel in the place of the most likely substitute fuel (in this case natural gas for drying energy). Even with these conservatisms, the sum of carbon stored in the forest plus products net of processing emissions rises on a sustainable trend.
Reproduced with permission to publish from Wood Fiber Science [19].

Comparing **Figures 3 and 4** shows that within some time frame the total storage from a sustainably managed forest producing products will exceed the carbon accumulation in an unmanaged forest, given assumptions of equal soil carbon and rates of decomposition of dead material. From this perspective, the carbon in the forest plus products less manufacturing emissions partially offset by internally generated biofuels is better than carbon neutral, producing a sustainable trend increase in the integrated forest plus product-carbon pools **(Figure 4)**. 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; however, for the single hectare example, it may take a rotation for the carbon in the wood product stores to offset the carbon lost from the decay of unused dead wood and short lived products. The carbon in the internally generated biofuel used for processing energy was removed from the atmosphere, stored in the forest, and then returned to the atmosphere when burnt for processing energy, thereby offsetting some of the processing energy need for fossil fuels. While the forest carbon for a single stand is restored at the end of each rotation, and remains stable over the long term as the new growth offsets the volume of removals used for products and biofuel, the displacement of fossil fuels produces a net reduction of atmospheric carbon (a positive carbon store). As noted in **Figure 1**, replacing the one-way flow of fossil fuel emissions by using a sustainably managed forest carbon resource to produce biobased products and energy reduces overall atmospheric CO_2 levels.

In regions where the proportion of forest carbon removed and stored in long lived products may be only half as great as this PNW example, the trend will still be increasing carbon stored or offset outside of the forest. If only short-lived products are produced and they are not reclaimed for their energy value, the product carbon stored plus displacement of fossil fuels may not exceed the forest decay after the initial harvest. However, all products, whether used directly as a fuel or used to substitute for other products will displace the emissions from those substitutes as evaluated next. Since the biofuel used to reduce the need for fossil fuel in production is internal to the mill, the chart reflects ALCI methods in accounting for the carbon retained in the wood products without considering indirect impacts from any change in product ouputs such as substitution. Recycling short- and long-lived products or additional collection of forest residuals would further increase the total carbon pools from a managed forest.

The alternatives to wood products

The most obvious missing carbon impact in Figure 4 is that which would have resulted without using wood.For every use of wood there are alternatives and every different product use results in a different life cycle carbon footprint impact [19,107]. For example, wood studs can be replaced by steel studs, wood joists by steel I-beams, wood walls by concrete walls, wood floors by concrete slab floors and biofuel by fossil fuel. Using the LCI data for comparing a steel floor joist to an engineered wood I-beam joist results in reducing the carbon footprint by almost 10 tons CO_2 for every ton of wood used (Figure 5) [107]. The same analysis found that substituting a lumber stud for a steel stud only reduces the carbon footprint by 2 tons CO_2 for every ton of wood used. In both cases, a ton of wood used stores approximately 0.4 tons of carbon, equivalent to 1.5 tons CO_2, over the life of the product, net of processing emissions.

Steel wall studs, before considering the need for insulation, do not produce nearly as many emissions as steel floor joists, since only a light gauge of steel is needed for vertical stacking-strength in the wall, whereas floor applications require much heavier gauge steel to avoid bounce. A wood-floor replacement for a concrete slab floor reduces the carbon footprint by approximately 3.5 tons CO_2 for every ton of wood used.

Every different use of wood involves a different impact on carbon stores and the displacement of fossil emissions from substitute products. The life cycle information collected in current wood-processing mills suggests a reduction of approximately 1.2 tons of CO_2 for every 1.0 ton of wood biofuel used in product-processing mills (Figure 5). When wood is used to displace coal, as would be the likely offset from using additional forest residuals in utility-power generation, approximately 1.9 tons CO_2 is displaced for every ton of forest residuals used. While biofuel results in a significantly lower displacement of carbon emissions than for most wood products, it still provides a good alternative since it might otherwise need to be burnt or land filled without capturing any energy value. This use of wood fiber for energy still has a significant and positive carbon-mitigation impact by using low-grade materials that are currently wasted, providing a substantial benefit over using natural gas, the most carbon-efficient fossil energy source used by mills for energy to dry the wood products.

Each of these life cycle comparisons between wood products and non-wood substitutes are based on the direct comparison between attributional LCIs. However, substituting one product for the other characterizes a change in output and the impact of that change when the wood, including its net storage of carbon, is used to displace the emissions from a functionally equivalent non-wood product is a consequential LCA, although it is limited in scope to the direct substitution of one product for another. Other indirect impacts not considered may be important.

There are enumerable opportunities for substitution that can substantially reduce LCI burdens making it difficult, yet important, to quantify the impacts. A survey of available substitution studies by Sathre and O'Connor [23] produced a meta-average value for wood substitution of 3.9 tons CO_2 reduction for every oven-dry ton of wood used to displace other structural materials (2.1 tons C stored for every ton C in the wood used). The range of displacement factors among the surveyed studies and Figure 5 suggests that to maximize climate change mitigation from available biomass resources, wood substitution

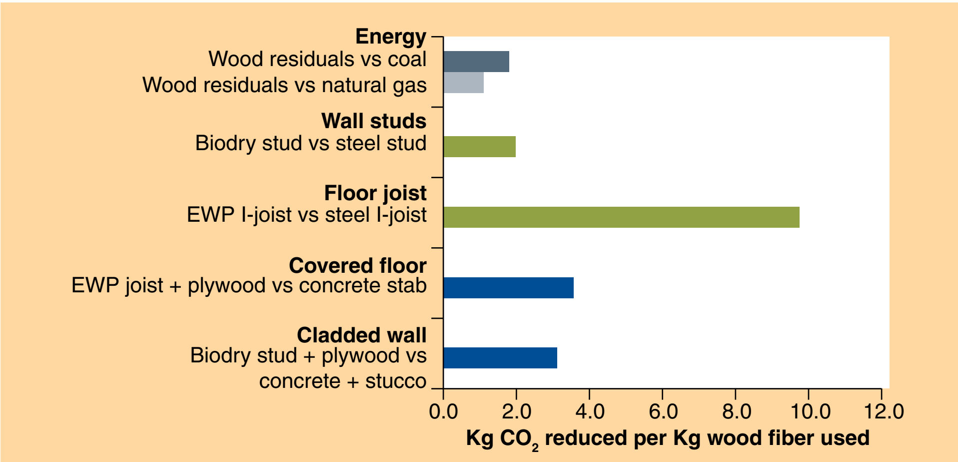

Figure 5. Carbon emission reduction by displacing non-wood products.
EWP: Engineered wood product.
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should be focused on the types of wood products or building systems that produce the highest possible GHG displacement.

To show the total carbon impact across all carbon pools resulting from forest management we add to the wood product stores minus net processing emissions as shown in Figure 4, the non-wood product emissions from substitution (Figure 6 [19,20]). We use the Sathre and O'Connor [23] estimate of the fossil intensive product emissions that were displaced by using wood products. This shows that the total carbon impact across all carbon pools (carbon stores and emission offsets) produces not only a sustainable positive trend in carbon storage, but that the rate of increase is greater than the maximum rate of growth in the forest. However, it is noteworthy that the substitution estimate is no longer specific to a direct substitution between product A to product B, but rather to an average range of substitution impacts per unit of wood products produced. Substitution was included for biofuels displacing natural gas in the processing mills but not for short-lived coproducts outside of the wood product LCI boundary resulting in a conservative estimate.

Using the life cycle analysis to examine all pools, including substitution, demonstrates that using wood to displace fossil-intensive products such as steel and concrete produces a sustainable reduction in atmospheric carbon, year after year, unlike the alternative (Figure 3), when considering carbon growth in the forest unharvested. Substitution produces permanent offsets, by reducing reductions in the one-way flow of fossil emissions at the time of harvest and wood use, independent of the products useful life, demonstrating that sustainable removals will generate sustainable increases in forest carbon storage and offset pools with exceptions limited to short-lived products that are neither burnt for their energy displacement value nor otherwise produce significant displacement of fossil intensive emissions.

Consideration for regional differences that may reduce the proportion of long lived products as in this PNW example can substantially lower the slope, for example, rate of carbon accumulation, but still offset the losses of carbon after harvest from the decay of dead wood left in the forest. Therefore while there will be stands that may provide very low rates of carbon accumulation across all pools, they are not likely to include stands that contribute significantly to the production of long-lived products.

Similar to the life cycle carbon tracking charts (Figure 6) for a single PNW stand, Figure 7 demonstrates both the similarity of impacts for a region with a much lower site productivity (lower growth potential), as well as stratification across a broad regional forest landscape rather than a single stand, in this example for the State and Private Inland Northwest (INW: Montana, Idaho and eastern Washington) based on the average growth and removal impacts for regionally stratified FIA inventory plots [24]. Using the average harvest rates over the last 3 decades as representative of the sustainable removal rate, harvests remain stable relative to the maturity of the inventory and forest landscape carbon remains nearly stable, essentially a carbon neutral forest with very little, if any, potential to increase harvest over that of the last 3 decades unless greater investments in management intensity were forthcoming. Forest carbon

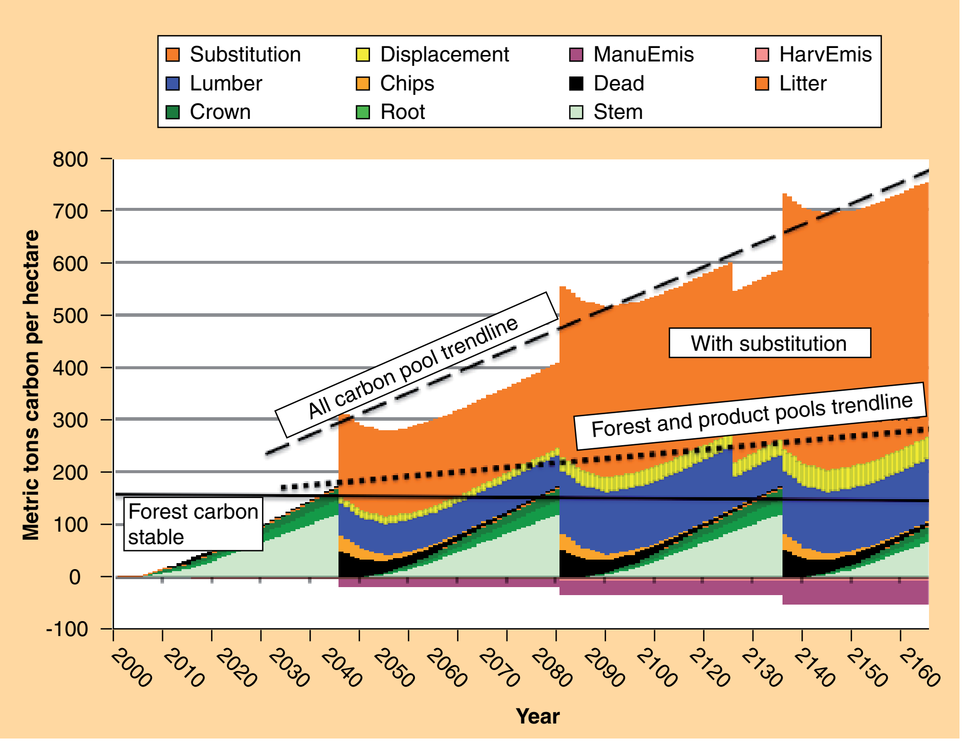

Figure 6. All carbon pools: forest, product, emissions, displacement and substitution. The substitution benefit of using long-lived wood products provides the greatest carbon leverage of all pools, adding to the forest, products and displacement pools less any processing emissions that are incurred in production. Soil carbon (not shown) would increase the total forest contribution to this carbon profile, but under sustainable management regimes, shows no significant change from rotation to rotation.
Reproduced with permission to publish from Wood Fiber Science [19].

storage for the single stand (Figure 6) is demonstrated across multiple rotations, whereas it is demonstrated to produce continuous positive increases in carbon mitigation at the landscape or forest level (Figure 7). Forest carbon for the single-stand cycles from one rotation to the next producing a stable average over the long-term. Viewed across all hectares within the rotation there is no change in forest carbon such that time preferences are not relevant to carbon measures at the forest landscape level assuming only sustainable management repeating the same treatment. While the total carbon stores plus substitution for the Inland Northwest region are lower than the PNW given substantially lower site-productivity and forest-growth rates, the results still show cumulative increases in other carbon pools. Since the product carbon pools are initiated at a point in time, the history of processing-related carbon pools from prior harvesting is excluded although will have stabilized after the useful life of products, for example, at approximately 80 years into the simulation to capture the historical impact from long lived products.

Harvest removals were essentially maximized, constrained by sustainable removal rates, while demonstrating a steady trend increase in products carbon from the harvest. The trend growth would be lower for shorter product lives or higher if landfill stores are included. Dead wood and short-lived products do not reflect a continuation in growth since decomposition occurs within the rotation period with no accumulation from multiple rotations. Displacement of fossil fuels from the use of mill residuals, as well as the emissions from processing energy continue to grow with sustainable harvesting and processing. Biofuel displacement of fossil energy does not assume any increase in removal of forest residuals. Implementing this would reduce the dead wood pool in the forest to a lower but stable level while producing a sustainably growing displacement pool based on the permanent reduction of emissions from fossil fuels. The transition to include removal of residuals would result in a one-time reduction in the dead wood forest carbon pool when residuals are not being burnt after harvest. More significantly the permanent displacement of fossil fuels grows sustainably with each harvest. The total carbon across all pools grows sustainably at approximately 2.7 tC/h/yr, approximately half that of PNW forests, reflecting the lower productivity of Inland Northwest forests relative to the Pacific Northwest forests.

Comparing carbon pools across forest management & wood use alternatives

The potential to decrease carbon emissions depends upon both better forest management as well as better selection on how we use wood. We illustrate five management and wood use alternatives for an average hectare of forest in the Pacific Northwest representative of the range of potential impacts (Figure 8 and Table 1). ALCIs for a base and intensive sustained management treatment are compared with an unmanaged old forest as a benchmark for the maximum carrying capacity in the forest.

Wood use alternatives are also compared. The average meta-analysis from many substitution studies noted earlier [23] is considered with the base and intensive sustained management alternatives. To demonstrate the potential for much higher carbon substitution, the average impact is replaced by the direct substitution of Engineered Wood Product (EWP) I-joists produced by the base forest management compared with the use of steel floor joists. To demonstrate the potential for a low substitution impact, all currently merchantable wood removed is used to produce biofuel. LCI attributes are simulated forward in time for 180 years in the PNW (four rotations). Processes include ALCAs for the regeneration, management,

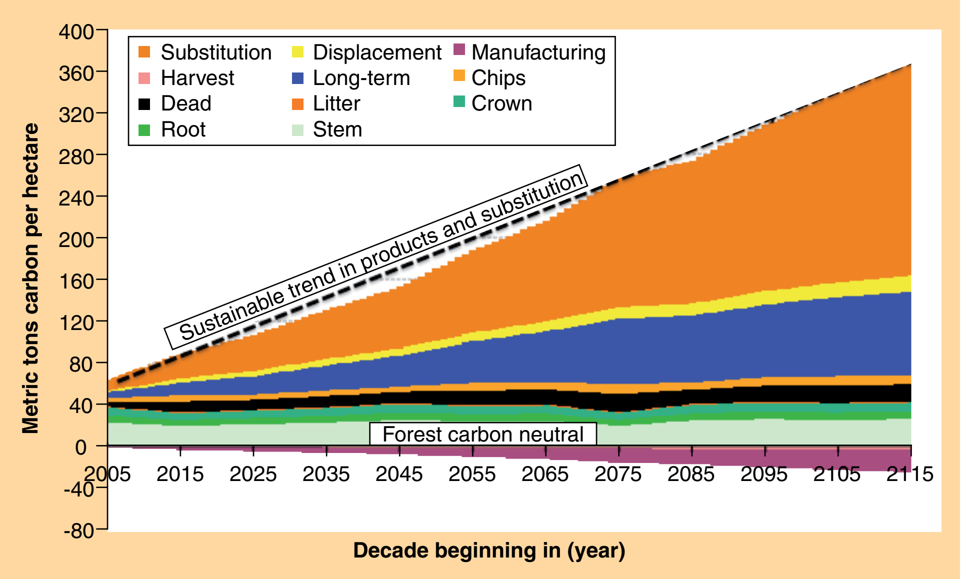

Figure 7. Landscape carbon accumulation for Inland Northwest state and private forests. Sustainable forest management across a landscape shows a stable non-declining forest-carbon pool, a stable short-lived product pool and dead-wood pool after the initial rotations with increasing long-lived products and substitution pools.
Reproduced with permission to publish from Wood Fiber Science [24].

harvest, transport and production of softwood lumber with cradle-to-gate coproducts of high-grade residuals serving composite products, pulp chips and biofuels that are consumed internally to reducing the use of fossil fuels. Forest carbon pools include forest roots, stem, crown and litter (dead wood). Soil carbon is excluded under the assumption of no change across a rotation, while landfill carbon is omitted for conservatism (both are discussed later). Product-carbon pools include long- and short-lived product stores and processing emissions with only the long-lived products and product substitution increasing over time. CLCAs were developed to derive the substitution impacts from displacing one ALCA by another without considering indirect impacts from the changes in outputs.

Many forest treatment and wood use strategies are possible with many contributing to increased carbon growth and product uses. CORRIM's forest resource reports provide a range of more intensive management alternatives that were considered to be easily achievable depending upon owner group

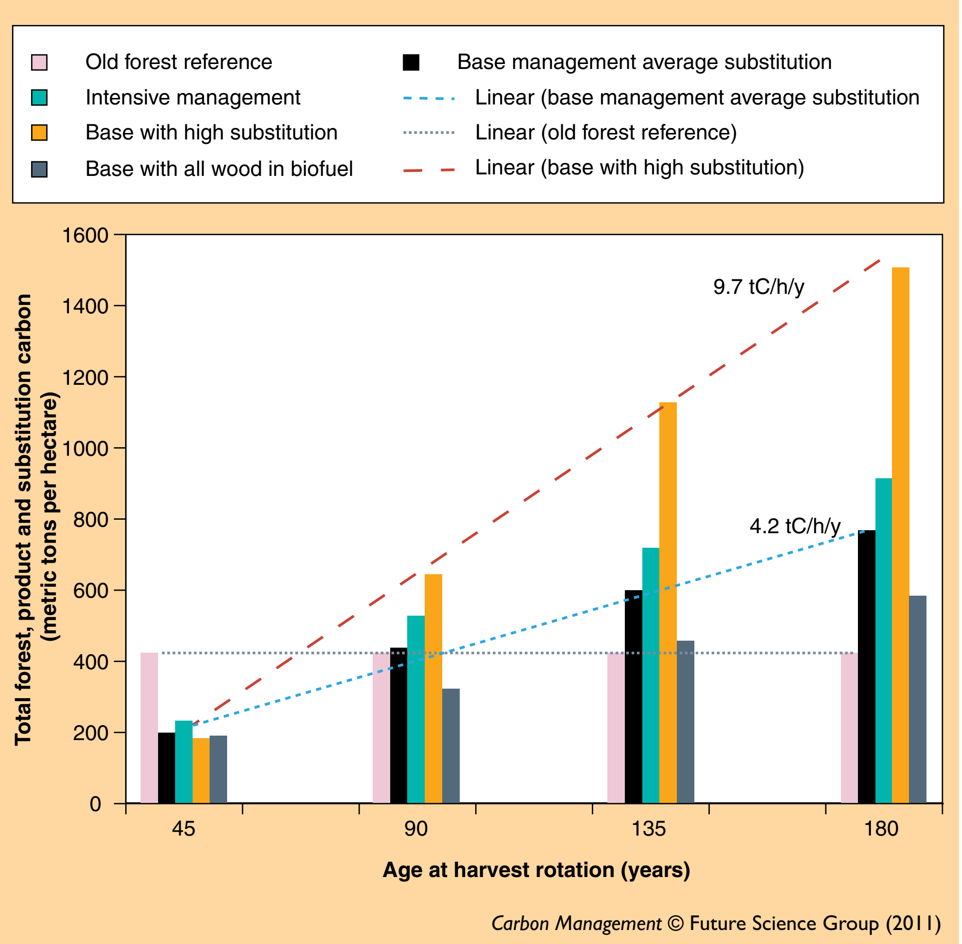

Figure 8. The impact of management and wood-use alternatives on total carbon mitigation.

Table 1. Forest-management and wood-use alternatives: sustained growth in total carbon (metric tons/hectare [tC/h] at the point of harvest)†.

	Year 45	Year 90	Year 135	Year 180	Sustained growth rate trend (tC/h/y; %)
Carbon pools					
Unmanaged forest	420	420	420	420	
Base: sustained management forest	189	189	189	189	
Stem removed	0	133	266	399	
Long-lived net processing	0	70	56	42	
Substitution meta-average	0	176	352	528	
Total carbon: alternatives					
Unmanaged forest: total carbon – forest capacity	420	420	420	420	0.0
Base-sustained management: total carbon – average substitution	189	435	597	759	4.2
Intensive sustained management alternative: total carbon – average substitution	226	520	714	907	5.0
Engineered wood products vs steel joist wood use: total carbon – high substitution	189	654	1121	1503	9.7
Wood biofuel vs coal: total carbon – low substitution	189	318	447	576	2.9

†Management age before removals.

intentions and the productivity potential of the land, assuming modest price or cost reduction incentives that might be expected from carbon mitigation policy initiatives or demand growth over time [7,8]. Alternative and more intensive management treatments stratified across private owners resulted in substantial volume and carbon responses ranging from 15 to 60% increases in forest volume across different regions. Many forest wood use strategies are possible, as illustrated in Figure 5.

The base forest management alternative with average substitution results in a sustainable trend increase in carbon stores and emission reductions of 4.2 tC/h/y. The sustainable rate of carbon mitigation across all carbon pools equals or exceeds the maximum rate of forest carbon absorption from regeneration to harvest surpassing the carbon carrying capacity of an unmanaged old forest by 90 years, without considering the mitigation from prior harvests that would have occurred before the older forest reached its carrying capacity age. A 20% increase is shown for the more intensive management alternative given the high industry share of private forests in the PNW that are already practising intensive management (5 tC/h/y). Using the example of EWP wood I-joists substituting for steel floor joists, the carbon mitigation trend is increased 130% to 9.7 tC/h/y as an indicator of the kind of decision that would be motivated with higher carbon values.

Using only wood for bioenergy, while the lowest motivation for using wood as a substitute, still produces a sustainable increase in carbon mitigation of 2.9 tC/h/y although this is 30% less than that produced by the average substitution across all studies. In this case, short-lived products, which result in no sustained long-term carbon mitigation impact in the other alternatives, are included with long-lived products as feedstock to offset coal-fired energy emissions.

For the US Southeast supply region total carbon under the base case [Data not shown] grows sustainably at 2.5 compared with 3.2 tC/h/y under more intensive management. The primary reason that these results are lower than for the PNW is that much more of the harvest is used in the form of chips serving short-lived paper markets with no contribution to long-term carbon storage and insufficient LCI data to demonstrate any substitution impact.

Referring back to the single treatment time tracking charts (Figures 4–6), Figure 8 and Table 1 focus on those carbon pools that survive past the end of each rotation, thus leaving out short-lived impacts such as the decay of dead wood in the forest and short-lived products. While these pools do contribute to an average impact across all rotations, they do not contribute to sustainable reductions in carbon emissions.

These comparisons tend to show that using sustainably managed forests with end-use designs that feature the best uses of wood support a sustainable increase in carbon stores and emission offsets whereas non-wood designs produce increases in emissions. With more direct substitution such as EWP I- joists displacing steel floor joists, the mitigation impact is large in spite of the much higher energy intensity in the EWP I-joist relative to solid wood joists.

Forest residual & fire reduction carbon mitigation opportunities

▪ Using forest residuals in addition to internally generated mill residuals as biofuel to displace fossil-fuel emissions

The use of wood mill residuals to augment the use of fossil fuel energy falls short of the total mill processing energy needed because other uses of wood residuals are of higher economic value, while also substituting for fossil-intensive product alternatives. For a typical PNW sawmill, only half of the energy needed, mostly for wood drying, is provided by mill process residuals, such as bark and sawdust, which represent approximately 12% of total log input (6% of aboveground biomass). When forest residuals, which are currently burnt or left to decay in the forest, can be economically retrieved and delivered to mill sites or other heat and power producers, additional fossil energy can be displaced [25]. Studies currently underway are designed to refine current estimates of the efficiency of bioenergy for displacement of petroleum-based fuels. At this time, there is a substantial effort to identify how much of this low grade woody biofuel might be available and how much energy it will take to recover it. The energy required to remove merchantable wood is approximately 7% of processing energy and their carbon equivalent emissions is as little as 1% of the total carbon stored in the wood removed. Similar results can be expected for the collection of low-grade forest residuals, suggesting that the carbon emissions from biofuel collection activity will be very low relative to the fossil emissions displaced.

▪ Forest residual biofuel availability

A recent study in eastern Washington, USA, measured almost 2000 piles of forest residuals and delivered a subset of them to an electric power plant [26]. While half of the aboveground wood was delivered to product mills, of the remainder, approximately 30% was considered uncollectable, leaving 35% of the total aboveground biomass as accessible. As some biomass is considered potentially important for nutrients and other values (Figure 9), a further net-down was applied, based on ecological data for the region. The net recoverable forest residual biomass was estimated to be almost 24%

of the total aboveground biomass. If it were recovered, this volume is almost four-times greater than the total biomass currently used in the wood product mills to produce energy. It is also much more than is needed for mill-processing energy, which could result in a substantial flow of biofuel to other energy users. As such, it represents a substantial opportunity to reduce emissions, if and when the cost of collection merits the effort. The amount of recoverable biomass varied across forest types but averaged at 19 t/h for these relatively low productivity interior forest types. Recovery volumes will be region-specific because of different forest productivity, species, logistics and terrain. Some of this material is already collected in regions where the terrain and logistics supports a lower collection cost. The recovery of forest residuals is much more prevalent in Europe, where the cost of energy and value of carbon are much higher than in the USA [108].

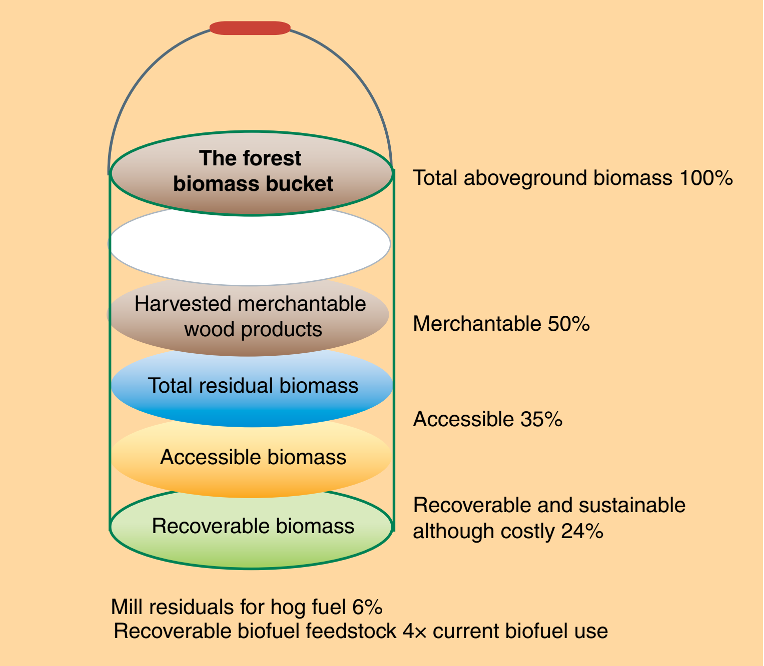

Figure 9. The forest biomass bucket and recoverable biofuel feedstock. Reproduced with permission to publish from the Washington Department of Natural Resources [26].

▪ Life cycle assessment of electric power plant comparisons

While research is ongoing to determine the relative efficiency of different biofuels in comparison with fossil fuels, interim estimates of the GHG emission comparisons for different power plants can be made directly from the US LCI database, a peer reviewed source of primary product life cycle data, which includes GHG emissions [103]. Using the US EPA TRACI impact method, as available in SimaPro software [109] each mega joule of electricity that a woody biomass plant produces generates only 4% of the emissions from a bituminous coal plant, using a fossil fuel base for comparison (Figure 10). This is in direct contrast to the proposed EPA method where the CO_2 uptake in the wood from the atmosphere is treated the same as if it were mined like coal rather than sourced from sustainably managed forests thereby ignoring the fact that the forest carbon uptake across the forest is equal to biofuel feedstock removals with no time lag. Using the EPA proposed accounting method, the biomass plant emissions would equal 86% of the emissions from the coal plant [27].

Under assumptions of a transition from forest residuals being left to decompose without burning and collection for use as a biomass feedstock, there would be increased carbon stored in the dead wood released slowly through natural decomposition had the residuals remained in the forest, compared with immediate release when burnt for energy. The displaced fossil fuel may be almost equal to the initial dead wood pool when displacing coal, resulting in essentially no period of time when the displaced fossil emissions were significantly less than the dead wood in the forest. Since natural gas is more efficient than burning wood, the carbon in forest residuals will exceed the natural gas emissions displaced until the residuals decay to less than the level of displaced emissions from natural gas. 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 [110].

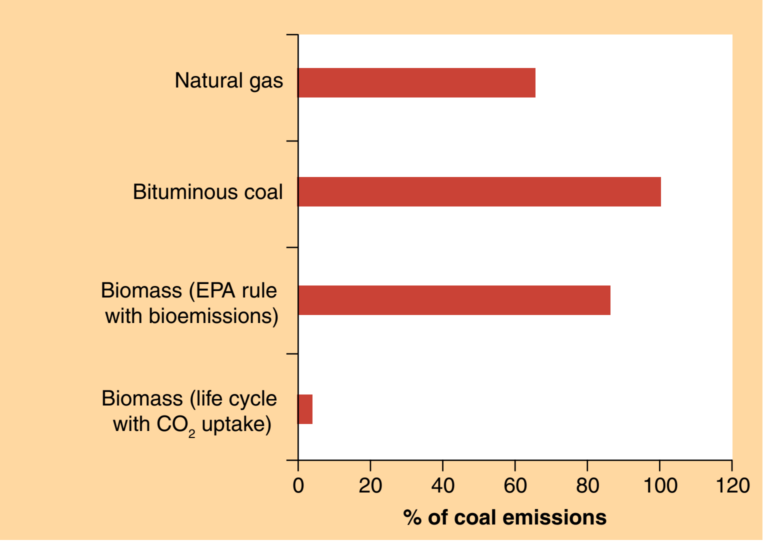

Figure 10. Electric power plant GHG emission comparisons. Adapted from unpublished data from CORRIM.

On an international level, a practical problem in accounting for net biofuel emissions is that some countries do not have accounting commitments, and are therefore not obliged to account for emissions from loss of terrestrial carbon. Therefore, any loss of carbon stock associated with the supply of biomass for bioenergy may not be considered. One potential solution might be to introduce 'end-user responsibility' for the impacts of biomass supply from countries that do not account for their emissions from loss of terrestrial carbon stocks [28]. The system boundaries of GHG accounting could be extended so that the end-user country would take full or partial responsibility for changes in the terrestrial carbon stocks in the producer country. Under an 'atmospheric flow' approach to carbon accounting, in which emissions and removals from a forest are determined on the basis of gross atmospheric fluxes between the forest or forest products and the atmosphere, the accounted emissions of imported bioenergy would always be equal to the carbon content of the biomass. Under an 'extended stock-change' approach, in which the annual removals or emissions from a country's forest are assumed to be equal to the net change in carbon stocks in biomass and soils, the emissions would depend on the source of the biomass. Ideally, accounting for terrestrial carbon stocks should strive for full-carbon accounting, to ensure that all anthropogenic emissions are accounted for and appropriate incentives are created.

Unsustainable management impacts

▪ Unsustainable consequences of no forest management

Increasing rates of fire are projected for the drier interior regions of the USA both as a consequence of a century of fire suppression resulting in unnatural overly dense stands [29] and the impact of climate change [30,31]. The rate of fires on unmanaged federal lands is many times higher than on managed lands. Fire simulations on Inland Northwest National Forests (Figure 11 [24]) show that forest carbon could continue to increase assuming 20th century fire rates and continued successful fire suppression efforts, although this does not account for the impact of other mortality agents such as the mountain pine beetle [24]. Figure 11 also shows that models that project a doubling of fire rates due to climate change essentially cap the carbon that will be stored in the forest. Since 2002, higher levels of carbon have been emitted from these lands than growth models predict was removed from the atmosphere by new growth. If the fire rates for the first decade of the 21st century continue, they suggest that these national forests have already become a carbon source (Figure 11). Without more aggressive fire risk reduction treatments and investment in reforestation of currently burnt sites, many more unmanaged interior forests will probably become emission sources rather than carbon storage sinks. This increase in wildfires coupled with lack of investment in reforestation represents both a lost opportunity to offset fossil-intensive product and fuel emissions, as well as a prospective decrease in forest carbon stores.

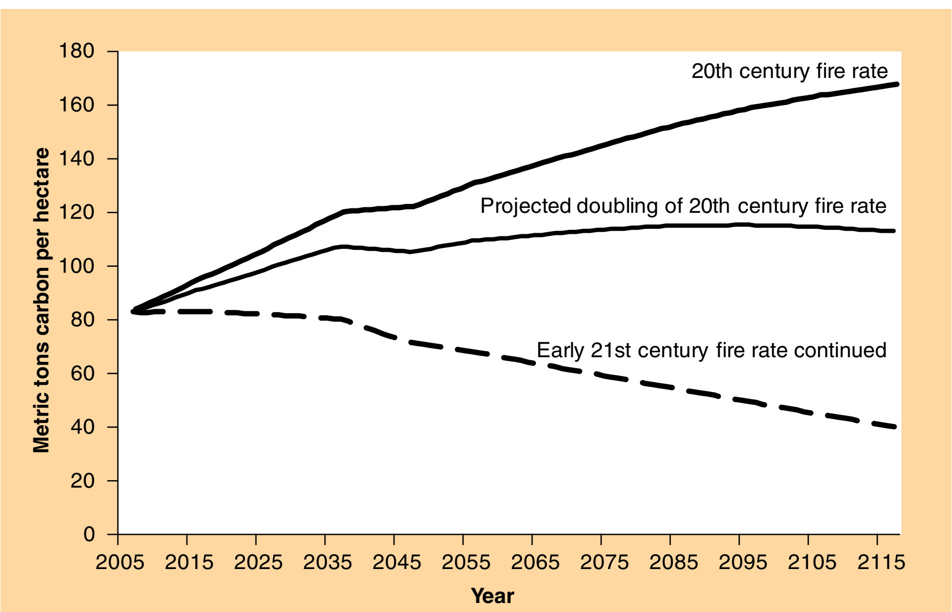

Figure 11. The impact of fire rates on carbon for inland northwest national forests (Idaho, Montana and Washington east of the Cascades). Simulation of harvests is projected at current levels with wildfires projected for each period. The percentage area burnt under three different burn-rate assumptions is allocated across all hectares (treated and untreated). The 20th century fire rate, is based on FIA inventory data history, the predicted doubling is based on composite analysis of FIA data combined with McKenzie *et al.* 2004 data on climate impacts [30], and the early 21st century rate is based on National Interagency Fire Center burn data by region allocated to USFS lands on a pro-rata basis. If the trend in average acreage burnt from 2002–2009 continues, it will take only 15–17 fire years to equal all the fires in the 20th century. Reproduced with permission to publish from Wood Fiber Science [24].

▪ Opportunities to reduce fire risk & increase total-carbon stores & offsets

Treatments can reduce the impact of wildfires [32,33]. Thinning treatments that removed trees less than 30 cm in diameter to restore a savanna-like overstory of larger trees, similar to pre-settlement conditions, were simulated for the Inland Northwest National Forests consistent with ecosytem management objectives. To meet the backlog of need for this region, simulations were carried out that assumed rapid implementation of treatments and a 400% increase in the amount of area treated (relative to the past decade) was applied to the most susceptible stands [24]. These simulations demonstrate how carbon gains can be achieved in the forest by continued growth of the larger trees and lower mortality rates, as well as increases in smaller diameter material for biofuel and other products that displace the use of fossil fuels and fossil fuel-intensive substitute products. A comparison of simulations across owner groups shows that the total carbon benefit from a 400% increase in the area treated with a thin-from-below strategy is approximately half that for sustainable harvest rates from State and Private forests in the Inland Northwest in 100 years (Figure 12). However, it is twice the forest carbon that will result from a continuation of recent fire rates on unmanaged National Forest lands.

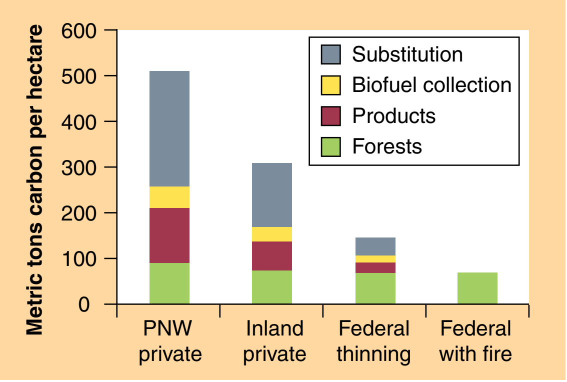

Figure 12. Total carbon stores at 100 years for PNW private, inland northwest state and private land, and inland northwest US Forest Service (federal) lands with and without rapid implementation of fire risk reduction treatments.
PNW: Pacific Northwest.
Adapted from unpublished data from CORRIM.

Data gaps & uncertainties

Landfill carbon accounting

Figure 7 does not include storage of wood and paper products carbon in landfills after they are discarded from use. The level of carbon storage would be higher in Figure 7 if storage in landfills were included. On a national level in 2005, approximately two-thirds of the wood and a third of the paper no longer used was discarded to landfills [34]. The rest was recycled or burnt. Of the amounts deposited, approximately 23% of wood and 56% of paper are subject to decay under anaerobic conditions. Approximately half of the total weights of gas emissions from decay are in the form of CO_2 and half are in the form of methane. In 2006, approximately half of all methane generated was captured and used for energy or flared [35].

Given that methane has an estimated global warming potential of approximately 21-times greater than CO_2, the methane emissions offset a substantial portion of the wood or paper landfill carbon storage. The half-life of decay in landfills for the portion that decays is approximately 29 years for wood and 14.5 years for paper [34]. After complete decay of the degradable portions, the methane and CO_2 emissions offset approximately 55% of the amount of wood carbon deposited and 135% of the average paper carbon deposited (assuming methane capture of 50%). Of the wood discarded from use approximately 35% currently remains stored. Placing paper in landfills currently results in approximately 35% more CO_2-equivalent emissions than if it were burnt without energy generation. The excess of emissions varies by paper type and would be lower (possibly without excess) for paper with a higher fraction of lignin because such paper is less subject to decay.

These figures suggest that greater carbon stores could exist in the landfill than was assumed in Figures 5–7. The state of the art in methane collection systems is a rapidly evolving field. Collection systems have increased the recovery or oxidization of methane from 20% in 1990, to 50% in 2006 [35]. Continued methane recovery improvements would result in increased levels of long-term landfill carbon storage with no negative GHG impacts. However, it is still better to recycle wood-based products to replace fossil fuel-intensive products or fossil fuel-energy sources directly than to put them in landfills.

Increases in biomass collection for energy will reduce the amount of material entering the landfill at the same time as methane emissions from the landfill are being technologically reduced. Despite the uncertainties in these estimates, these trends suggest that the overall carbon footprint from the disposal phase of using wood products will be improving as improved waste management technologies are implemented. Best forest management and wood use strategies will not be determined by best landfill management except, perhaps, to motivate increased recycling and recapture of the fuel value in wood waste rather than landfill.

Carbon in the soil

Cleveland and Liptzin [36] conducted a meta-analysis of both soils and soil microbial biomass across grasslands, forests, and forest types in both temperate and tropical regions of the world. They found a remarkably constant ratio for linkages between carbon (C), nitrogen (N) and phosphorus (P) in nutrient cycling in terrestrial ecosystems indicating that the carbon accumulation in the soil is constrained by other nutrient elements, of which N and P are the most studied [37]. It also suggests that soil-carbon accumulation would not follow a linear model of indefinite accumulation through time because of inherent feedbacks on nutrient accumulation and decomposition that can be assessed for particular soils using elemental stoichiometric analysis. The relatively constant ratios among elements for each soil suggest that there is a carbon-carrying capacity for each site, but, it is not driven by latitude or forest type since the total amount of soil C varied by an order of magnitude across study sites at different latitudes with different forest types [37].

While there are two models of soil organic carbon (SOC) accumulation; a linear model and a saturation model, Stewart *et al.* assess the relative merits of these theories using agricultural soil studies as input data [38]. The linear model, suggests no carbon saturation with increasing carbon inputs. They tested the linear model against a saturation model, which theorizes an asymptotic SOC accumulation with increasing inputs of carbon into the soil system. The saturation model suggests that with increasing carbon inputs to the system, less carbon accumulates as the soil reaches a saturation point. Pooled data results from all soil types and management regimes support the asymptotic SOC accumulation theory; however, some studies where intensive agricultural management maintains SOC below saturation levels support the linear model theory.

Where severe wildfire is part of the landscape, this issue will be particularly prevalent since research on soil carbon losses from fire indicate that a severe fire can reduce soil carbon by 30% [39] with up to 60% of the carbon lost during severe wildfires from mineral soil layers [40]). With lower intensity burns, these loss rates are not as likely [41] and with time after disturbance, soil carbon can recover to pre-burn levels [10].

Yang and Luo expanded the use of stoichiometry principles to assess the change in C:N ratios for various elements in forested ecosystems across different stages of stand development [42]. Their meta-analysis of 39 independent studies found that C:N ratios in soils, forest floor and litter remain relatively constant through time. Only the C:N ratio in plant tissue increases during stand development, as we would expect from changes in stem wood relative to foliage and roots over time. While Yang and Luo indicate that C:N ratios do not change during stand development, we must also assess what the potential is for changes in total soil carbon storage under management.

Covington postulated a model of soil-carbon loss after forest harvest of up to 50% [43]. A competing theory by Yanai *et al.* [44]) suggests that with careful management, SOC will not be reduced. The largest driver for these differing impacts is the level of soil disturbance, compaction and soil degradation, all of which can be managed with appropriate policies. Another meta-analysis of the impact of forest harvesting on soil carbon by Johnson and Curtis found that harvesting had little or no impact on soil carbon in the 26 studies they analyzed [9]. Ter-Mikaelian *et al.* also conducted a review of the literature and could find little evidence for a reduction in soil carbon from forest management [12]. Norris *et al.* found no loss of soil carbon after harvest over a 30-year chronosequence study; by comparison, some stands regenerating after fire did show the decline postulated by Covington [43] but those sites regained their original soil carbon stores after 30 years. In a field study, Fredeen *et al.* found no significant difference in soil and forest floor carbon between old growth and young second growth forests in central British Columbia, although they did find that old forests contained more carbon in standing stocks, as one would expect [11]. In a more recent meta-analysis, Nave *et al.* found no significant difference in mineral soil carbon between harvested and unharvested sites, although there were significant differences in forest floors between treated and untreated sites, particularly for hardwood forests [45]. The results included studies that had post harvest plowing, ripping and broadcast burning. A third of the studies sampled all soil layers, whereas the other two-thirds sampled only the shallow soil layers. Harrison *et al.* found that studies that sample only the shallow layers or forest floor to derive soil C estimates can underestimate total soil C by 24–73% [46]. The differences can change the interpretation of results from these studies since changes in the upper layers can greatly overestimate total C impacts of any treatments.

Yanai *et al.* also suggest that SOC may actually be increased with appropriate management inputs [44], for example, an application of urea fertilization as part of the management regime has been shown to increase both forest productivity and soil carbon accumulation for some soils [17,18,47]. This result is consistent with the research on C:N:P ratios from Cleveland and Liptzin, which suggests that in nutrient-limited soils, increasing nitrogen content will result in more carbon retention in the soil to maintain the C:N:P ratios in dynamic equilibrium [38].

In Sweden's boreal region, a lower availability of nitrogen (N), has elevated the attractiveness of fertilization [48]. Experiments have shown that it is possible to more than double the rate of stem wood production in some forest stands. Sweden is also increasing removals of slash harvest for production of renewable fuel. Current estimates of approximately a third of the potential slash being removed may be able to triple the renewable fuel production considering technological and efficiency improvements [108]. They do show soil carbon continuing to accumulate in the long term, slowing somewhat with slash removal, although resulting in only a small offset to the fossil fuel displacement benefits.

The meta-analyses, the basic elemental models of stoichiometry and field research results are congruent and help us to place in context what is known and unknown about the impact of forest harvesting on soil carbon accumulation in forest soils. The most basic conclusion is that adding more carbon to the forest soils through maintaining all the dead wood on site after harvest, or foregoing harvest entirely will not necessarily result in a significant increase in carbon stored in forest soils relative to the benefits of greater use of biomass for renewable energy. The carbon accumulation in forest soils is largely driven by soil moisture, carbon-nitrogen dynamics and climate [49,50], but not by the amount of wood retained on site. Processes related to nutrient availability, litter fall input rates, decomposer community, decomposition rates and relative intractability of lignin to decay, will drive the equivalent of the soil carbon carrying capacity for a given forest site. The larger research question that has yet to be fully explored is how best to identify the soil carbon carrying capacity for a given site and across landscapes with any degree of accuracy. Knowing this information will help identify best biomass removal practices while retaining long term sustainability.

The most important impact observed from management practices is the impact of fertilization on nutrient deficient soils. Adams *et al.* found urea fertilization increased site productivity resulting in increases in both aboveground carbon and soil carbon, although no significant increase or decrease in soil carbon can be expected over time from a specific sustained rotation and treatment prescription [17]. These research results suggest that policies that encourage sustainable forest management will motivate investment in increased growth and site productivity, which can promote increases in both the rate of aboveground biomass and soil carbon accumulation. Sustainable forest management supports activities that increase soil carbon contrary to some concerns. Increasing values for carbon will increase the importance of investing in nutrients that enhance both aboveground and belowground site productivity [51].

Consequential life cycle analysis

▪ Using general equilibrium economic models for consequential life cycle impacts

Substitution does not take place without market changes affecting prices that increase the demand for some goods while decreasing demand for others. As an instructive example of providing consequential life cycle measures based on general equilibrium models, Resources for the Future developed a model including interindustry detail across multiple sectors based on the North American Industry Classification System and evaluated the impacts of carbon prices over four adjustment periods based on energy use estimates of carbon intensities for each sector [52].

In the very short run, before output prices can be changed, profits fall. When output prices rise to reflect the higher energy costs, there is a corresponding decline in sales as a result of product and/or import substitution. Ultimately, the mix of inputs will also change and, with a full general equilibrium analysis, longer-term capital will be reallocated and replaced with more energy-efficient technologies.

Over time, petroleum markets, cement, iron and steel, aluminum, lime and chemicals, non-metal minerals, and mining are hit by an increase in the cost of carbon (e.g., carbon tax), while domestic utilities are able to pass costs through without competition at the border. The model takes into account the fact that the demand for steel depends not only on the price of steel but also on the price of everything in the economy. Where price is highest, demand is lowest. Emission reductions in the USA result from less use of fossil fuel-intensive products; however, a substantial portion of these reductions might be offset by increased carbon emissions overseas associated with increased imports.

While the results infer the impacts of a consequential life cycle assessment across many different product sectors, the level of detail is limited to broad sectorial averages that cannot capture the substantial differences in fossil energy intensity across products and carbon pools demonstrated in **Figures 2–10**. Developing the level of detail required to characterize the impact of changing prices or product specific incentives on product substitution given the substantial number of products with substantially different fossil intensities does not appear to be practical. Consequential life cycle analysis linked to economic models is useful in identifying negative feedbacks in some cases, but will probably not be effective in identifying the many opportunities for improvement that evolve from making direct ALCA comparisons between different management strategies, processing methods, material selection or building design.

▪ Non-market ecosystem performance impacts

Of greater concern may be the consequential impacts on non-market values, such as habitat, which because it is a good with no price, is not represented in general equilibrium economic modeling. When the supply of habitat is derived from the same sustainably managed forest lands that contribute to carbon the joint production of habitat and carbon outputs does not require the same degree of concern on interactions with the rest of the economy. However, in order to avoid habitat losses as carbon values or incentives increase, an increase in the value placed on the habitat through regulatory minimum standards, or compensating incentives may be required.

The impact of managing forests to reduce carbon emissions under sustainably managed lands may have relatively little impact on species that survive in generally shorter rotation forests since they are also producing the high carbon stores and offsets across all carbon pools. Using stand diversity measures for habitat suitability, Lippke *et al.* demonstrated that more intensive management than current commercial rotations can increase harvest levels (and products carbon) without significantly reducing habitat suitability in the US Pacific Northwest [53]. While habitat that is dependent upon old forest structures are in short supply, affecting some species that are already identified as endangered, intensifying management on hectares already under commercial management has relatively little impact on old forest habitat. Of much greater importance, conversion of unmanaged forests to shorter rotation forests, would reduce old forest habitat in response to increased economic returns to reduce total carbon emissions. Alternatively, on commercially managed forests intentionally thinning stands with longer rotations could increase old forest habitat [54]. In one study, alternatives to intentionally increase availability of old forest structures resulted in a 20% increase in carbon emissions for a few decades, declining to approximately 6% thereafter [53]. However, the transition to long rotations and thinning to intentionally produce old forest habitat are very costly to the landowner and are made more costly by the reduction in total carbon to the degree that it has value.

However, habitat impacts cannot be easily generalized. Dry forest stands in the western interior are already overly dense from a century of fire suppression and are experiencing increased fires as previously noted [24]). Thinning to reduce fire risk can, in this situation, restore historic stand structure conditions and avoid future fire fighting and forest rehabilitation costs, while increasing carbon and restoring historic forest habitat, a triple win [55] with carbon benefits complementary to historic forest habitat. In general, while the principles/methods to protect critical habitat have common elements [56], the protection of habitat and other non-market ecosystem concerns must be considered at a much more local and site-specific level than carbon, given the variation in species and their preferred forest structure conditions.

While these examples barely hint at the consequential impacts of different policies and price changes on outcomes it is useful to review what can be learned about the effectiveness of various policies from ALCA data and comparisons between alternatives, in particular identifying the potential for unintended policy consequences that may be counterproductive to objectives.

Unintended consequences

By tracking the inputs and outputs for each stage of processing, the LCI of a product can be traced from cradle-to-grave and compared with other products and processes, providing a blueprint for life cycle carbon accounting across all carbon pools. However, carbon incentives are frequently based on the impact of one carbon pool at a time, such as incentivizing an increase in forest carbon without regard to its impact on product carbon, which may more than offset the change in forest carbon; or incentivizing the production of liquid fuels without considering where the feedstock might be sourced and its impact on carbon.

Life cycle carbon accounting exposes many unintended policy impacts such as:

- Carbon exchanges that incentivize reduced harvesting, which can contribute to greater emissions from using more fossil fuels than can be offset by increasing forest carbon stores;
- Ignoring substitution of wood for fossil intensive products since it has the highest potential leverage in reducing emissions;
- Incentivizing low-value fuels such as ethanol that will divert feedstock from higher leverage fossil emission displacement options such as composite wood products;
- Considering biogenic boiler emissions no different than fossil emissions when intending to constrain fossil emissions [57], which will discourage the use of biomass for energy, increasing rather than decreasing emissions;
- Renewable fuel standards/requirements for utilities that force the diversion of feedstock from other higher leveraged uses of the biomass and fragment the supply reducing the opportunity for investments in efficient scale mill uses of the feedstock.

In contrast with these unintended consequences, a pollution tax on fossil carbon removed from deep pools would be passed forward as a cost increase in the market proportional to the amount of fossil carbon being used and the cost difference would motivate the use of wood to displace fossil emissions proportional to their carbon intensity [58,59]. Acknowledging the poor acceptability of any tax in the USA, a pollution tax could be made income-neutral in order to reduce negative economic impacts. However, if the tax is not levied on imports and exports in order to be consistent with world trade agreements that prohibit tariff barriers, the cost difference could still cause an unintended market share change at the boarder, increasing untaxed imports that may offset part of the domestic carbon benefit and shift economic activity off shore [52]. Many countries already have taxes on fuels similar to a carbon tax contributing to a complexity of tax instruments and current cross-country imbalances in the cost of fossil fuels and carbon emissions.

Therefore, while attributional LCI/LCA carbon accounting provides direct comparisons between specific alternatives providing insight on opportunities for improvement, it is not sufficient to characterize a market response to price changes such as a carbon tax or other policy incentives such as tradable permits. Consequential life cycle accounting that attempts to take into account the impact of carbon policy across sectors (such as changes in land use and differential responses across product alternatives, including where substitution occurs) requires additional knowledge about response relationships between carbon price changes and supply and demand responses at a detailed product level.

Since the range of substitution alternatives is so large, many have suggested it cannot be quantified and must be left out of carbon mitigation measurements. However, since the impact tends to dominate all other wood product impacts in scale, estimates without including substitution are essentially meaningless. Ironically, substitution for energy has been more readily accepted since the biomass being used results in only a narrow range of impacts across a few different fossil energy uses, reducing the range of uncertainty. By contrast, the substitution of wood for fossil intensive products not only stores the carbon in the product for the life of the product, it displaces emissions from fossil intensive products with much higher leverage than using wood for bioenergy, but is considered difficult to quantify.

Comparisons across international research

There are both similarities and differences in situations across the globe. Differences result from variations in climatic, ecological, economic and cultural conditions. Climatic and ecological factors lead to different forest productivity, species and rotation lengths, which affect the extent to which forestry can contribute to climate change mitigation. Economic factors such as carbon taxes and relative prices for building materials affect the competitiveness of forest biomass as a substitute for non-wood materials and fossil fuels. Cultural factors affect, among other things, the history of use and desirability of different building materials, the attitudes toward forest exploitation and the effectiveness of standards or regulations. International comparisons go beyond technical carbon accounting and we use as our example, Sweden, where sustainable management is practiced and the research efforts have been similar to the approaches being taken to achieve national carbon-mitigation objectives in North America.

The standing stock of stem wood in Swedish forests has been increasing during the last 60 years, and is expected to continue increasing during the coming 100 years owing to improved forest management and the effects of climate change (Figure 13 [111,112]). This provides opportunities to use renewable forest resources as part of a strategy to transition to a more sustainable, carbon-neutral society. Sweden and several other

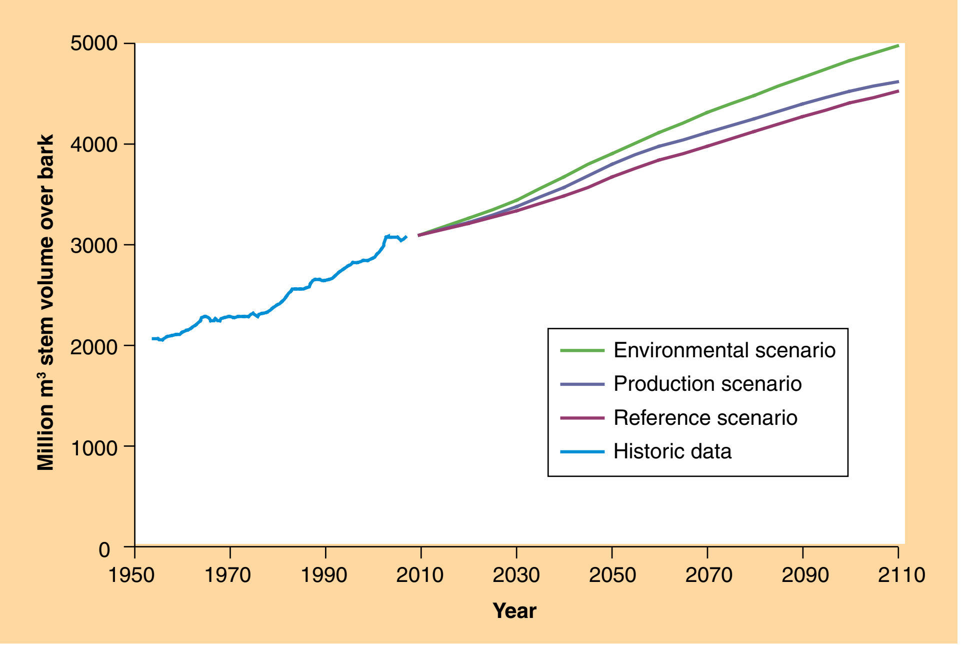

Figure 13. Historical and projected future standing stem volume on productive forest land in Sweden.
Data for 1954–2008 from Swedish Forest Agency [111].
Projections for 2010–2110 from Swedish Forest Agency [112].

European countries have implemented carbon taxes or similar instruments on fossil fuels, which are meant to internalize the external costs of climate change and impose a financial incentive to reduce the emission of GHGs to the atmosphere. This goal is realized in the short term by reduced energy use or by fuel switching to less carbon-intensive fuels. In the medium term, it can be expected to lead to investment decisions favouring less carbon-intensive industrial production. In the longer term, carbon policies could promote permanent structural changes in production and consumption patterns, including a transition from fossil fuel-based products to renewable products that reduce climate change impacts. The use of forest products, including biofuels and wood-based products, is expected to increase significantly owing to these factors.

In Sweden, a carbon tax has been in effect since 1991 and is applied to end-use fossil fuels based on their carbon intensity [111]. The level of the tax increases gradually and consistently, to provide stable incentives for transitioning to a lower-carbon economy. This has provided favourable conditions for the use of biofuels. The Swedish use of bioenergy has increased from approximately 50 to 140 tera-watt-h (TWh) per year, during the last 30 years and is expected to continue to increase (Figure 14 [113,114]). During this time the Swedish annual final energy use has been approximately 400 TWh per year.

Although standing biomass stock is expected to increase in the future, demand is also increasing for forest-related outputs, such as wood, bioenergy, climate stability, watershed protection, biodiversity and recreation. Since forestland area is limited, efficient use is important. One option is to increase biomass production on part of the forest land area through intensified management activities such as fertilization or species selection, thus allowing other forest land to be dedicated to other uses. Forest growth on mineral soils in boreal regions is often limited by a low availability of N and fertilization is one element of forest-management intensification that has shown particular promise in increasing yields in boreal forests [48]. In Sweden, increased attention is being placed on optimized fertilization of forestland. Beginning with the first-field experiments with N fertilization in the 1920s, substantial experience has been accumulated in the effects of fertilization on Swedish forests. Experiments have shown that it is possible to more than double the rate of stem-wood production in some forest stands by optimizing the availability of essential nutrients, while, avoiding the leaching of nutrients to the groundwater [60]. Recent analysis has shown the climate change mitigation potential of forest fertilization. Fertilization of 10% of Swedish forest land could increase annual usable biomass production of 8.3 million t dry matter, of which 37% is large-diameter stemwood [51]. If used to substitute fossil fuels and non-wood materials, the annual net GHG emission would decrease by 12.7 or 19.5 million t CO_2e if the reference fossil fuel is fossil gas or coal, respectively. This reduction corresponds to 19 or 30% of the total Swedish GHG emission in 2007. A significant one-time carbon stock increase would also occur in wood products and forest biomass.

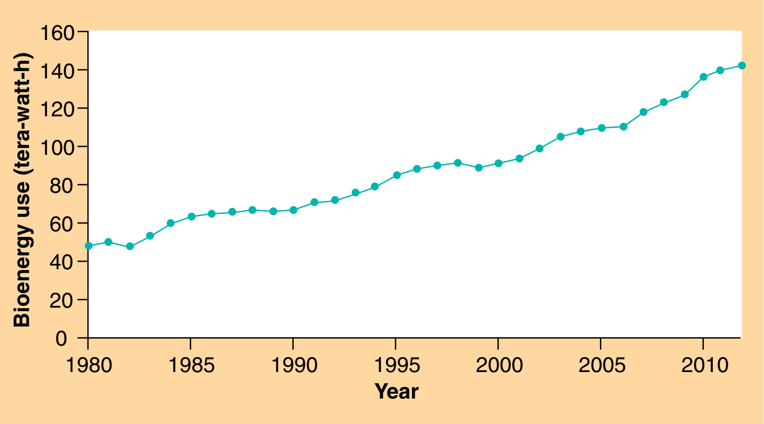

Figure 14. Annual bioenergy use in Sweden from 1980 to 2012.
Data for 1980–2009 from Swedish Energy Agency [113].
Projections for 2010–2012 from Swedish Energy Agency [114].

A life cycle perspective on forest products is important, considering the growth of the raw materials, the co-production of diverse products, the services provided by the materials and fuels and the efficient post-use management of the material resources. A recent analysis of life cycle primary energy use and CO_2 emission of an 8-storey wood-framed apartment building in Sweden showed that it is possible to have negative carbon emissions over a building's life cycle [61]. The study covered all life cycle phases, including acquisition and processing of materials, on-site construction, building operation, and demolition, and materials disposal. The building operation was found to use the largest share of life cycle energy use, becoming increasingly dominant as the lifespan of the building increases. The type of heating system strongly influenced the primary energy use and CO_2 emission, and a biomass-based system with cogeneration of district heat and electricity achieved low primary energy use and very low CO_2 emissions. The use of biomass residues from the wood products chain to substitute for fossil fuels further reduced net CO_2 emission. A negative life cycle CO_2 emission could be achieved owing to the wood-based construction materials and biomass-based energy supply system.

Resource-use efficiency can be increased through appropriate management of wood-based building materials at the end of the building service life. The waste-management sector, which traditionally has received and disposed of materials, such as construction site and demolition waste can, thus, be a source of valuable resources. Resource use efficiency can be maximized by integrating the material and energy flows between the forestry, wood processing, construction, energy systems and waste management sectors. This integration is already underway, and can be further optimized. The potential benefits of post-use material recovery are greater for wood than for concrete or steel [62]. Recovered wood material can be cascaded (i.e., reprocessed and re-used for a different material application) or can be used as a bioenergy resource [63]. Material cascading can be facilitated by 'design for disassembly' of buildings to allow the removal of wood products with minimal damage at the end of the building life, to maintain their potential for further re-use as a material. Nevertheless, overall system efficiency is increased if the feedstock energy value of the wood material is recovered at the very end. The duration time of the carbon storage of wood products is of minor importance if the end-of-life products are used to replace coal, which provides a permanent carbon emission avoidance, roughly equal to the carbon stock in the wood [64]. This will also depend on the efficiency of the biomass conversion plants, which is high in Scandinavia and comparable with fossil plants.

Harvest slash is increasingly recovered and used as bioenergy in Sweden and there is ongoing research regarding stump harvesting for bioenergy. Recent annual harvest of branches and tops in Sweden is approximately 7 TWh and the estimated potential harvest of branches and tops in Sweden is in the range of 16–25 TWh/year [108]. Potential stump harvest in Sweden is estimated to be in the range of 21–34 TWh/year. Current recommendations limit stump harvest to no more than 10% of potential harvest area, while on-going studies determine the environmental effects of larger scale harvesting [115].

The amount of fossil energy input required to recover and transport forest biofuels depends on several factors including the recovery method, concentration of biomass per forest land area, degree of biomass processing, scale of operation, transport distance and transport mode [16]). Several Swedish and Finnish studies have analyzed this and expressed the fossil energy use as a percentage of the heat energy in the delivered biomass. Wihersaari analyzed five slash-recovery chains with chipping at the harvest site, the roadside, the terminal or the end-use facility, finding the fossil energy inputs to vary between 2 and 3% of the energy in the delivered biomass [65]. Lindholm *et al.* analyzed several slash and stump recovery chains, finding an input energy range of 2–5% of the energy in the biomass [66]. Gustavsson *et al.* analyzed slash recovery and transport to local, national and international end-users, with energy inputs averaging approximately 2, 4 and 6% of the biomass energy, respectively [16].

Eriksson *et al.* conducted an analysis of the carbon stocks and flows associated with forest management of Norway spruce and forest product usage in a Swedish context [67]. They modeled forest growth under three management regimes (traditional, intensive and fertilized) to determine the carbon stocks in trees and soil, the production levels of harvestable biomass and the fossil emissions associated with each regime. They considered three intensities of harvest-residue management: no removal, removal of harvest slash and removal of harvest slash and stumps. Variations over the range of forest-management alternatives on biomass and soil carbon were 30% (low to high) while the variation on different wood uses were 100% (low to high). They found soil carbon levels to increase in all three regimes during the first 100 years and then asymptotically approached a level that was highest for the fertilized regime. Removal of slash and stumps caused a slightly lower increase in soil carbon levels, but also led to increased fossil fuel substitution from its use as biofuel. If fossil coal was replaced, the decreased fossil fuel emission was on the order of ten-times greater than the decreased soil carbon stock. The highest level of avoided net carbon emission of 3.7 tC/h/y occurred with fertilized forest management, removals of slash and stumps, stem wood used as construction material, and with coal as the avoided fossil fuel (Figure 15 [67]). The lowest level of avoided net carbon emission of 0.7 tC/h/y occurred with traditional forest management, slash and stumps remaining on-site, stem wood used as biofuel, and with natural gas as the avoided fossil fuel.

Eriksson *et al.* also discussed their modeled forest management regimes in comparison with the option of non-management and non-use of forest land [67]. They observed that in the long term, the carbon stock in unmanaged forest biomass and forest soil will reach a dynamic equilibrium, where carbon stock increases caused by tree growth will be balanced by decreases caused by respiration and decomposition. Since no forest products are produced, other non-wood materials and fossil fuels will be used instead, resulting in relatively greater net carbon emissions. Since the substitution benefits of forest products are cumulative, while the carbon sink in forest biomass and soils is limited, the managed use of forests becomes more attractive as the time horizon lengthens.

An important factor that varies significantly between countries is the level of wood use in building construction, which affects the potential extent of wood substitution benefits. Table 2 shows that the share of wood for

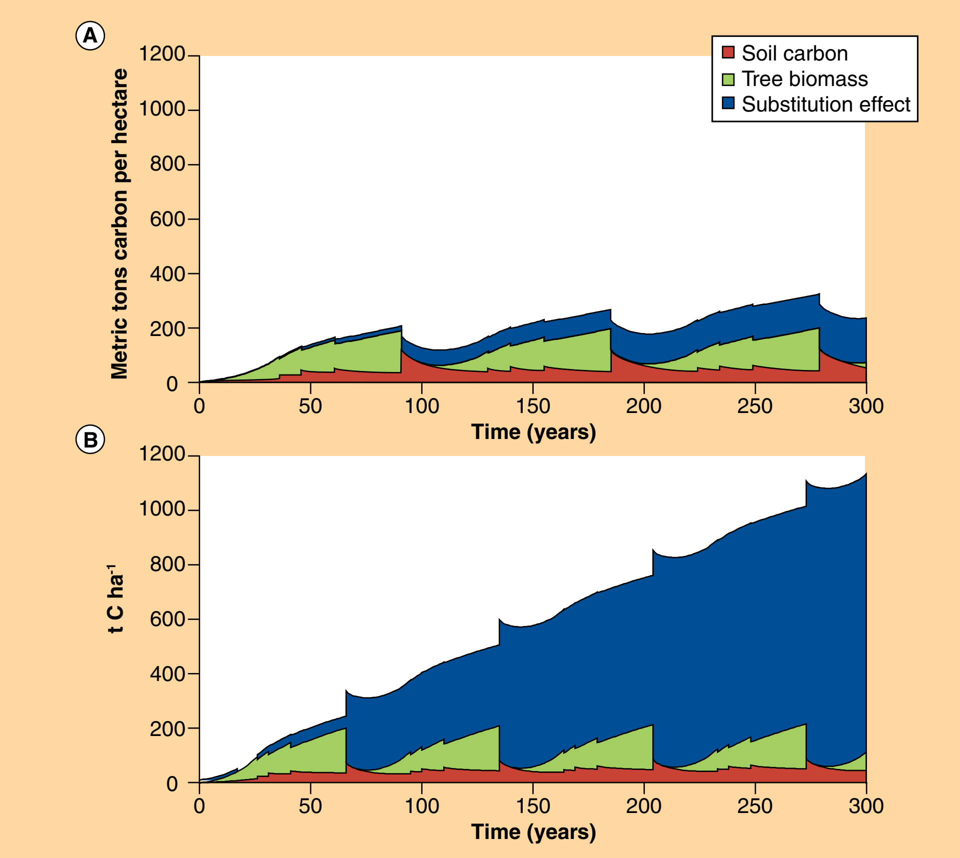

Figure 15. Development over time of the carbon stock in the soil (organic matter and dead and decaying biomass not removed) and in the living tree biomass (including live roots), and accumulated carbon emission reduction owing to product substitution (A) for the combination of parameters giving the lowest reduction in net carbon emission and (B) for the combination of parameters giving the highest reduction in net carbon emission.
Reproduced with permission to publish from *Canadian Journal of Forest Research* [67].

constructing one- and two-family houses is relatively high in Nordic countries and in North America, but is rather low elsewhere in Europe [68].

Wood is commonly used in Nordic countries for single-family houses, but is less common in multi-storey apartment buildings. In recent decades, wood has shown signs of increased market penetration in many European countries; for example, in Germany the amount of timber used for construction of one- and two-family houses increased from 8% in 1993 to 11% in 2000. There are large differences between regions within the country and between different types of buildings.

This spatial distribution of wood product use affects the potential GHG benefits of material substitution. Forest growth, wood processing, material use and waste disposal may occur at different sites, and possibly different countries. For example, the international and intercontinental trade in wood-based products and fuels is increasing and there is a large potential for exporting prefabricated wooden buildings, or lumber to be used for wood construction, from forest-rich countries to other regions that predominately use brick or concrete construction. This process would be encouraged by the wider establishment of economic policy instruments for climate change mitigation (such as taxation of carbon emission and fossil fuel use), which economically favor less carbon-intensive materials such as wood [58]. By exporting biomass to be used in applications that result in high CO_2 emission or energy use reductions per unit of biomass, the total CO_2 emission reduction from the available supply of biomass could be increased. For example, the total number of new buildings built per year in Nordic countries is small in relation to the total quantities of biomass potentially available. If the export potential were ignored, the additional biomass would then be used for other uses with lower efficiency of emission reduction, or would be left in the forest. However, if additional biomass were exported and used instead of non-wood buildings in other countries, a larger share of the biomass could gain the higher emission reduction per unit of biomass, thus resulting in a greater overall emission reduction globally.

Science-based conclusions & limitations

As demonstrated previously, there are many options available to reduce carbon emissions both in the way we manage the forest and the way we use products and biofuels. In this article, there are many complexities in attempting to determine best practices and supportive policies for reducing carbon emissions. While there are similarities in impacts across many developed country forests, there are substantial differences in situations across the globe. While afforestation provides a one-time opportunity to increase the carbon stored in forests, sustainably managing forests provides many opportunities to reduce carbon emissions by using wood as a carbon store, while at the same time displacing fossil intensive products and fuels. Many studies have concluded that the largest single mechanism for reducing carbon emissions is substitution, which depends upon how the wood is used [66,69–71]. Situations are substantially different in many developing countries where the infrastructure to use wood structurally may be lacking and most wood is used for heat with the land base competing for food production. While life cycle methods may be appropriate for developing countries, life cycle data are lacking both as they relates to wood processing and forest management and forest structure in most developing countries. Results from developed countries are supported by many requirements to measure and track the impact of forest uses on carbon across every stage of processing. Conclusions including key limitations in data quality include the following.

▪ Necessity of tracking carbon impacts across all linked stages of processing

The goal of reducing GHGs suggests decreasing the use of fossil fuel-intensive products and fuels that provide a one-way flow of GHGs to the atmosphere and increasing carbon storage in other pools, such as growing forests and using forest products and biofuels that displace the use of fossil fuels and fossil-intensive products. Understanding the direct and indirect substitution impacts between fossil fuels and forests is essential to ensure that policy decisions do not result in unintended consequences, such as reducing forest growth or failing to use forest products and biofuels that substitute for fossil-intensive products and fuels. This requires a science-based method to track the carbon through forest regeneration and management and each successive processing stage through product use, and ultimately end-of-life management. Comparing the life cycle inputs and outputs across all stages of processing for an array of alternative forest treatments, processing methods, material/product selection and building design alternatives provides quantifiable measures of performance-improvement opportunities supporting better investments and policies.

▪ Sustainably managed forests provide the opportunity to sustain a maximum rate of carbon absorption

The utilization of wood from the forest determines the leverage by which forest carbon can displace fossil emissions. While maximizing forest growth contributes more wood to utilize, the dominant source of carbon mitigation comes from sustainably displacing fossil emissions through the use of wood since the carbon stored in the forest is a one-time creation and can only contribute to sustainably reducing carbon emissions by harvesting the wood to substitute for other materials.

Table 2. Share of wood construction in one and two family house construction in selected countries or regions.

Country	Share of woodconstruction (%)
USA	90–94
Canada	76–85
Nordic countries	80–85
Scotland	60
UK	20
Germany	10
The Netherlands	6–7
France	4

Data from [68].

▪ Sustainably managed forests are essentially carbon neutral

The life cycle research results accumulated over the last decade does not lead one to assume forest carbon neutrality, rather it demonstrates that the emissions from burning biomass for energy and the products produced from forest removals are being offset by the sustained growth in forest carbon removed from the atmosphere even after deducting any emissions from unused dead wood left in the forest. Sustainable management is a key element in any 'forest certification'.

▪ Peer-reviewed LCI/LCA data are available

Life cycle inventory data have been collected and reviewed and are available, such as the US DOE NREL LCI database for both forests and mill processing as well as for fossil fuels and fossil-intensive products. LCA comparisons to alternative fossil-intensive uses demonstrate how to achieve improved environmental performance with reduced GHG emissions. Life cycle data also provide measures of the alternative/substitute materials that are displaced, including the volume of renewable biofuel produced that displaces non-renewable fossil fuels and their emissions.

▪ Counterproductive incentives/carbon exchanges

Carbon exchanges, regulations and incentives differ across countries but frequently reward one or more carbon pools independently resulting in counterproductive impacts on carbon emissions from other pools. Obvious examples include:

- Carbon exchanges that incentivize not harvesting, which can contribute to greater emissions from using more fossil fuels than can be offset by increasing forest carbon stores;
- Ignoring substitution of wood for fossil fuel intensive products since it is difficult to measure even though it has the highest potential leverage in reducing emissions;

- Incentivizing low valued fuel substitutes such as ethanol that will divert feedstock from higher leverage displacement options such as composite wood products;
- Regulations that do not properly distinguish processing differences such as considering biogenic boiler emissions no different than fossil emissions ignoring that biomass carbon was being absorbed by the forest at the same rate as it was being burnt for energy;
- Renewable fuel requirements for utilities that divert feedstock from higher leverage uses.

There are many options to reduce carbon emissions

Carbon-storage options include:

- Storing carbon in the forest, knowing that ultimately, the rate that carbon is removed from the atmosphere through net new growth will slow down, and in the event of a disturbance may emit more carbon than if harvested;
- Sustainably harvesting wood from the forest before growth slows down and storing the carbon in wood products while offsetting fossil fuel consumption;
- Reducing fire risks in unmanaged forests by thinning, while also producing biofuels and carbon stored in wood products, which also avoids many costs incurred in fighting fires and rehabilitating the land;
- Investing in shorter rotation and higher yielding crops as well as developing lower cost collection technologies to collect and process smaller trees and forest residuals.

Processing options include:

- Using more renewable fuels;
- Increased recycling and collection of wastes for at least their fuel value;
- Reallocation strategies that target reductions in the highest fossil emission intensive products. End-of-life options include recycling and recapturing the energy value in wood products to replace fossil energy;

Construction and design options include:

- Codes that are based on integrated life cycle impacts;
- Using products and processes that produce the least amount of carbon emissions;
- Incentives that increase the cost of every product proportional to its carbon emission intensity can motivate the efficient use of every grade of wood fiber where it can have the greatest impact.

Landfill emissions are a waste management problem that can be improved

While the data quality for landfill emissions is poor and not well linked to the time that waste is deposited in the landfill, the substantial emissions of methane from oxygen constrained decay in the landfill can offset carbon stores from biomass waste. While recapture of methane released from landfill for its energy value is improving, biomass waste recapture for energy or product recycling is also improving reducing the need for landfill. Best forest and product management choices for carbon mitigation do not depend upon the carbon stored in the landfill except perhaps to increase recycling.

Soil carbon & biomass growth productivity can be increased

While there is little evidence of a loss in soil carbon for different sustainably managed forest rotations, where there are nutrient deficiencies fertilization can increase both aboveground and belowground productivity, thus reducing net carbon emissions by increasing carbon stock in standing biomass and forest soils, as well as increasing the supply rate of biomass for material and fuel substitution.

The energy required & emissions produced to collect biomass currently left in the forest is low

Removal of merchantable wood contributes only approximately 7% to processing energy requirements, and their carbon equivalent emissions as little as 1% of the total carbon stored in the wood removed. Similar results can be expected for the collection of low-grade forest residuals and other wastes when carbon values are high enough to offset the collection costs, which will also produce new rural economic activity. European experience shows that fossil fuel energy inputs for recovering and transporting harvest residues are approximately 3–5% of the available energy in the recovered biomass. The carbon emissions from biofuel-collection activities will only be a small percentage of the fossil emissions displaced. However, the low cost of fossil fuels minimizes the opportunities to economically collect biofuels, especially in North America in the absence of internalizing a cost of carbon emissions.

Supply responses with higher carbon values

Forest supplies can increase substantially with low cost incentives and have already increased through improved forest regeneration technology on industrial lands. It is the comparatively low cost of fossil fuels that limits the collection of forest residuals or other wood wastes that could be used for energy. If price changes or other incentives result in supply responses that go beyond this low cost supply source and compete with resources serving other sectors there may be partially offsetting carbon emissions, such as producing agricultural products from less productive land, and almost certainly from exporting carbon and economic activity across borders where symmetry in incentives or carbon taxes is not achieved.

Supply responses that convert unmanaged forestland to managed forestland

While many forests are underutilized, conversion of some unmanaged lands that provide old forest habitat that has been declining may warrant increased valuations and incentives to maintain old forest habitat as increasing carbon values are competitive with old-forest

Executive summary

Objectives & methods: the global carbon cycle & life cycle data

- The goal of reducing GHGs suggests displacing the one-way flow of GHGs from fossil fuel-intensive products with forest products and biofuels from carbon-neutral forests.
- While afforestation provides a one-time increase in forest carbon, life cycle analysis of all processes where wood displaces non-wood identifies many more opportunities to sustainably reduce emissions.

Carbon in the forest & the impact from many different uses of wood

- Life cycle research demonstrates that the emissions from sustainably produced products or biomass for energy are being offset by the forest carbon removed from the atmosphere.
- Non-wood products can replace every wood product, but most are fossil fuel emission intensive. Meta-data from substitution studies averages 3.9 $KgCO_2$ reduced per Kg of wood used.
- Using sustainably grown wood in the Pacific Northwest to substitute for fossil-intensive products results in a total carbon trend increase of 4.2 tC/h/y; increasing to 9.7 tC/h/y for direct wood versus steel joist substitution; or 2.9 tC/h/y when wood is used exclusively as a biofuel, the lowest leverage yet still effective use.

Forest residuals & fire reduction carbon-mitigation opportunities

- Accessibility studies show that as much as 24% of aboveground carbon could be accessible for biofuel feedstock; four-times the bioenergy currently being used in processing mills.
- Scandinavian countries with carbon taxes are far ahead in utilizing forest residuals.
- Using forest residual biomass as feedstock for utilities produces only 4% of the emissions from coal.
- A continuation of recent US public forest fire rates will result in carbon emissions from unmanaged and overly dense forests. Thinning treatments can restore forest health and double carbon stores.

Data gaps & uncertainties

- Landfill carbon stores, while uncertain, are projected to increase with little impact on management and wood-use strategy, except to motivate increased recycling and energy recapture.
- Soil carbon changes little under sustainable rotations, however increased fertilization to reduce nutrient deficiencies increases above and belowground carbon consistent with commercial management objectives.

Consequential life cycle analysis

- Attributional life cycle data can be collected down to the individual component level identifying opportunities for improvement in material selection design and processing methods.
- General equilibrium economic models can estimate consequential life cycle impacts including indirect impacts but only for broad sectorial changes of limited value in design and product selection.
- Increasing carbon values may encourage conversion from no-management to short rotations raising the opportunity cost to maintain old forest sensitive habitat provided on public lands.
- Carbon exchanges, regulations and incentives differ across countries but frequently ignore interactions across carbon pools resulting in many unintended and counterproductive impacts.

Comparisons across international research

- There are similarities in research methods and findings across the globe in spite of substantial variability in forests, cultural use patterns and economic conditions.
- Many studies have concluded that the largest single mechanism for reducing carbon emissions is substitution of renewable wood resources for fossil-intensive products.
- European carbon tax methods are contributing to increased use of forest residuals for biofuels reducing emissions and fossil fuel dependence, while also contributing to substitution in construction materials.
- In Sweden, fertilization, use of residuals for biofuels and stem wood for construction materials avoided 3.7 tC/h/y carbon emissions, five-times higher than traditional management using stem wood for biofuel.

Science-based conclusions & limitations

- There are many opportunities to reduce carbon emissions. Forests provide low cost carbon capture and displacement of fossil emissions if and when carbon values or fossil fuel costs increase
- Tracking carbon across every stage of processing can avoid counterproductive policies and support incentives that increase the cost of products proportional to their carbon emissions

habitat. However, it is less costly to manage lands to produce old forest habitat than to depend upon no management. In dry forest areas in particular, historic habitat has been substantially diminished as a consequence of a century of fire suppression resulting in overly dense stands supporting different species. In this case, thinning stands to reduce fire risks will also reduce carbon emissions and restore historic habitat, a unique situation where carbon emission reduction and restoring habitat are complementary.

▪ Forest productivity varies substantially across regions

While there are substantial differences in forests across the globe, the findings from life cycle studies on softwood-growing regions remain quite similar with the high leverage opportunities to use more wood where it can displace the most fossil intensive products. More detailed regional analysis will be required to support the best uses of biomass in each region.

Future perspective

Better policies will be instituted and contribute to carbon mitigation as the benefits of LCI/LCA are more broadly recognized and LCAs more frequently used. Substitution provides the highest leverage, suggesting research on improved products, designs and materials use are good investments for the future. Sustainably managed forests currently provide low cost carbon capture and storage that can be substantially increased. However, prices and/or incentives will have to increase in order to support investments responsive to aggressive mitigation and energy independence objectives. The increased use of renewable resources to reach these objectives will not be achieved, so long as the low cost of fossil emitting alternatives are embedded in current market costs.

Natural variations across forests are large, as are cultural differences across countries requiring more regional and site-specific analyses for credibility and efficient implementation. More effective education on the many unintended consequences flowing from current policy and on the many opportunities that can improve environmental performance will be critical. Efficiency in carbon mitigation and reducing the hidden tax from energy dependence depends heavily on the ability of policy changes to induce higher costs proportional to carbon emission intensity in product uses that will induce improvements in product selection, processes, design, use of residuals and waste, and forest management. Markets will ultimately acknowledge the importance of carbon mitigation through better education on life cycle impacts, resulting in increasing demand for products that improve carbon mitigation.

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