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Determining the Carbon Footprint of Wood

by

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KEYWORDS

carbon, carbon footprint, forestry, life cycle assessment, life cycle inventory, sequestration, wood, wood products

EXECUTIVE SUMMARY

In reviewing the many LCAs conducted on wood products and wood structures, there was a lack of consistency and completeness in the studies. Inconsistencies or information lacking in the reviewed LCI and LCA studies can be grouped into four main categories. In general, these studies

- Did not account for carbon from all five carbon pools as identified by the IPCC (2003).
- Assumed that the global carbon pool is steady.
- Did not verify whether wood came from a sustainably managed forest.
- Varied scopes considerably.

Not All Carbon Pools Are Considered

According to the *IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry*, accounting of the forest stock include five carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon. Most studies limited the scope to emissions related to above-ground biomass considering only the roundwood. The environmental impact of above-ground biomass should include all carbon emissions released due to fertilizer use, road construction, landing sites, logging residue, wood processing, wood processing residue, and transportation. Carbon that is stored in soil and below-ground biomass is significant and should be considered in an LCA of wood.

Current LCA methodology is to consider the sequestered carbon as a net value in the LCI that is shown separately in the reporting of impacts. However the industry's own product category rule

(PCR) allows for the assumption that CO_2 emitted due to the burning of wood products is equal to the wood sequestered by forests during the growing process, that is, a neutral CO_2 balance. It does not require accounting for soil carbon changes due to forest growth or harvest, nor the effect on carbon pools due to below-ground biomass, other above-ground biomass, deadwood, or litter.

Not All Forests Have Equivalent Carbon Pools

A primary premise of carbon-neutrality of wood is based on a steady carbon pool in all forests worldwide. But there is a common misconception that steady deforestation rates equate to steady forest carbon pools. However, a net deforestation rate cannot be used as a sole indicator of the quality of forests.

Between 2000 and 2010, the world total forest area lost is approximately 130 million hectares (321 million acres), which was 3.2% of the total forest area in 2000. According to a recent report from Global Forest Watch, Canada and Russia have become leaders in deforestation, averaging a combined global tree cover loss of 67,337 km^2 (26,000 square miles) each year.

Worldwide, 39% of the frontier forests are under moderate or high threats that can cause declines in wildlife and plant populations or large-scale changes in the age of the forest. The long growth period of wood makes a young forest much different than a mature one in terms of carbon sequestration. Yet there is rarely consideration of the age of a forest when conducting an LCA.

Not All Forests Are Sustainably Managed

Carbon neutrality of wood products is also based on the assumption that the wood comes from a sustainably managed forest. While forest certification is generally growing, it is still a small portion of total acreage accounting for only 25% of the acreage in the U.S. and 10% globally (ASTM 2015). For those forests that are certified to a forest standard, this does not ensure that the forest practices are sustainable.

For example, these programs recognize that techniques and rate of harvesting, road and trail construction and maintenance, and the choice of species affect long-term soil degradation or adversely impact water quality, quantity or substantial deviation from stream course drainage patterns. But current sustainable forestry management schemes currently only monitor, rather than enforce, these practices. Even worse is that these factors are not included in any LCI or LCA rules, schemes, or best practices. Thus the industry realizes that practices affect the environment but do not encourage their inclusion in an environmental assessment or LCA.

Inconsistent Scopes

The life cycle assessments of wood harvesting, wood products, and wood structures have inconsistent scopes. Inconsistencies were most common in the life-cycle stages considered, the intermingling or confusion between biological and industrial carbon, the treatment of sequestered carbon dioxide, the intermingling or confusion between carbon dioxide and carbon dioxide equivalent, and the accounting of carbon offsets (wood material substitution or displacement factors).

In addition, many studies assumed that the carbon flux related to the use of biogenic materials was carbon neutral. But few full life-cycle assessments have been made of energy use and carbon emissions associated with wood products from harvest (including regrowth to preharvesting levels) to disposal that would support that assumption.

Missing Impacts

Although this paper focused on carbon footprint, there are huge environmental issues besides carbon dioxide emissions that should be considered when evaluating the environmental impact of wood. **While the sequestration of carbon makes it favorable to forest products to consider only the carbon footprint, a full assessment should include all significant impacts.** For example, harvesting removes species and not all previous species can be supported in the lack of diversity in the replanted forests.

Another impact missing from LCI studies is human health. Human health effects of burning wood and wood pellets are sometimes considered in terms of particulates. However, many more emissions to air are due to the combustion of wood and biomass including (USEPA 2015):

- Fine particulate matter (PM2.5)
- Carbon monoxide (CO)
- NO_x, VOCs, PAHs, black carbon
- Heavy metals (arsenic, lead, mercury)
- Air toxics such as benzene

Even though some impact categories, such as biodiversity or land use change, can have a large uncertainty due to specific regional differences, and are not included in EPDs yet, it is important that they are included in LCI as best available information to assess the full environmental impact of wood (Grant 2015). **At a minimum, land occupation (in area-years) should be disclosed.**

Research Needs

Accounting for carbon from all five pools. To account for the true environmental impact of wood, all carbon that is affected by wood growth and harvest and use should be accounted for in LCA studies. LCA practitioners, decision makers, and the forestry industry could all benefit from a best practice guide on how to account for carbon from all five carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon.

Disclose wood source and deforestation rate. There should be a requirement to disclose wood source and deforestation rate from the source location in LCA. This would ensure the reader that the five carbon pools were considered in the study, and that the carbon emissions and sinks are calculated or estimated rather than assumed.

Consider age and rotation of trees. A requirement to consider age and rotation of trees in LCA would be useful. Different species and ages of trees sequester carbon dioxide at different rates, and older trees sequester much more than younger trees.

Model forest management activities. LCA practitioners would benefit from basic framework for modeling forest management activities in LCA. Understanding forest management activities may seem daunting, however a basic framework would facilitate the practitioner including these activities in LCA studies of wood.

Consider upstream impacts. Forest management activities should be included in life-cycle stage A1. Yet, full consideration of these impacts is rare in current LCA studies of wood. There should be a mandatory requirement to consider the upstream (forest management) impacts.

Report sequestered carbon separately. Sequestered carbon should be reported separately in LCA studies. This should be considered a best practice and promoted among LCA practitioners. The sequestered amount needs to be shown separately from carbon emissions so that practitioners know how much carbon dioxide is released back to the atmosphere when the wood reaches the end-of-life stage.

Study of impact with and without harvesting. A study of impact with and without harvesting is needed with the do-nothing scenario as a base case. Sampson and Hair found that that the 25-year-old forest sequesters about 1.1 kg (2.5 lb) of CO_2 per tree per year, while the 120-year-old forest sequesters about 2.7 kg (6 lb) per tree per year (Sampson and Hair 1996). As a simple thought experiment, assuming the increase in sequestration is linear, harvesting at 25 years (which common practice in the Southeast) eliminates the opportunity for the tree to sequester an additional 170 kg (380 lb) of carbon if harvested at 120 years. If the tree were harvested at 220 years, which is well within the natural lifespan of the tree, an additional 430 kg

(940 lb) of carbon could be sequestered. Using this approach, each tree harvested causes a negative carbon sequestration of over one-half tonne (1/2 ton) of CO_2. Of course, this is a simplistic approach and more needs to be done to have better estimates of the foregone sequestration due to early harvest.

Create regional LCI data for forest products. The often-cited reason for not including using biodiversity, land use, and other forest management impacts has been that these vary regionally and the regional data are not available. Regional data is not available for much of other LCI—just consider the lack of data for manufacturing materials and products in China. **For forest products, as a start, regional data could be developed for the Pacific Northwest and the southeastern U.S. and for Canada.** Many of the studies referenced in this paper have some process data for these regions. Proxy data should be used and is generally better than no data at all. If proxy data or the regional data are not correct, it will motivate the development of more accurate data, as has been the case for many product manufacturers.

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DEFINITIONS

Table. Definitions related to woody biomass

Terms and phrases	Definition	Source
Bark	Organic cellular tissue that is formed by taller plants (trees, bushes) on the outside of the growth zone (cambium) as a shell for the wooden body.	(FAO 2004)
Biomass from pre-commercial thinnings	Stems, branches, bark, needles/leafs.	(Vis, et al. 2010)
Black liquor	Alkaline spent liquor obtained from digesters in the production of sulfate or soda pulp during the process of paper production, in which the energy content mainly originates from the content of lignin removed from the wood in the pulping process.	(FAO 2004)
Cable yarding	The process of moving logs to a landing through a series of cables stretched from the road to the end of a harvesting corridor	(Johnson, et al. 2005)
Commercial thinnings	Selective cuttings in middle age and maturing stands, a part of felled trees have value for wood processing industry, mainly as pulpwood.	(Vis, et al. 2010)
Cutter chips	*Wood chips* made as a by-product of the wood processing industry, with or without bark.	(FAO 2004)
Feller-buncher	A cutting device mounted on a woods tractor that travels through the stand to cut and bunch trees	(Johnson, et al. 2005)
Felling	Severing the standing tree from the stump	(Johnson, et al. 2005)
Forest	Land with tree crown cover (or equivalent stocking level) of more than 10 percent and area of more than 0.5 ha (1.24 acres). The trees should be able to reach a minimum height of 5 m (16.4 ft) at maturity in situ. May consist either of closed forest formations where trees of various storys and undergrowth cover a high proportion of the ground; or of open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10 percent. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10 percent or tree height of 5 m (16.4 ft) are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest. Includes: Forest nurseries and seed orchards that constitute an integral part of the forest; forest roads, cleared tracts, firebreaks and other small open areas within the forest; forest in national parks, nature reserves and other protected areas such as those of special environmental, scientific, historical, cultural or spiritual interest; windbreaks and shelterbelts of trees with an area of more than 0.5 ha (1.24 acres) and a width of more than 20 m (65.6 ft). Rubberwood plantations and cork oak stands are included. Excludes: Land predominantly used for agricultural practices. [Note: Since the FAO definition includes "plantations," tree	(FAO 2000)

	farming activities in North America are presumed to be considered forests.]	
Forests available for wood supply (FAWS)	Forest where any legal, economic or specific environmental restrictions do not have a significant impact on the supply of wood. Includes: areas where, although there are no such restrictions, harvesting is not taking place.	(Vis, et al. 2010)
Frontier forest	Large, intact natural forest ecosystems that are relatively undisturbed and large enough to maintain all of their biodiversity, including viable populations of the wide-ranging species associated with each forest type.	(World Resources Institute 1997)
Logging residues	Woody biomass by-products that are created during harvest of merchantable timber. Note: Logging by-products include tree tops with branches and they can be salvaged fresh or after seasoning	(FAO 2004)
Lump wood residues	Cut-offs created during sawing of timber.	(Vis, et al. 2010)
Manual felling	Felling operations done by a person operating a chainsaw	(Johnson, et al. 2005)
Other wooded land	Land either with a tree crown cover (or equivalent stocking level) of 5 to 10 percent of trees able to reach a height of 5 m (16.4 ft) at maturity in situ; or a crown cover (or equivalent stocking level) of more than 10 percent of trees not able to reach a height of 5 m (16.4 ft) at maturity in situ (e.g. dwarf or stunted trees) and shrub or bush cover. Excludes: Areas having the tree, shrub or bush cover specified above but of less than 0.5 ha (1.24 acres) and width of 20 m (65.6 ft), which are classed under "other land"; Land predominantly used for agricultural practices.	(FAO 2000)
Pre-commercial thinnings	Selective cuttings in young stands, felled trees have no value for wood processing industry.	(Vis, et al. 2010)
Sawdust	Fine particles created when sawing wood.	(FAO 2004)
Slabs	Parts of *woody biomass* created when cuts are made into the edges of logs and whereby one side shows the original rounded surface of the tree, either completely or partly, with or without *bark*.	(FAO 2004)
Stemwood	Part of tree stem from the felling cut to the tree top with the branches removed, including bark. Part of the tree that is the main product of forests. Also known as roundwood.	(Vis, et al. 2010)
Stumps and roots	Parts of the whole tree volume, which exclude the volume of the above-stump woody biomass. The height of the stump is taken to be that at which the tree would be cut under normal felling practices in that country or region. Excludes: Small roots.	(FAO 2000)
Thinning	Selective cuttings from forest stands	(Johnson, et al. 2005)
Trees outside forests	Trees on land other than forest or other wooded land. Includes: Trees on land that meets the definitions of forest and of other wooded land except that the area is less than 0.5 ha (1.24 acres) and the width is less than 20 m (65.6 ft); scattered trees in permanent meadows and pastures; permanent tree crops such as fruit tree orchards and coconut palm plantations; trees in parks	(FAO 2000)

	and gardens, around buildings, in hedgerows and in lines along streets, roads, railways, rivers, streams and canals; trees in shelterbelts and windbreaks of less than 20 m (65.6 ft) in width and 0.5 ha (1.24 acres) in area.	
Wood chips	Chipped woody biomass in the form of pieces with a defined particle size produced by mechanical treatment with sharp tools such as knives. Wood chips have a subrectangular shape with a typical length 5 to 50 mm (0.2 to 2 in.) and a low thickness compared to other dimensions.	(FAO 2004)
Wood processing industry by-products and residues	Woody biomass by-products originating from the wood processing industry as well as the pulp and paper industry.	(Vis, et al. 2010)
Woody biomass	The mass of the woody parts (wood, bark, branches, twigs, stumps and roots) of trees, alive and dead, shrubs and bushes, measured to a minimum diameter of 0.01 in. (0 mm) (d.b.h. [diameter at breast height]). Includes: Above-stump woody biomass, and stumps and roots. Excludes: Foliage.	(FAO 2000)

Table. Other relevant definitions related to forest biomass

Item	Definition	Source
Biomass expansion factor	Multiplication factor that expands growing stock, or commercial round-wood harvest volume, or growing stock volume increment data, to account for non-merchantable biomass components such as branches, foliage, and non-commercial trees.	(IPCC 2003)
Fuel wood	Stemwood and branches used as a fuel.	(Vis, et al. 2010)
Growing stock	The living tree component of the standing volume.	(FAO 2000)
Industrial wood	Wood, of which quality satisfies quality requirements of the wood processing industry (paper and pulp industry).	(Vis, et al. 2010)
Net annual increment	Average annual volume over the given reference period of gross increment less that of natural losses on all trees to a minimum diameter of 0 cm (0 in.) (d.b.h. [diameter at breast height]).	(FAO 2000)
Non-industrial wood	Wood, of which quality does not correspond to quality requirements of the wood processing industry (pulp and paper industry, sawmills, construction).	(Vis, et al. 2010)
Recovery rate	Ratio of collected biomass to volume of biomass available for collection.	(Vis, et al. 2010)
Standing volume	Volume of standing trees, living or dead, above-stump measured overbark to top (0 cm [0 in.]). Includes all trees with diameter over 0 cm (d.b.h. [diameter at breast height]). Includes: Tops of stems, large branches; dead trees lying on the ground that can still be used for fibre or fuel. Excludes: Small branches, twigs and foliage.	(FAO 2000)
Surplus of stem wood	Unutilized part of the net annual increment that can be potentially used for energy in a sustainable way.	(Vis, et al. 2010)
Wood fuel	A fuel made of woody biomass: wood chips, pellets, briquets, chopped wood, etc.	(Vis, et al. 2010)

ACRONYMS

ATFS = American Tree Farm System

CSA = Canadian Standards Association

CITES = Convention on International Trade in Endangered Species of Wild Fauna and Flora

CORRIM = Consortium for Research on Renewable Industrial Materials

EBN = *Environmental Building News*

FAWS = Forests available for wood supply

FSC = Forest Stewardship Council

ILO = International Labour Organization

IPCC = Intergovernmental Panel on Climate Change

ILO = International Labor Organization

LCA = Life-cycle assessment

LCI = Life-cycle inventory

OSB = Oriented strand board

RPA = Resources Planning Act

SETAC = Society of Environmental Toxicology and Chemistry

SFI = Sustainable Forestry Initiative

WHO = World Health Organization

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by Emily Lorenz,[*] Martha VanGeem,[†] Ke Li,[‡] Thomas Lawrence,[§] and Rita Schenck[**]

Introduction

When assessing the environmental impact of wood, it is challenging to achieve a clear understanding based on the numerous studies that are available. Although some studies conclude that using wood is preferable to other materials under certain conditions, or while evaluating a limited set of environmental impacts, the published studies lack consistency in scope, transparency, and conclusions.

Policymakers, life-cycle assessment (LCA) practitioners, architects, and others are interested in knowing the true environmental impact of using or substituting wood products. However, these

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assessments can't be made without understanding the upstream impacts, the impacts related to use (including any supplementary materials to ensure functional equivalency), and the emissions created at the end of life due to incineration, energy recovery, or waste disposal in a landfill. The overall environmental impact of harvesting trees and converting them to wood products or burning them for fuel needs to be understood (Ingerson 2009).

LCAs of wood products have been conducted with discrepancies in terms of the scope and boundary definition, data quality, inventory construction with co-product/byproduct allocation, and impact analysis methodology. Thus, caution needs to be taken when comparing or interpreting these studies.

Global forest pools. A primary premise of carbon-neutrality of wood is based on a steady carbon pool in forests worldwide. But, the carbon dioxide and methane emissions during the deforesting process are also not well understood. Variation in deforestion among countries exists and some regions, such as Africa, Latin America, and Asia, are facing a near-term crisis due to deforestation. Even though the worldwide deforestation rate is declining, it does not represent the deterioration of the quality of forests. There are 4 billion hectares (9.9 billion acres) of forest coverage in the world, only about 1.3 billion hectares (3.2 billion acres) are considered frontier forest (FAO 2010). Frontier forests are largely undisturbed natural forest ecosystems that are able to maintain their biodiversity. Put another way, of the 4 billion hectares (9.9 billion acres) of forest coverage, over two-thirds have been disrupted by anthropogenic influence.

Are wood products carbon neutral? A majority of existing life-cycle inventory (LCI) or LCA studies start with the assumption that wood products are carbon neutral (Johnson 2008). These studies go on to reaffirm the premise of carbon neutrality by calculating the amount of carbon dioxide that can be sequestered in trees (assuming that carbon pools in the forest are steady) and then balancing that with the carbon dioxide emissions that are released into the atmosphere upon end-of-life (disposal in landfill or incineration), that is, a net flux of zero (Johnson 2008). Beginning with this assumption does not accurately calculate the carbon entering and leaving the system boundary.

Researchers also reach the conclusion that wood products are carbon neutral not because wood products have zero or negative emissions at the end-of-life stage. Instead, an accounting practice that is common with wood studies is to show the credit gained by replacing other materials with wood products (net negative emissions at end-of-life). If only forest stock and wood product stock are considered (not including offset emissions from replacement of fossil-fuel sources), wood products are not carbon neutral.

As a technical matter, it is more appropriate to evaluate net carbon emissions by calculating the photosynthetic sequestration as negative carbon emissions to the atmosphere. Then, all releases for all other processes that release carbon to the atmosphere are treated as positive carbon emissions. Much (perhaps the majority) of the photosynthetic sequestration of trees is transferred to sub-surface biomass, either roots or microorganisms, but reliable data are not available to quantify this sequestration effect, and consequently it is ignored in LCA studies.

Approach

This paper begins with an explanation of the steps involved in establishing a forest, including practices specific to different regions of the world. This is followed by a generic description of the timber manufacturing process. A discussion of sustainable forestry, global forest stock, and rates of deforestation are presented as related to the status of global carbon pools. Best practices related to LCA, including various guidance for performing LCA on forest products, are given next. A literature review of LCAs of wood products is offered, which is concluded by recommendation of best practices to ensure the assessment and transparent presentation of the true environmental impact of wood products.

Limited LCA that only assesses one environmental impact are not generally recommended or useful when evaluating sustainability. However, this paper focuses on carbon dioxide emissions, carbon dioxide equivalents, or global warming potential primarily. This is due to the overwhelming amount of information produced on this environmental impact category or emission only, and the likewise lack of information on any other environmental impact categories. Where possible, mention of additional environmental impacts is included, but they are not the main focus of this paper.

In this paper, the term carbon refers to the different states of carbon in the life cycle of a tree or wood product. Initially, carbon dioxide is absorbed in living trees. That carbon dioxide is converted to organic carbon during the process of photosynthesis, and is stored in all parts of the tree. At the end of life of the tree, that carbon is re-released into the atmosphere as methane or carbon dioxide when the tree or any portion thereof is burned or decomposes.

The Assessment and Recommendations section of this paper provides a summary of findings and recommendations for future research.

FORESTRY INDUSTRY OPERATIONS

There are differences in the process of growing a tree depending on whether the forest is managed (or otherwise impacted by human intervention) or it is natural. In the natural cycle, a seed is released from an older tree that embeds in the forest floor. Given that right conditions of moisture, nutrients, and adequate sunlight, the seed will grow steadily into a tree. As the tree grows and becomes larger, it continues to sequester the more carbon annually.

In a managed forest, the basic steps in the life cycle of a tree are the same; it is only the order, frequency, or intensity of the steps that change depending on the management strategy (Johnson, et al. 2005). The life cycle begins with the development of seedlings, typically in a greenhouse, then preparation of the site for planting of a seedling. After establishing a forest stand through site preparation and planting, the forest stand must be treated until it reaches harvest maturity. Steps in the treatment process can include thinning and fertilization.

During harvest in both natural and managed forests, trees are felled, processed, loaded, and transported to a processing facility. These steps, as well as differences in regional and worldwide practices, are detailed in the following sections.

Establishing a Forest Stand

Acres of land may be planted at one time, and seedlings planted by hand or machine, depending on the sophistication of the forest manager. Where a forest stand has been cleared, seedlings may be planted without the use of any kind of tilling. Fertilization may or may not be applied at planting. Some forest stands are seeded naturally by leaving a few trees unharvested to provide a source of new trees.

Treating Forest Stands until Harvest

Many different techniques can be employed to hasten or encourage the growth of the trees. In commercial forests, it is common in evergreen stands to selectively cut trees in young forest stands (also known as pre-commercial thinning). The trees felled during these thinnings typically have no value in the timber industry (Vis, et al. 2010). Once a stand is more mature, commercial thinnings fell trees that have some value, usually as pulpwood (Vis, et al. 2010).

Fertilizers can also be applied to encourage growth in the forest stands. Typical fertilizer mixtures include different proportions of nitrogen, potassium, and phosphorus (Johnson, et al. 2005).

When treating a forest stand, the forest management intensity is typically related to fertilizer application frequency and number of pre-commercial thinnings. The management intensity also differs depending on the region where the forest stand is located. Various equipment can be used to apply fertilizer to the stands, with helicopter use common.

Harvest

All parts of the tree, except the foliage, are considered woody biomass. No matter how the tree gets to its harvest time, the process for harvesting trees is similar. Roads and landing sites must be constructed in or near the forest stand. Trees are felled, either by a feller-buncher or through manual felling. Trees are then processed by stripping them of branches, twigs, and foliage, which is known as logging residue, on site. Logging residue can remain in place, be removed at the site that the tree is felled, or it can be hauled to a central location at the harvest site for processing (Johnson, et al. 2005).

Transportation is required on site to move felled trees to a loading point. This can be accomplished through skidding or cable yarding.

The main wood product, trees without limbs and tops, is then called stemwood (or roundwood). Stemwood is hauled to a central place where it is loaded on to logging trucks to be transported to a manufacturing facility. Primary equipment used during skidding, loading, or transporting on site are skidders, front loaders, or tractors (Eshun, Potting and Leemans 2012). Most stemwood is first sent to a timber industry facility (or a sawmill) to create dimension lumber or other solid-wood products.

After the stemwood is transported out of the forest, the logging residue is either transported off site for further processing (such as energy recovery as fuel at saw mills) or incineration (burned as waste at a facility), or is burned in place or left to decompose on site (Ingerson 2009).

All the carbon dioxide emissions released due to fertilizer use, road construction, landing sites, logging residue, and transportation should be included in the upstream profile of forest products such as dimensional lumber.

Regional Differences

Southeast United States. In Johnson, et al. (2005), typical forest-stand management strategies for the southeast United States were presented. Due to the fairly gentle-sloping or flat terrain, mechanized methods for planting, management, and harvesting are employed most commonly. A small feller-buncher is typically used for pre-commercial thinning, and a feller-buncher is also used for felling during harvest. Whole harvested trees can be transported to a landing using typical skidding techniques where machines are used to process trees into logs. Johnson, et al. (2005) notes that "since whole trees are moved to the landing, the removed carbon from the site includes both the stem and the crown."

Scenarios for different forest management intensities were developed by Johnson, et al. (2005) using the U.S. Forest Services Resources Planning Act (RPA) allocation. In the southeast United States, a high-intensity forest management scenario includes "fertilization every 4 years over the 25-year life of the stand." **Fertilization occurs at years 2 and 16 for the medium-intensity scenario.**

Pacific Northwest United States. In the Pacific Northwest of the United States, treatment and harvesting are more likely to occur on steep terrain, thus trees are typically processed at the location where they are felled for easier transport of the logs to the transport location (Johnson, et al. 2005). Manual felling is usually employed, and a person operating a chainsaw also removes limbs and treetops. The trees or logs are typically transported to a landing using cable-yarding. "Since limbs and tops of the trees are left on the site, **removed carbon for Pacific Northwest systems includes only the carbon associated with the stem** (Johnson, et al. 2005)."

Still using the U.S. Forest Services RPA allocation, a high-intensity and medium-intensity forest management scenarios for the Pacific Northwest United States, developed by Johnson et al. (2005), include "**fertilization at years 20, 30, and 40 and pre-commercial thinning at year 15.**"

Non-industrialized Nations. As an example, about 80% of the timber in Ghana comes from natural, unmanaged tropical forests (Eshun, Potting and Leemans 2010), so there is no human intervention related to establishing a forest stand or managing it until harvest. This also means that forests in Ghana are being depleted (Eshun, Potting and Leemans 2012), but that topic will be discussed in detail in another section.

At harvest, trees are felled and tree branches are removed with chainsaws at the felling location. Trees are then skidded to a central processing location where they are loaded to be transported to a manufacturing facility. Juvenile or damaged trees and logging residue are typically left in the forest (Eshun, Potting and Leemans 2012).

TIMBER INDUSTRY OPERATIONS

Forest products can be transformed into many different timber-industry products: dimension lumber (air-dried or kiln-dried), plywood or oriented strand board (OSB), engineered-wood products, veneer, paper, or furniture (Eshun, Potting and Leemans 2010; Eshun, Potting and Leemans 2012; Gower, et al. 2006; Ingerson 2009). This paper will focus primarily on dimension lumber, but references to other products may be necessary.

Either at the harvest site or in the log yard, all products are sorted initially by quality and size according to whether it is sufficient for dimension lumber and furniture, or that it more appropriate to be used for plywood, veneer, paper, or other non-solid-wood products. Wood-processing residues and logging residue may be used in the pulp and paper industry, may be used as fuel, or may be taken to a landfill. Stemwood is transported to a sawmill for primary processing into dimension lumber.

Primary Processing

At the sawmill, the bark of the stemwood is removed and a combination of head-rig sawing, edging, and cross cutting is used to create dimension lumber (Eshun, Potting and Leemans 2010; Ingerson 2009). Many different types of saws can be employed during primary processing including chainsaws, band saws, frame saws, radial saws, or circular saws (Eshun, Potting and Leemans 2012). The dimension lumber is then air or kiln dried. In the U.S., virtually all lumber used for buildings is kiln dried, with a recommended moisture content of 19% or less for framing lumber (Simpson 1999). Industry recommendations are to dry wood to a moisture content that is equivalent to that average moisture content that it will be exposed to at service.

During this primary processing, wood-processing residues are created. Some of these residues include sawdust, bark, cutter chips, wood chips, or lump wood residues. The amount of residue that is created varies greatly depending on the equipment used and the final product (Ingerson 2009). For example, less sawdust is created with each cut by a thinner blade than a thicker one.

All the carbon dioxide emissions released due to wood processing, wood processing residue, and transportation should be included in the upstream profile of forest products such as dimensional lumber.

SUSTAINABLE FORESTRY

One of the basic premises behind the assumption of carbon neutrality of wood products is that the wood comes from a sustainably managed forest. The problem with that assumption is that "**ninety percent of the world's forests are not certified** to any forest standard (Sustainable Forestry Initiative 2015." According to 2016 Census data through May 2016 as well as 2015 Census data, approximately one-third of forest product imports to the U.S. come from Indonesia, 10% from Thailand, and 10% from China (USCB 2016).

In response to a memo from acting assistant administrator for the Office of Air and Radiation, Janet McCabe, on November 19, 2014 (McCabe memo), which credits the use of woody biomass for energy as reducing emissions, a group of 78 scientists warn of the precedent set by treating woody feedstock as carbon free. In the McCabe memo, it is proposed that all wood from sustainable forest can be treated as carbon free. The scientists state, "At maximum, 'sustainability' implies that forest harvesting does not exceed growth, which is a necessary, but not sufficient condition for carbon neutrality, as found by the SAB [scientific advisory board]. At minimum, sustainability practices can help reduce soil erosion and other environmental impacts of forestry or agricultural production (Aneja, et al. 2015)."

Forestry management practices play a role in the sustainability of carbon sequestration contributions. "**Management regimes that reduce the standing stock of timber, even if they produce a sustainable flow of timber over time, will have smaller GHG benefits than regimes that maintain high stand volumes** (Ingerson 2009)."

"Harvest operations can affect soil and forest floor carbon stores through physical disturbance. Surprisingly little is known about these effects, but in general, logging can be expected to reduce forest floor carbon. Early research by Covington (1981) indicated that forest floor biomass decreased by half during the 15 years following clear-cutting of northern hardwood stands, presumably due to faster decomposition and reduced deposition of litter (Ingerson 2009)." **Logging activities release a lot of carbon into the atmosphere that is not captured and stored in wood products** (Heiken, Jelen and Stevens 2008)**.**

Forest degradation and land-use change are responsible for 20% of recent anthropogenic carbon emissions (Ingerson 2009).

When analyzing the carbon storage potential of a forest, most tools focus on the big trees (crop trees). But there is a tremendous amount of carbon that is contained in the old-growth forest ecosystem, including "dominant trees, minor tree species, shrubs and forbs, dead wood and snags, soil organic matter, and other wildlife (Heiken, Jelen and Stevens 2008)."

"**For older forests with a low risk of major disturbances, conversion to young, fast-growing forest will cause large amounts of GHG [greenhouse gas] emissions as the old stand is removed . . . and it may take decades or even centuries for a sustainable harvest regime to work off this initial carbon debt** (Ingerson 2009)**.**"

Only a small percentage of wood removed from forests ends up as durable goods or construction products. According to one study, as little as 15% of the initial carbon stored in a live tree is retained in forest products (Heiken, Jelen and Stevens 2008). Most wood ends up as waste or non-durable goods (paper and pallets). Logging kills trees, which stops them from storing carbon and stops them from transferring carbon to the soil**.** Logging accelerates decomposition rates by removing forest canopy and raising soil temps. **Logging debris is frequently burned, which immediately releases carbon to the atmosphere.** Logging practices also increase the risk of forest fire; logging releases more carbon than forest fires (Heiken, Jelen and Stevens 2008). Soot created during burning also has the added detrimental effect of depositing black carbon on glaciers and ice sheets, which can accelerate their melting.

The question is how do we ensure sustainable forestry practices? In the U.S., there are two prominent schemes for evaluating sustainable forest management, yet **it is unclear whether these programs ensure sustainable forestry (taking into all of the issues previously cited).** One is the program developed by the Forest Stewardship Council (FSC) and the other by the Sustainable Forestry Initiative (SFI). Both programs are presented in more detail in the Appendices.

"Chain of custody," or documentation of the source of the forest product, is necessary so that the LCI practitioner and consumer can determine the source of the forest product. For example, forestry practices in the U.S. and Canada are generally considered better than those in some developing countries. Knowing the source of the forest product will help ensure that products from countries with non-sustainable forestry practices will not be considered to have the same life-cycle impact as those products manufactured in countries that use sustainable practices.

Sustainable Forestry Scheme Comparison

Internationally, forest certification systems are generally recognized when they comply with FSC or a standard endorsed under the Program for the Endorsement of Forest Certification schemes (PEFC), which in North America includes the SFI program, the American Tree Farm System (ATFS), and the Canadian Standards Association (CSA). **While forest certification is generally growing, it is still a small portion of total acreage accounting for only 25% of the acreage in the U.S. and 10% globally** (ASTM 2015).

Not all programs are equal, and more recently a number of comparisons of the FSC and SFI programs have become available. One such comparison was provided by *Environmental Building News* (EBN) and is summarized herein (Roberts 2015).

The EBN comparison focused on areas of forestry practice that could create irreversible ecological damage:

- Use of pesticides;
- How old-growth forests are managed;
- Treatment of endangered or threatened species; and
- Allowance of clear cutting.

Pesticides. SFI currently bans chemicals on two World Health Organization (WHO) lists (Type 1A and 1B) that are considered extremely hazardous and highly hazardous, respectively. However, the SFI program allows the use of these chemicals if there is no other alternative. In the SFI program, the forest manager needs to document the reason why no alternative is available.

Alternatively, the FSC also bans WHO Type 1A and 1B chemicals, and additionally its own list of highly hazardous pesticides. FSC also allows the temporary use of these banned chemicals, however, forest managers must apply and be granted an exemption **prior** to using the chemical. In the application for an exemption, the forest manager must explain how it will safeguard the ecosystem and human health.

Old-growth forests. SFI only requires support of conservation programs, which assumes that programs are already available. It also does not require protection of old-grown stands within SFI-certified forests. FSC prohibits harvesting or road construction on old-growth forests.

Species. SFI only requires that timber companies have a program to protect endangered or threatened species. FSC requirements for protecting these species are much more thorough and have specific outcomes. FSC requires foresters to monitor species and maintain or support species recovery goals.

Clear cutting. SFI limits clear-cut areas to 49 hectares (120 acres). FSC limits clear-cut areas to smaller sizes, but also requires protection of natural systems simultaneously. This is missing from the SFI allowance.

GLOBAL FOREST STOCK AND RATES OF DEFORESTATION

Forests are essential for the ecosystem services of the earth. As some of the most important and primary productivities, forests contribute significantly to food and energy security and soil and water conservation. They are the world's largest repositories of terrestrial biodiversity. More importantly, they are vital in mitigating global climate change by serving as carbon sinks. Current forest ecosystems store more carbon than is present in the atmosphere (Ingerson 2009). **Land plants (and the soil they grow on) contain about 10 times more carbon than all the anthropogenic carbon in the atmosphere** (Heiken, Jelen and Stevens 2008).

Deforestation

The assumption that wood products are carbon neutral is based on the assumption that global carbon pools are steady. Throughout history, population growth and increased anthropogenic activities have led to significant deforestation. Since the end of the last great ice age 10,000 years ago, forest coverage of the earth has reduced from 6 billion hectares (15 billion acres) to about 4 billion hectares (10 billion acres). The rate of deforestation reached about 5.2 million hectares (13 million acres) per decade at the beginning of the 21st century (FAO 2010). Before 1950, the pace of deforestation was greater than the population growth rate. Since then, the rate of deforestation has been slowing compared to the population growth rate.

Table 1 summarizes the historical rate of deforestation of tropical and temperate forests. It suggests that the deforestation has decreased, especially for temperate forests. According to the Forest Resources Assessment (FRA) 2010 estimation, **the net deforestation rate at the global level is 0.13% per year between 2000 and 2010** (FAO 2010), which is lower than the rate of 0.20% between 1990 and 2000. However, the absolute value of the deforestation is as large as 5.2 million hectares (13 million acres) per year. In developing countries, tropical forests are "too often used for firewood, resulting in the immediate release of stored carbon (Heiken, Jelen and Stevens 2008)."

Table 1. Estimated Deforestation By Types of Forest and Time Period

Years	Tropical Forest, million hectares (acres)	Temperate Forest, million hectares (acres)
Pre-1700	10 (25)	400 (988)
1700-1849	110 (272)	180 (444)
1850-1919	70 (173)	140 (346)
1920-1949	235 (580)	100 (247)
1950-1979	315 (778)	20 (50)
1980-1995	220 (544)	5 (12)
1996-2010	110 (272)	0

Source: Estimates based on (FAO 2010)

Deforestation rates vary by country. While many countries have been able to stabilize their forest area, **nine countries are experiencing net deforestation rates of more than 2%** (more than 10 times the global rate), which will result in the loss of most of their forests within the century. Latin America lost 88 million hectares (220 million acres) (9%) of forest area from 1990 to 2010 (FAO 2010). African countries lost 75 million hectares (185 million acres) (10%) of their forest area in the same time period. In addition, 20 more countries have net deforestation rates exceeding 1% per year and another 20 have rates of more than 0.5%.

During the period 2005-2010, forest areas were stabilized or increased in 80 countries, which include several of the world's largest forested countries: the Russian Federation, the United States of America, China and India. The positive changes in the deforestation rate were mainly due to the improved forest management and afforestation efforts.

According to a recent report from Global Forest Watch, Canada and Russia have become leaders in deforestation, overtaking more tropical countries like Brazil. The study found that **Russia and Canada combined to make up about one-third of global tree cover loss between 2011 and 2013,** averaging a combined 67,337 km^2 (26,000 square miles) each year. **These Boreal forests act as major carbon sinks, keeping vast carbon reserves out of the atmosphere**, and this loss, primarily attributable to forest fires, is a disconcerting trend for GHG emissions (Phillips 2015). Forest fires can also distribute black carbon on glaciers, accelerating their melting.

Although the deforestation rate is decreasing gradually, the quality of the forests is deteriorating. Between 2000 and 2010, the world total forest area lost is approximately 130 million hectares (321 million acres), which was 3.2% of the total forest area in 2000. The net lost rate of 0.13% was due to the fact that 78 million hectares (193 million acres) were gained from planted forests and natural forest expansion. Therefore, the net deforestation rate cannot be used as a sole indicator of the quality of forests.

The long growth period of wood makes a young forest much different than a mature one. **Planted reforesting usually favors monoculture forest, which decreases biodiversity, causes erosion and sediment pollution,** and results in less attractive landscape (Gronow 2001). Although these modified forests remain to provide important economic and ecological services, they may not support the complex and inimitable ecological communities and processes and cannot sustain themselves in the long term (Gronow 2001).

Five Carbon Pools

In terms of global climate change, frontier forest ecosystems play an irreplaceable role as a carbon sink. According to the Intergovernmental Panel on Climate Change's *IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry*, **accounting of the forest stock includes five carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon** (IPCC 2003)**.** The frontier forests store approximately 433 billion tonnes (477 billion tons) of carbon, which is more than all carbon that will be released from fossil fuel burning in the next 50 years, at the global emission rates at late 1990s (Dixon, et al. 1994). As previously discussed, the environmental impact of above-ground biomass should include all the carbon emissions released due to fertilizer use, road construction, landing sites, logging residue, wood processing, wood processing residue, and transportation.

Addressing below-ground biomass, **harvesting will cause reduction of soil carbon by an average of 8±3%** with a 95% confidence interval (Nave, et al. 2010). **The loss of these forests will cause the releasing of this carbon into the atmosphere as carbon dioxide. This process is irreversible.**

Forest Age

"Old forests store far more carbon than young forests. Most old forests are still growing and absorbing carbon. Mature forests cannot be converted into young forests without losing most of the carbon to the atmosphere (Heiken, Jelen and Stevens 2008)." For northeastern U.S. maple-beech-birch forests, a 25-year-old forest sequesters about 1.1 kg (2.5 lb) of CO_2 per tree per year, while the 120-year-old forest sequesters about 2.7 kg (6 lb) per tree per year (Sampson and Hair 1996).

Part of the reasons that old trees still absorb carbon is that they have to send carbon below ground to maintain the ecosystems that support them. "**Scientists estimate that 45% of all the carbon transferred to the atmosphere by humans has been released due to forest exploitation**. Though forest releases are less than total emissions from all uses of fossil fuels, many would be surprised to find that, in recent decades, **CO_2 emissions resulting from human-**

induced changes to forests exceed CO_2 emissions from the transportation sector (Heiken, Jelen and Stevens 2008)**.**"

In addition, research has indicated that forest age is important in determine carbon pools and fluxes in forested ecosystems. **The net ecosystem productivity of boreal and temperate forest younger than 10 years is -0.1 and -1.9 Mg C ha^{-1}yr^{-1} (-90 and -170 lb C per acre per year) respectively, indicating a source to the atmosphere** (Pregitzer and Euskirchen 2004)**.** On the contrary, the frontier forests contribute at least 10% of the global net ecosystem productivity. The boreal and temperate regions of the Northern Hemisphere were reported to sequester about 1.3 ± 0.5 gigatonnes (1.4 ± .5 gigatons) of carbon per year (Luyssaert, et al. 2008).

In 1997, the World Resource Institute (WRI) reported the significant losses of the frontier forests, which were large, ecologically intact, and relatively undisturbed natural forests (World Resources Institute 1997).

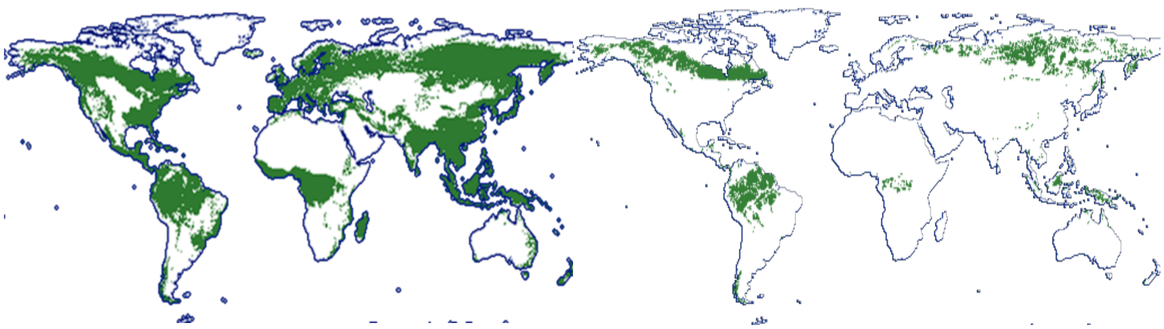

Figure 1. Comparison of the frontier forests coverage on the earth 8000 years ago (left) and today (right) (World Resources Institute 1997).

According to the WRI report, only 22% of the earth's original forest remains in large, relatively natural ecosystems (**Fig. 1**). **Table 2** summarized the total remaining forest and frontier forest worldwide. It is clear that while most regions, except Africa and Asia, have more than 50% remaining forest, approximately 46% of the world's original forests has been converted to farms, pastures, and other uses over the past 80 centuries (World Resources Institute 1997). The converted portion has been heavily altered by people and doesn't resemble a pristine forest.

Table 3 presents human activities that threaten the world's frontier forests including logging, roads and infrastructure, agricultural clearing, and excessive vegetation removal. **Worldwide, 39% of the frontier forests are under moderate or high threats that can cause declines in wildlife and plant populations or large-scale changes in the age of the forest** (World Resources Institute 1997)**.** The largest threats worldwide are logging at 72% and infrastructure at 38%. Regional values vary and are presented in the table.

Table 2. Total Area in Original, Current, and Frontier Forest (World Resources Institute 1997)

	Original Forest (1000 km^2)(ii)	Remaining Forest (Frontier and non-Frontier Forest) (1000 km^2) (ii)	Total Remaining as a % of Original Forest	Total Frontier Forest (1000 km^2) (ii)	Frontier Forest as a % of Total Original	Frontier Forest as a % of Total Remaining Forest
Africa	6,799	2,302	34%	527	8%	23%
Asia	15,132	4,275	28%	844	6%	20%
North and Central America	12,656	9,453	75%	3,909	31%	41%
— Central America	1,779	970	55%	172	10%	18%
— North America	10,877	8,483	78%	3,737	34%	44%
South America	9,736	6,800	70%	4,439	46%	65%
Russia & Europe	16,449	9,604	58%	3,463	21%	36%
— Europe	4,690	1,521	32%	14	0.3%	1%
— Russia	11,759	8,083	69%	3,448	29%	43%
Oceania (i)	1,431	929	65%	319	22%	34%
World	62,203	33,363	54%	13,501	22%	40%

Notes: (i) Oceania consists of Papua New Guinea, Australia and New Zealand (ii) 1000 km^2 = 386 mi^2.

Table 3. Percentage Area of Frontier Forest at Risk of Various Threats (World Resources Institute 1997)

		Percent of Threatened Forest Frontiers at Risk From:				
Region	Percent of Frontier Forest Under Moderate or High Threat (i)	Logging	Mining, Roads, and Other Infrastructure	Agricultural Clearing	Excessive Vegetation Removal	Other (ii)
Africa	77	79	12	17	8	41
Asia	60	50	10	20	9	24
North and Central America	29	83	27	3	1	14
Central America	87	54	17	23	29	13
North America	26	84	27	2	0	14
South America	54	69	53	32	14	5
Russia & Europe	19	86	51	4	29	18
Europe	100	80	0	0	20	0
Russia	19	86	51	4	29	18
Oceania (iii)	76	42	25	15	38	27
World	39	72	38	20	14	13

Notes: (i) Frontier forests considered under immediate threat, as a percent of all frontier forest assessed for threat. Threatened frontier forests are places where ongoing or planned human activities are likely, if continued over coming decades, to result in the significant loss of natural qualities associated with all or part of these areas (for example, causing declines in, or local extinctions of, wildlife and plant populations, or large-scale changes in the age and structure of these forests).
(ii) "Other" includes such activities as overhunting, introduction of harmful exotic species, isolation of smaller frontier forest islands/ through development of surrounding lands, changes in fire regimes and plantation establishment.
(iii) Oceania consists of Papua New Guinea, Australia, and New Zealand.

LIFE-CYCLE ASSESSMENT

LCA is a methodology to quantify the environmental impact of a product or process over its life cycle**. An LCA considers impacts related to all aspects of a product's life cycle—from the first stages of harvesting and extracting raw materials from nature**, to transforming and processing these raw materials into a product, to using the product, and ultimately recycling it or disposing of it back into nature. An LCA that is performed according to ISO 14040 (ISO 2006b) and ISO 14044 (ISO 2006c) includes four iterative steps:

- Goal and scope definition
- Life-cycle inventory (LCI)
- Life-cycle impact assessment (LCIA)
- Interpretation

An LCA of a product compiles environmental impacts due to:

- Extraction of materials and fuel used for energy.
- Manufacture of the product.
- Transportation of the product and any input fuel or materials or output waste.
- Assembly and construction of the product.
- Operation related to the product, including energy and water consumption, maintenance, repair, and renovations.
- Demolition, disposal, recycling, and reuse of the product at the end of its functional or useful life

A reasonably comprehensive set of effects includes land use, water use, biodiversity, resource depletion, climate change (or global warming), acidification, smog formation, ozone depletion, eutrophication, and toxicity.

An LCA involves time-consuming management of large quantities of data. Software such as SimaPro, Open LCA, or Gabi provides calculation engines and links to data for common building materials and options for selecting LCA impacts.

Goal Definition and Scoping

The first step of any LCA process is defining the goal and scope in order to ensure the consistency of the LCA that is to be performed. The most important element to be decided in this stage is to define the functional unit to benchmark the performance of different products. The choice of functional unit is arbitrary. A general practice of wood products LCA chooses a unit area of the product (such as a square feet of sheathing or flooring material), which makes comparing different research results challenging.

The scope definition delineates the boundary conditions within which the data is collected. A general cradle to grave system boundary for a full LCA includes the contents in **Figure 2**.

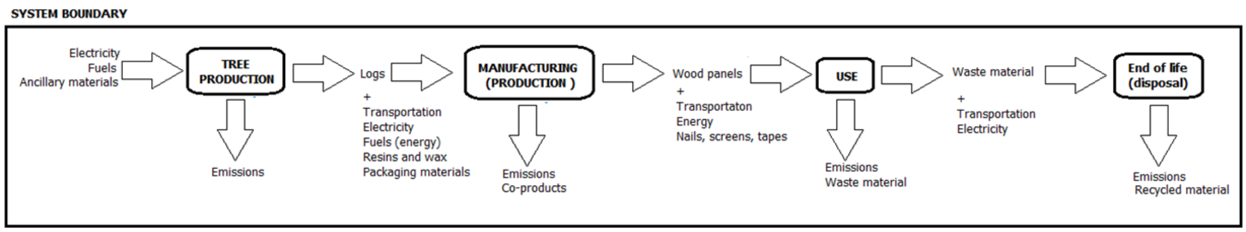

Figure 2. System boundary for a general, cradle-to-grave life-cycle assessment.

Sometimes, a cradle to gate study is performed for the purpose of simplicity, which generally defines the boundary as depicted in **Figure 3**.

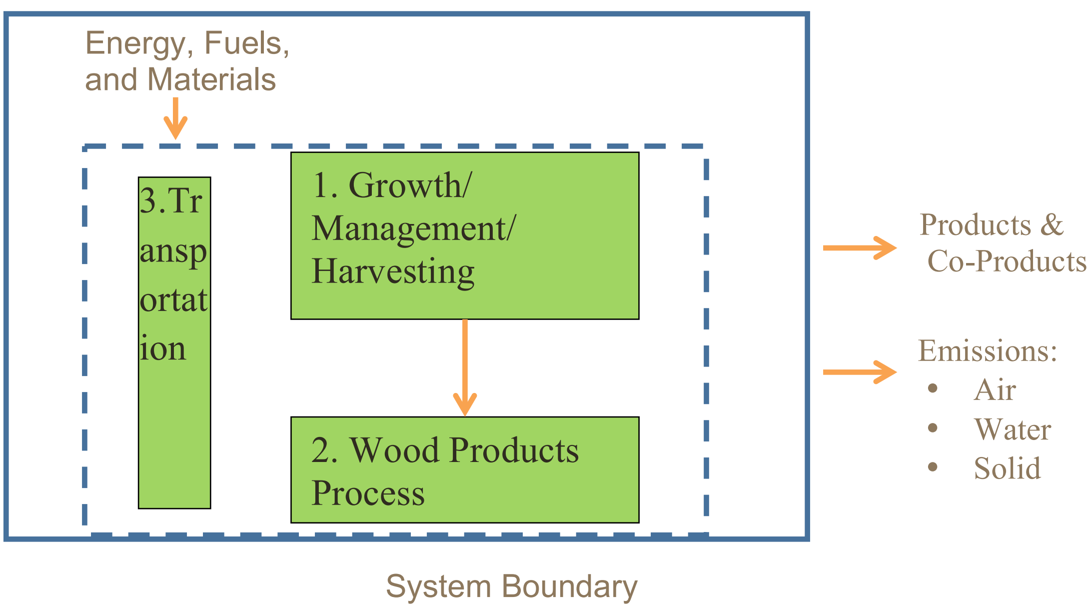

Figure 3. System boundary for a cradle-to-gate life-cycle assessment of a wood product.

In addition to delineating the physical system boundary—what is included and what is not—during scoping, many other decisions are made. For example, the modeling conventions for the electric grid, for allocation of co-products and wastes, for temporal_issues, for data quality, and for filling data blanks are all decided. The audience, the type of report, and the type of review are all determined during scoping. Scoping is an iterative process, in which financial and temporal limitations may require changes in the project.

Life Cycle Inventory

The second step of an LCA, the life-cycle inventory, is focused on an accurate material and energy balances for each process step and for the system to be analyzed. An LCI accounts for all the individual environmental flows to and from a product throughout its life cycle. It consists of the materials and energy needed to make and use a product and the emissions to air, land, and water associated with making and using that product. All the material and energy inputs are determined based on the functional unit, which is determined during scoping.

The challenges of constructing an inventory are mainly data availability and handling of co-products. **For example, data collection for harvesting wood in a forest would require the information on all the equipment, engine type, fuel type, and quantities consumed, working times, and emissions into air, water and soil while using any of the equipment, in addition to the issues of soil carbon release, waste wood decomposition or combustion, etc.**

The inventory should also include the previously mentioned five carbon pools in the forest stock: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter, and (5) organic soil carbon. In LCI, when data are limited, the best available data or proxy data should be used.

The data collection process can be unexpectedly complex, taking more resources than any other part of the study. For example, without any input from the technosphere, such as planting or harvesting, an inventory of wood in a forest performed by one of the authors contained 41 inputs from nature, 151 emissions to water, 175 emissions to air, and 20 emissions to soil. Therefore, many inventories are built with some commercial databases, which cause uncertainties in the analysis if not handled with caution.

Impact Assessment and Interpretation

In the next phase of LCA, the LCI data are assigned to impact categories and the effect of the inventory flow within each impact category is characterized. Among LCA practitioners, this phase is called life-cycle impact assessment (LCIA), and it consists of category definition, classification, and characterization. According to ISO 14044 (2006c), the only mandatory steps in life-cycle impact assessment are classification and characterization, and models for characterization are typically developed outside the scope of an LCA. In characterization, factors are assigned according to a substance's contribution to the impact category. Models for each kind of impact are developed (usually outside of the LCA community), and they have been aggregated together into a portfolio of LCIA methods. The U.S.-based portfolio method is Tool for the Reduction of Environmental and Chemical Impacts (TRACI). The TRACI method includes mid-point models because they do not measure impacts at the endpoint (for example, human mortality). Most endpoint models (also called damage categories) require values-based weighting to achieve a score. Midpoint models are more commonly used because the outputs are metrics such as CO_2 equivalent, which are relatively easy to quantify. End point models, which quantify impacts such as toxicity or biodiversity, are more controversial due to the metrics used for quantification, the variation in available data for different materials, or regional variations

In the classification step, all substances in the LCI are sorted into classes according to their impacts on the environment. Some portfolio impact methods have more impact categories than others. For example, Ecoindicator 99 divides the substances into twelve classes: minerals, fossil fuels, land use, carcinogenesis, respiratory effect chemicals, green house gas, ozone depleting chemicals, radionuclides, eco-toxic chemicals, water withdrawal, and acidification and eutrophication chemicals. Once substances are classified into impact categories, they are characterized using characterization factors to create LCIA results. The LCIA results are in units of the impact indicator, and all the LCIA results for a given impact assessment category are added together to provide the LCIA results of that impact category.

Methods such as Ecoindicator 99 further weight the results to achieve an eco-point score. The Intergovernmental Panel on Climate Change (IPCC) GWP method focuses solely on the indicator of global warming potential, measured in CO_2 equivalents. This method is incorporated into all LCIA portfolio models.

Category selection consists of identifying which impact categories are relevant to the product being studied. Classification consists of assigning substances into impact categories. For example, the gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and others contribute to climate change; therefore, they are assigned to the impact category called climate change or global warming, along with the other gases that contribute to climate change. There are many impact categories from which to choose. The categories chosen depend on the goal and scope of the LCA. **Table 4** lists some possible impact categories.

Table 4. Some Impact Categories for Performing a Life-Cycle Assessment

Climate change	Human toxicity, air	Ecotoxicity soil, chronic
Depletion of biological reserves	Human toxicity, soil	Ecotoxicity water, acute
Depletion of fossil reserves	Human toxicity, water	Ecotoxicity water, chronic
Stratospheric ozone depletion	Human Health Carcinogens	Acidification
Eutrophication	Respiratory inorganics	Species extinction
Photochemical smog	Respiratory organics	Noise impacts

In addition to reporting LCIA results for the selected impact categories, LCA studies often report inventory results that are not the result of characterization, but simply add up the inventory results. For example, cumulative energy demand, land occupation, and freshwater consumptive use are all examples of LCI results that are commonly reported in an LCA. Other kinds of inventory results are also sometimes seen, such as the production of hazardous or non-hazardous waste, or the use of renewable and non-renewable energy or materials. These inventory results can be useful to point out opportunities for improvement in the manufacturing process, but if a comprehensive list of impact categories are employed in the study, the impacts of the production of waste is integrated into the LCIA results, and thus reporting these inventory results is a form of double counting of the impacts of a product. As an example, the use of renewable energy will decrease the climate change, fossil fuel depletion, acidification, and eutrophication of the product being studied. The use of recycled materials may or may not decrease the overall impacts of a product, depending on the details of the recycling process.

One can argue that a key impact of forest product production is the occupation of land, since nearly a third of all land is occupied by forests or plantations, and therefore those lands may not be used for other purposes. However, few LCA studies of forest products consider land occupation in their analyses.

LCI Boundary

The usefulness and comparability of an LCA or LCI depends on where the boundaries of a product are drawn. A common approach is to consider all the environmental flows from extraction to deconstruction (including reuse, recycling, and disposal, if necessary).

An upstream profile can be thought of as a separate LCI that is itself an ingredient to a product. For example, the upstream profiles related to dimension lumber is essentially an LCI of forestry operations, which can be imported into an LCI of timber operations, which is then imported into an LCI of the dimension lumber. The LCI of dimension lumber itself can then be imported into an LCI of a product, such as a structure

The LCI of materials generally do not consider embodied energy and emissions associated with construction of manufacturing plant equipment and buildings, nor the heating and cooling of such buildings. This is generally acceptable if their materials, embodied energy, and associated emissions account for less than 1% of those in the process being studied. For example, the Society of Environmental Toxicology and Chemistry (SETAC) guidelines indicate that inputs to a process do not need to be included in an LCI if they

- Are less than 1% of the total mass of the processed materials or product,
- Do not contribute significantly to a toxic emission, and

- Do not have a significant associated energy consumption.

Life-cycle Stages

The naming convention developed in EN 15804 (CEN 2012) is used to describe the life-cycle stages and modules used throughout this paper and is summarized in **Table 5**. Detailed explanations of the product stage modules (A1-A3) are also included in the forest industry operations and timber industry operations sections.

Table 5. Life-cycle Stages of Wood Products

Life-Cycle Modules and Stages		Notes
Product stage		
Module A1	Raw material supply	See explanation of forestry industry operations
Module A2	Transport	Includes transport from the forest to the sawmill or secondary processing facility
Module A3	Manufacturing	See explanation of timber industry operations
Construction stage		
Module A4	Transport	
Module A5	Construction-installation process	
Use stage		
Module B1	Use	
Module B2	Maintenance	
Module B3	Repair	
Module B4	Replacement	
Module B5	Refurbishment	
Module B6	Operational energy use	
Module B7	Operational water use	
End-of-life stage		
Module C1	Deconstruction demolition	
Module C2	Transport	
Module C3	Waste processing	
Module C4	Disposal	

Life-cycle Assessment Guidance

It is important that an LCA be technically robust, transparent, and repeatable. ISO standards 14040 (2006b) and ISO 14044 (2006c) can assist LCA practitioners in ensuring robustness, transparency, and repeatable of studies, but there is significant opportunity for customization of LCA studies, as long as the assumptions and choices made during the study are clearly outlined in the LCA report. For example, an LCA study can consider any combination of life-cycle stages (see Table 5); the only requirement is that a study scope includes the minimum stages of A1-A3 (commonly known as cradle-to-gate). This means that a study that includes A1-A5 is valid, as well as one that includes A1-A3 plus B4. It is important that individuals realize that a study can include many different combinations of life-cycle stages.

In assessing the embodied impact of forest products, there is a lack of consistency in the terminology used as well as the resulting indicator in the various standards or schemes. Treatment of biomass, biogenic carbon, and sequestered carbon also varies. And the term "embodied carbon" can be synonymous with the following terms: carbon footprint, climate change, global warming, global warming potential, embedded carbon (Anderson and Thornback 2012).

Furthermore, sometimes embodied carbon includes carbon dioxide and other times it includes carbon dioxide equivalent (which includes methane, nitrous oxide, and other gases). Also the time period of study of the carbon cycle must be clearly indicated—100 years is often used but it can vary. All of these can have a major effect of the results of the study.

Research guidelines. To standardize research results from certain schemes or for certain product groups, guidance documents have been developed that give more detail on how to perform LCA. In one such guidance document, *Research Guidelines for Life Cycle Inventories* (Briggs 2010), the information that is required to be reported, data requirements and sources, and reporting requirements are detailed. In addition, there is an entire section devoted to the scope of the analysis, which includes required information such as stages of analysis, the system boundary, and the level of detail that must be reported.

The Consortium for Research on Renewable Industrial Materials (CORRIM) developed its research guidelines "to ensure a consistent and comparable approach among the various institutions, panels, and task groups conducting CORRIM research (Briggs 2010)." The guidelines are intended to be used for any industry or product under study as part of a CORRIM LCI project.

Definition of industry and product. Because the research guidelines can be used for any industry or product, an important requirement of the guidelines is to properly and sufficiently define the industry or product under study. The three categories of required information include a general description of the industry, a detailed explanation of how unit factors were derived, and an explanation of secondary products or assemblies that are most commonly produced from the primary industry (Briggs 2010).

Boundary. One requirement of the *Research Guidelines for Life Cycle Inventories* to ensure consistency is to recognize and separately analyze the five life cycle stages of a product. For forest products, the first phase of the life cycle (A1) is considered the growth and extraction phase, which includes planting, thinning, fertilizing, and harvesting, among others (Briggs 2010).

All changes in the five carbon pools of the forest stock should be included. Thus, forest operations would be included in any LCI conducted by researchers for the CORRIM program. The other five life-cycle stages include manufacturing, construction, service life and use, and recycling and disposal. Transportation between each stage is also included in the analysis.

Reporting requirements. When reporting typical or average plant results, a detailed flow or process diagram is requested. The CORRIM *Research Guidelines for Life Cycle Inventories* also request that research results be provided per unit product, and that all materials types and amounts, energy types and amounts, and emission types and amounts to air, land, and water be reported. Data ranges or an explanation of how data averages were determined must also be explained. Emissions to air, land, and water that must be reported according to the CORRIM guidelines are listed in **Table 6**. Note that LCA is generally performed and reported in metric for international consistency, but IP units have been added to the table as an example.

TABLE 6. Reporting Requirements of Essential Emissions According to CORRIM Research Guidelines (Briggs 2010)

Emissions to air	Unit (SI)	Unit (IP)
Carbon dioxide	0.00 g	0.00 lb
Carbon monoxide	0.00 g	0.00 lb
Sulfur oxides	0.00 g	0.00 lb
Nitrogen oxides	0.00 g	0.00 lb
Nitrous oxides	0.00 g	0.00 lb
Particulates and fumes	0.00 g	0.00 lb
Emissions to water		
Biochemical oxygen demand	0.00 g/L	0.00 lb/gal.
Suspended solids	0.00 g/L	0.00 lb/gal.
Dissolved solids	0.00 g/L	0.00 lb/gal.
pH	n/a	n/a
Polynuclear aromatic hydrocarbons (as benzo-a-pyrene)	0.00 g/L	0.00 lb/gal.
Emissions to water	0.00 g/L	0.00 lb/gal.
Solid waste	0.00 kg	0.00 ton

Data requirements. The CORRIM *Research Guidelines for Life Cycle Inventories* requires that the origin of industry data shall be indicated as either measured or derived. Preference is that each unit process (called machine centers) be investigated separately. **An example of a sawmill in the guidelines indicates that unit processes include debarking and bucking, kiln drying, planer mill, and others. Results from each of these should be reported separately.** Units of measure, as well as ranges of typical values for each unit process, should be reported, according to the CORRIM guidelines.

Treatment of biogenic carbon. No guidance is given on treatment of biogenic carbon in the *Research Guidelines for Life Cycle Inventories*.

Product category rules. For a given product category, consistency in LCA studies can be ensured by the application of a set of product category rules (PCR). The primary purpose of a PCR is to specify rules, requirements, and guidelines for conducting LCAs and developing environmental product declarations (EPDs) within a given product category.

PCR development for building products is standardized by ISO 14025 (ISO 2006a) and ISO 21930 (ISO 2007). Program operators also provide input to the process through their general program instructions, as do industry stakeholders. Pro*duct Category Rules (PCR) For Preparing an Environmental Product Declaration (EPD) For North American Structural and Architectural Wood Products* (Wood PCR) was published in May 2013 (FP Innovations 2013). FP Innovations is the program operator that developed the Wood PCR.

Definition of product category and product. One of the most important functions of a PCR is to define the product category for which the PCR applies. For the Wood PCR, the product group is general defined as primary wood building products, not including furniture or case goods. The PCR is also not valid for any products that have been treated with preservatives or fire retardants, which are covered in a separate PCR. Building products included in the scope of the Wood PCR are lumber (timber), glued-laminated timber (glulam), laminated veneer lumber (LVL), finger-jointed lumber, structural composite lumber, battens, molding, pre-fabricated wood I-joists, shakes, shingles, plywood, oriented strand board (OSB), medium-density fiberboard (MDF), particleboard, and veneer. The products included in the scope of the Wood PCR generally are governed by ASTM D9-09ae1, *Standard Terminology Relating to Wood and Wood-Based Products*; ASTM D1038-05, *Standard Terminology Relating to Veneer and Plywood*; and ASTM D1554-10, *Standard Terminology Relating to Wood-Base Fiber and Particle Panel Materials* (FP Innovations 2013).

LCA boundary. For an LCA, the PCR will typically set the goal and scope of the study, including the life-cycle stages that should be included. According to the Wood PCR, EPDs can be created based on a cradle-to-gate or a cradle-to-grave scope. For the cradle-to-gate scope, the LCA must include the life-cycle stages of extraction of raw materials, including reforestation; the transportation of these materials to the manufacturing site; and the manufacture of the wood building product. Specifically, this includes logging and forest management, creation of roundwood, debarking and cutting, drying, and final processing, which may include planning, sanding, gluing, pressing, or assembling. It also includes the extraction, processing, transportation, and manufacturing (that is, the upstream profile) of the materials and energy used to manufacture the wood building product. For example, this includes the upstream profile of the glue and electricity.

The “gate” is defined as the place where the wood product leaves the production facility; it does not include shipping to the customer or subsequent stages after leaving the plant gate.

Data requirements and cut-off rules. In the Wood PCR, Sections 7.4 and 7.5 set the requirements for inclusion or exclusion of data and data quality, respectively. It requires that all data that are reasonably available should be included in the calculations. If data are not reasonably available, cut-off criteria for mass and energy flows is 1%, unless they are known or expected to cause environmentally relevant emissions. In addition, according to the Wood PCR, “At least 95% of the mass flow shall be included and the life cycle impact data shall contain at least 95% of all elementary flows that contribute to each of the declared category indicators (FP Innovations 2013).”

Hazardous and toxic materials and substances do not fall under these cut-off criteria; they must always be included in the inventory. The terms “hazardous” and “toxic” are not defined in the Wood PCR.

Impact categories and characterization factors. The environmental impact categories that must be determined by an LCA are also stated explicitly in the PCR. This ensures that all products in a given product category will evaluate and report the same environmental impact categories. Similarly, a PCR establishes a characterization method for a given product category. There are several methods available that characterize life-cycle inventory data into environmental impact categories. Choosing one characterization method for a PCR ensures transparency and consistency within the product category.

As stated in Section 9.1 of the Wood PCR, the environmental impacts must be calculated based on the U.S. EPA TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) characterization method. The environmental impact categories and life-cycle inventory values that must be determined in the LCA and reported in the EPD are listed in **Table 7**. Note that land occupation is not considered. Yet, one of the areas where the forestry industry creates the greatest environmental impact is in land use or land use change.

TABLE 7. Declaration of Environmental Impacts, Use of Resources, and Generation of Waste (reprinted from Table 3 of the Wood PCR)

Category Indicator	Unit
Global warming potential (GWP)	kg CO_2 equivalent
Acidification potential	moles H+ equivalent or kg SO_2 equivalent
Eutrophication potential	kg N equivalent
Smog creation potential	kg NO_x equivalent or kg O_3 equivalent
Ozone depletion potential	kg CFC-11 equivalent
Total primary energy consumption	
Non-renewable fossil	MJ
Non-renewable nuclear	MJ
Renewable (solar, wind, hydroelectric, and geothermal)	MJ
Renewable (biomass)	MJ
Material resources consumption	
Non-renewable materials	kg
Renewable materials	kg
Fresh water	L
Waste generated	kg

Treatment of biogenic carbon. Wood PCR provides guidance on accounting for biogenic carbon. **It allows for the assumption that CO_2 emitted due to the burning of wood products is equal to the wood sequestered by forests during the growing process, that is, a neutral CO_2 balance.** This is inconsistent with previous discussion on deforestation and the age of forests. T**he Wood PCR does not account for soil carbon changes due to forest growth or harvest, or the effect on carbon pools due to below-ground biomass, deadwood, or litter. In addition, it does not require that wood be sourced from a sustainably managed forest to subtract CO_2 emissions for the global warming potential impact indicator**; it only requires that the wood producer document its fiber source.

Wood PCR states that, "the amount of carbon stored in wood building products in use and in wood building products in the landfill are considered GHG removals and expressed as CO_2 equivalents. The quantities calculated from these two removal models are then subtracted from GHG emissions (from fossil fuels, etc. and the CH_4 and N_2O of the biomass combustion emissions). The net quantity is used in the calculation of the GWP impact indicator (FP Innovations 2013)."

Note here that the carbon storage during use and disposal is being used to offset the emissions for the production of the wood product, and thus the carbon sequestration is being counted twice.

Greenhouse gas protocol. Developed by WRI and World Business Council for Sustainable Development (WBCSD), the *Greenhouse Gas Protocol Product Life Cycle Accounting and*

Reporting Standard (Product Standard) gives guidance on how to perform LCA studies with a limited environmental impact focus: one which only considers greenhouse gas emissions. The primary purpose of the Product Standard is to give guidance on quantifying and reporting GHG emissions and removals (WRI and WBCSD 2011).

Because the greenhouse gas emissions are tracked via LCA, the standards underlying the Product Standard are ISO 14040 (ISO 2006b) and ISO 14044 (ISO 2006c).

System boundary. According to the Product Standard, the system boundary includes all life cycle stages in an attributional LCA approach from cradle to grave. For transparency, all attributable and non-attributable processes are required to be detailed in a process map. Any processes excluded from the analysis must be disclosed and justified. **The Product Standard also requires reporting of methods used to calculate land-use change impacts in the GHG inventory.**

Data requirements and cut-off rules. Primary data is required for all processes in the control of the company performing the assessment. The Product Standard requires that data sources and quality be assessed for any significant process.

Impact categories and characterization factors. For the Product Footprint standard, only the carbon dioxide equivalent emissions and removals are tracked through the life cycle. Individual substances that must be inventoried include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs). Additional greenhouse gases may be tracked as long as they are included in the inventory.

Specific characterization factors or methods are not required in the Product Standard, however **the source and date of 100-year factors used must be reported. The final inventory results are required to be reported in carbon dioxide equivalent (CO_2eq.).**

Treatment of biogenic carbon. All emissions from biogenic, non-biogenic, and land-use change shall be reported in the total CO_2eq. per unit of analysis. **Biogenic and non-biogenic emissions, and those related to land-use change, must be reported separately.**

LIFE-CYCLE ASSESSMENT OF WOOD PRODUCTS

Wood-based products are frequently considered to be carbon neutral due to the fact that forests sequester significant amounts of carbon dioxide. It is important to understand that this sequestration does not include all greenhouse gas emissions related to wood products, nor does it ensure carbon neutrality of wood products. Gower (2003) notes that "almost all the forest product sequestration estimates are based on gross C [carbon] accumulation. That is to say, GHG emissions from harvest, transportation of the roundwood or chips to processing plants (i.e., pulp and paper mills, sawmills), mill emissions, and transportation of the forest products to regional distributors and consumers are ignored. Life cycle analysis (LCA) can be used to quantify total GHG emissions for a forest product from cradle (i.e., forest establishment) to grave (i.e., final fate)." Ingerson agrees in stating that "**scientists have yet to demonstrate that there is a net C storage in forest products if a complete LCA, from cradle to grave, is completed** (Ingerson 2009)**.**"

Article 3.4 of the Kyoto Protocol recognizes an increase in the forest's carbon stocks as a net CO_2 emissions reduction measure. **Many scientists have recognized that the Kyoto Protocol has a flaw by not accounting for CO_2 emissions due to the incineration of biomass.** Searchinger et al. state that this flaw could "severely undermine greenhouse gas reduction goals (Searchinger, et al. 2009)." This flaw could create incentives to clear land, including long-established forest, since it is considered carbon neutral. When in fact, clearing forests to burn causes significant releases of carbon dioxide (Searchinger, et al. 2009). And of course, the harvesting of trees cuts off all future carbon sequestration that might be performed by the living tree.

For the construction industry, the structural use of wood and wood based materials is gaining popularity as a green building strategy largely because wood is a renewable resource. A U.S. Department of Agriculture report summarized 26 peer-reviewed articles on 17 wood products in United States and concluded that lower environmental emissions are associated with using wood for building construction (Ritter, Skog and Bergman 2011). However, there are significant carbon emissions during the harvesting, transportation and manufacturing process of wood products, which were ignored in these studies. **A recent article on the LCA of electricity generation using wood pellets suggests that the total greenhouse gas emissions are 73% more than coal-based generation** (Klein, et al. 2016). The objective of this section is to review life-cycle carbon accounting from cradle to grave and identify if and where uncertainties are larger enough to impact forest management practices and wood products policy.

Discussion of wood products as a way to global carbon imbalance has been ongoing for two decades. Realizing the complexity of the analysis of full carbon circle of wood products, LCA was widely accepted as a quantitative methodology. The majority of the research concluded that wood products were advantageous in carbon balances. In their review of 66 articles, Sathre and O'Connor (2010) reported an average displacement factor of 2.1, which means that replacing non-wood products with each ton of carbon in wood products reduces total greenhouse gas emissions by 2.1 tons of carbon. They propose that wood products contribute to the reduction of carbon emission through the mechanisms listed below.

- Less fossil fuel consumption in manufacturing: Obtaining wood requires less total energy, in particular, fossil fuel energy.
- Carbon storage in the forest: Under the assumption of sustainable management of forest, soil carbon stock maintains a dynamic equilibrium level over multiple rotations. **The forest soils often stores more carbon than forest biomass.**
- Carbon storage in products: 50% of dry weight of wood materials is carbon, which comes from the CO_2 removed from the atmosphere by the growing tree. For this reason, it is believed that the **atmospheric carbon concentration is affected by changes in the size of the wood product pool instead of the size of the forest itself** (Sathre 2010).
- Avoided fossil fuel emissions due to biomass substitution: Many biomass residues are created during forest and timber operations. **Biomass residues due to forestry and timber operations could be used as biofuel to replace fossil fuels**. Practically, they can be burnt in the manufacturing facility to provide heating and drying energy for wood material instead of just burning residues onsite with no energy recovery.
- Carbon dynamics in landfill: **Degradation of wood products generates methane, whose global warming potential is 25 to 36 times greater than that of CO_2.** However, it is believed that collecting the methane emissions and using them as an energy source through better landfill management is possible.

However, many integrated carbon pools are involved in the global carbon cycle that can impact best practices and policy. Besides the five pools in the forest stock defined by IPCC, two other important pools are the wood product stock (fixed carbon in dry wood) and the substitution pool (carbon emission implication of competing products). The positive values of life cycle carbon emission reduction are based on the assumption that wood is substituted materials with greater carbon footprints, such as fossil fuel. Therefore, the carbon emission of wood products was credited by the chosen substitution products.

Perez-Garcia, Lippke, et al. (2005) systematically analyzed the carbon sequestration of wood product in different carbon pools. Using a series of models with LCA data provided by the Consortium for Research on Renewable Industrial Materials (CORRIM) (Bowyer et al. 2004), they analyzed the effects of alternative harvest cycles on carbon accounts and compared to a no harvest alternative. **Table 8** shows the comparison of forest carbon stocks under different harvesting schedules and the no harvesting scenario. It is noteworthy that the no harvesting scenario demonstrates an upper bound to forest stock since it assumes no disturbance over the period yet it is not representative of natural forest conditions. This trend is in agreement with the recent study by Knauf, et al. (2015). The results suggest that shorter harvest cycle does not lead to greater carbon emissions. However, the afforestation practice does reduce the forest carbon stock in the long term.

Table 8. Carbon Stock in Forest Pool for Different Harvesting Schedules (Perez-Garcia, Lippke, et al. 2005).

	Average Net Forest Carbon, tonnes per hectare (tons per acre), for a given timeframe in years			
Rotation length	0-45 years	0-80 years	0-120 years	0-165 years
45 years	70.60 (31.46)	67.30 (30.02)	71.25 (31.78)	74.45 (33.20)
80 years	60.46 (26.94)	106.90 (47.68)	94.45 (42.12)	110.50 (49.28)
120 years	60.46 (26.94)	106.95 (47.70)	137.38 (61.27)	121.30 (54.10)
No harvest	60.17 (26.84)	124.03 (55.32)	185.53 (82.75)	238.55 (106.39)

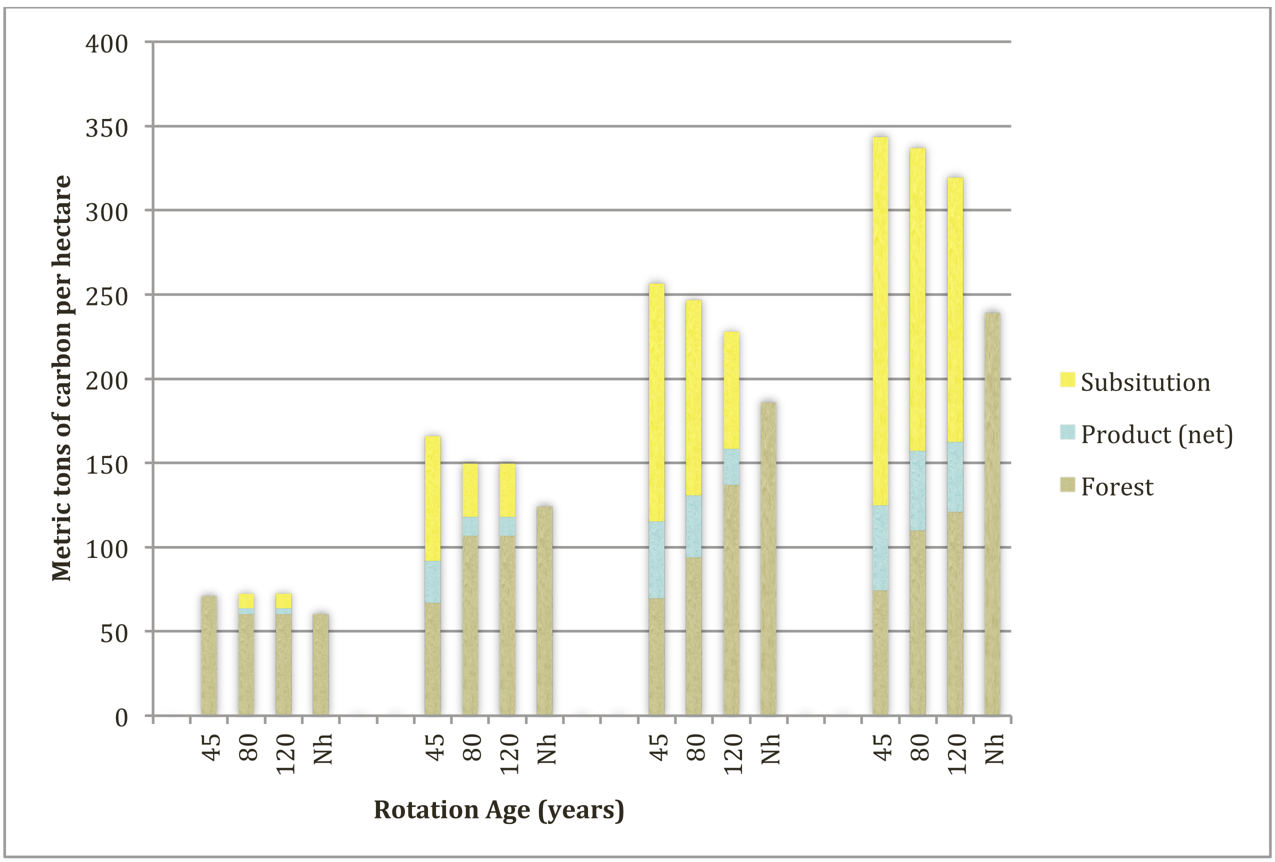

Figure 4. Average annual carbon in forest, product, and concrete substitution pools for different rotations after 45 years, 80 years, 120 years, and no harvest, respectively. The four sets of bars indicate time periods of 45, 80, 120, and 165 years. Note: Nh = no harvest. Adapted from data in Perez-Garcia, Lippke, et al. (2005).

When all three carbon pools are considered, as shown in **Figure 4**, the shorter rotations increases the productivity of the land therefore increasing the product stock and stock in the substituted products. However, if the substituted product stock is removed, the summary of the stock in forest and wood products for the afforestation scenarios are lower than the stock in the no harvesting scenario in long term (larger than 45 years). **This means that afforestation practices do not remove more carbon from atmosphere than the no harvesting scenario.** According to this analysis, carbon neutral of wood product is only true when the credit was given for the reduction of carbon emission by substituted products.

Werner and Richter (2007) conducted a thorough review of the LCA studies of wood products before 2006. They noticed that these studies differ "considerably in terms of completeness (life cycle stages included, assessment methods), transparency (description of methodological assumptions, characteristics of the products, available data, etc.) and scientific rigor (for example, related to the functional equivalency); the results of these studies can therefore not be compared across studies and product groups." However, the conclusion of most, if not all, research indicates a positive impact on reducing the global warming potential (as indicated in Appendix I). In order to understand the variety of LCA research, it is useful to discuss some general sources of uncertainty in LCA of wood products.

Table 9 is the literature summarized by Sathre and O'Connor (2010).

Table 9. Literature Summarized by Sathre and O'Connor (2010)

Reference	Energy for material production	Process reaction emissions	Biomass residues for energy	Carbon stock in products	Carbon dynamics in forest	End-of-life management	Time horizon
Börjesson and Gustavsson, 2000	Included	Included	Included	Discussed	Included	Landfilling; energy recovery	Cradle to grave (100-year); cradle to cradle (300-year)
Buchanan and Levine, 1999	Included	Not included	Not included	Discussed	Discussed	Not included	Cradle to gate
Eriksson et al., 2007	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
Gustavsson et al., 2006	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
Gustavsson and Sathre, 2006	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
John et al., 2009	Included	Included	Not included	Discussed	Not included	Landfilling; energy recovery	Cradle to grave, 60-year service life
Jönsson et al., 1997	Included	Included	Not included	Not included	Not included	Energy recovery without fossil fuel substitution	Cradle to grave, 40-year service life
Knight et al., 2005	Included	Included	For wood processing	Not included	Discussed	Not included	Cradle to gate
Koch, 1992	Included	Not included	For wood processing	Discussed	Discussed	Not included	Cradle to gate
Künniger and Richter, 1995	Included	Included	For wood processing	Not included	Not included	Energy recovery without fossil fuel substitution	Cradle to grave, 60-year service life
Lippke et al., 2004	Included	Included	For wood processing	Discussed	Discussed	Landfilling	Cradle to grave, 75-year service life
Petersen and Solberg, 2002	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 50-year service life

Petersen and Solberg, 2003	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 45-year service life
Petersen and Solberg, 2004	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 45-year service life
Pingoud and Perälä, 2000	Included	Included	Included	Discussed	Discussed	Energy recovery	Cradle to grave, permanent transition to wood-intensive constructio n sector
Salazar and Meil, 2009	Included	Included	Discussed	Temporary storage, linked to disposal	Discussed	Landfilling; energy recovery	Cradle to grave, 100-year service life
Salazar and Sowlati, 2008	Included	Included	Not included	Discussed	Not included	Landfilling	Cradle to grave, 25-year service life
Scharai-Rai and Welling, 2002	Included	Included	Not stated	Not included	Not included	Energy recovery	Cradle to grave, varying service lives
Sedjo, 2002	Included	Included	For wood processing	Discussed	Discussed	Not included	Cradle to gate
Upton et al., 2008	Included	Included	Included	Included	Included	Landfilling; energy recovery	Cradle to grave, 100-year service life
Werner et al., 2005	Included	Included	Included	Stabilizes at higher level, no net effect	Discussed	Energy recovery	Steady-state condition assumed after 2130

Table 10 summarizes the boundary selection of some more-recent literature. An X in any given scope column does not signify that all forest management effects such as soil impacts, releases from below ground biomass, biodiversity, and loss of other flora and fauna have been included. It should also be noted that the use stage is not clearly defined in each study and can vary.

Table 10. Boundary Selection of Some More-recent Literature

Products	Region	Year	Included in scope					Software	Database
			Forest management	Transportation	Manufacturing	Use stage	Disposal		
Building materials (Bribián, Capilla and Usón 2011)	Europe	2011		X	X	X	X	SimaPro v7.1.8	Eco-invent v2.0 (2007)
Wooden building material (Pajchrowski, et al. 2014)	Europe	2014		X	X	X	X	SimaPro v7.3	IMPACT 2002+; Eco-indicator 99/E; CML; IPCC
Irish wood (Murphy, Devlin and McDonnell 2015)	Ireland	2014	X	X	X			SimaPro v7.3	Eco-invent v2.0 (2007); PRé Consultants
Forest products (Perez-Garcia, Lippke, et al. 2005)	U.S.	2005	X	X	X	X		LMS	CORRIM
Wood wall (Frenette, et al. 2010)	Canada	2010		X	X	X	X	ATHENA	IMPACT 2002+; Eco-indicator 99; TRACI
Typical Australian residential townhouse (Islam, et al. 2015)	Australia	2015		X	X	X		SimaPro	AusLCI
Forest resource activities (Johnson, et al. 2005)	U.S.	2005	X					SimaPro v5.9	Eco-indicator 99/E
Wood Fuel Pellet (Reed, et al. 2012)	U.S.	2012			X	X			TRACI
Softwood (Puettmann, Oneil and Milota, et al. 2013)	U.S.	2013	X	X	X				TRACI
Softwood	U.S.	2013	X	X	X				TRACI

(Puettmann, Oneil and Bergman 2013)									
Softwood (Puettmann and Oneil 2013)	U.S.	2013	X	X	X				TRACI

LMS = Landscape Management System

Uncertainties in the LCA of Wood Products

Many factors contribute to the uncertainty of LCA. The following discussion focuses on uncertainties caused by methodology. It is common in LCA of wood product to assume beneficial use of wood residuals and sustainable forest management. These two assumptions are important for the analysis results.

Uncertainties caused by co-products problem. Many co-products exist for the wood industry. The total impacts of the industry need to be distributed adequately into different products of interest. There are two methods to handling the distribution, namely allocation and system expansion. Allocation splits the impacts into different products according to certain rules, most generally by mass or economic value.

System expansion expands the system boundary of the study to include another system that could attribute to the impacts of co-products therefore the net impact of the determining product can be calculated by subtracting the impacts of those co-products from the total impacts. Two examples were demonstrated in a recent report for the uncertainty associated with the allocation. Note that LCI data is generally collected and reported in metric for international consistency, and that is the case in the tables in this section.

Wood for windows frames – example. A study in a LCI of wood frame windows showed that 65% of the wood biomass harvested leaves the windows production line; this makes allocation of harvesting and processing processes an essential topic of LCAs of wood windows. So, all residues through the production chain were considered as co-products or waste, based on the market value. **Table 11** shows the results of the inventory analysis.

Table 11. Selected LCIA Results of a Standard Window with Different Allocations

Wood window frame LCIA when modeling:	GWP 100 kg CO_2/window	Acidification kg SO_2/window
Residues as waste	-24,000	1.85
Residues as co-product	-4130	1.07

Treating residues as waste or co-product could change the results by over 80%.

Sawmill example. Different ways of allocation could lead to different results too. Allocation of energy consumption and CO_2 emissions for sawmills were made in three different ways: by volume, by mass, and by economic value. **Table 12** shows the differences due to allocation method. If allocation by mass is used, the sawmill should first be subdivided into the different processes. If economic allocation is used, the sawmill is modeled as one single process because economic values are not available for intermediate products. Economic allocation and mass allocation provide similar results. **In contrast, the carbon footprint is about 10% less for the allocation by volume than by economic value**.

Table 12. Comparison of the Three Different Allocation Approaches for a Sawmill

Allocation approach	Volume based	All to sawn timber	Economic (Market price based)
Electricity use at the sawmill	MJ/m^3	MJ/m^3	MJ/m^3
Bark	4	0	0.3
Raw chips, particles	39	0	4
Dry chips and cuttings	189	0	0.3
Sawn timber	232	286	280
Heat use at the sawmill	MJ/m^3	MJ/m^3	MJ/m^3
Bark	11	0	1
Raw chips, particles	28	0	19
Dry chips and cuttings	1160	0	1
Sawn timber	1199	1294	1269
CO_2 emissions at the sawmill	kg CO_2/m^3	kg CO_2/m^3	kg CO_2/m^3
Bark	0.094	0	0.010
Raw chips, particles	0.741	0	0.159
Dry chips and cuttings	4.41	0	0.010
Sawn timber	9.3	10.6	10.4

Uncertainties caused by neglecting impact of forest management. As discussed in previous sections, many existing LCAs of wood product were conducted using commercial databases. However, most commercial databases do not include resources and emissions of forest management processes. This includes BUWAL250, Ecoinvent, ETH-ESU 96, Franklin USA 98, IDEMAT 2001, Industry data 2.0, LCA Food DK, and EIO databases. The databases also do not include carbon pools from all five primary sources. The general forest management practices involve seeding, site preparation, pre-commercial thinning, harvesting, stump to truck, and hauling. During these processes, resources such as fertilizer, water, fuel etc. will be consumed and emissions to air, water and soil will occur. The only available inventory data for U.S. forest management is from CORRIM studies (Johnson, et al. 2005; Oneil, et al. 2010). **Table 13** summarizes this limited input data for forest management.

Table 13. Forest Management Data: Energy and Fuel Consumption (Johnson, et al. 2005).

Electric, fuel and lubricant consumption		
Seedling, site prep, plant, precom. thin.		
Fuel	114	L/hectare
	0.515	L/m^3
Lubricants	2.06	L/hectare
	0.009	L/m^3
Electric	101	MJ/hectare
	0.455	MJ/m^3
Stump to truck		
Fuel (diesel)	652	L/hectare
	2.93	L/m^3
Lubricants	11.7	L/hectare
	0.053	L/m^3
Hauling	92	km
Fuel (diesel)	933	L/hectare
	4.20	L/m^3
Lubricants	16.8	L/hectare
	0.076	L/m^3
Total planting and harvest operation		
Fuel	1700	L/hectare
	7.65	L/m^3
Lubricants	30.6	L/hectare
	0.138	L/m^3

Emissions are hard to measure in the forest. Johnson et al. (Johnson, et al. 2005) also presented the projected emissions to the air related to the forest management using SimaPro EcoIndicator 99 (E)/Europe EI 99 E/E (**Table 14**).

Table 14. Projected Emissions to the Air (Johnson, et al. 2005).

	kg/m^3 of harvested log
Aldehydes	1.69E-04
Ammonia	3.19E-04
CO	7.70E-02
CO_2	3.99E-01
CO_2 (fossil)	9.25E+00
CO_2 (non-fossil)	2.51E-03
Dust (SPM)	2.11E-04
Formaldehyde	2.44E-03
Methane	6.29E-03
N_2O	2.34E-03
NO_2	7.63E-04
Non-methane VOC	3.78E-02
NO_x	1.67E-01
Organic substances	1.16E-04
Particulates (PM10)	1.15E-02
Particulates (unspecified)	7.38E-04
SO_2	1.94E-03
SO_x	4.38E-02
VOC	3.22E-05

Neglecting these resource and emissions would bring uncertainty to the analysis.

Uncertainties caused by different impact assessment methods. Different impact analysis methods use different ways to model the fate of wastes. Even with the same method, the parameters of the model might be different due to the fact that the fate and risk varies from regionally. This difference is also a source of uncertainty in LCA analysis. As an effort to estimate the significance of the uncertainty caused by neglecting forest management and different impact methods, the forest management with different intensity scenarios was modeled for a local wood products company with SimaPro 8.2.

Assessment of Methodological Uncertainty

Forest management. The purpose of the assessment is to quantify the uncertainty associated with neglecting forest management and the use of different databases. Two products from a company located in Georgia, one for roofing and the other for sheathing, were chosen for the purpose of comparison. The rationale of the choice is the data availability on LCA of stages other than forest management.

For the sake of comparison to existing life cycle data, the functional units were chosen to be 1 square meter (11 square feet) of a specific product with a service life of 60 years. The use phase is ignored because it depends more on the construction of the building instead of a single material.

Since the company located in the Southeast, the data from Johnson, et al. (2005) were used for the forest management flows. The input for three different management intensities was derived from the report by Johnson et al. (2005) Appendix II summarized the assumptions on forest management with different intensities. These data were used to calculate the input for two forest management cases. In the Southeast, the industrial and non-industrial private forests classified as low, medium, and highest classes are 37%, 58%, and 5%, respectively. In the Pacific Northwest, these classifications are 42%, 46% and 12%, respectively. According to this classification, the material bill can be calculated for the Southeast (base case) and the Pacific Northwest (alternate case).

The material and energy bills for the two forest management cases are summarized in **Table 15**. Note that LCA is generally performed and reported in metric for international consistency, and that is the case in this section. Since there is not much difference between the two management scenarios, only the base case was analyzed. This data was used as input to SimaPro to analyze the GWP of the two wood products. Comparison of the GWP in the forest management stage was then compared with the value for manufacturing and end of life stage, which was based on the operational data of the company.

Table 15. Material and Energy Input for the Two Scenarios of Forest Management in Southeast. Cost and Energy Consumption—Base and Alternate Case: System Costs and Fuel Consumption

	Base case	Alternate case	Units
Electric, fuel and lubricant consumption			
Seedling, site preparation, planting, pre-commercial thinning			
Fuel	114	168	L/hectare
	0.515	0.578	L/m^3
Lubricants	2.06	3.03	L/hectare
	0.009	0.01	L/m^3
Electric	101	101	MJ/hectare
	0.455	0.347	MJ/m^3
Stump to truck			
Fuel (diesel)	652	878	L/hectare
	2.93	3.02	L/m^3
Lubricants	11.7	15.8	L/hectare
	0.053	0.054	L/m^3
Hauling	92	92	Km
Fuel (diesel)	933	1220	L/hectare
	4.2	4.2	L/m^3
Lubricants	16.8	22	L/hectare
	0.076	0.076	L/m^3
Total planting and harvest operation			
Fuel	1700	2270	L/hectare
	7.65	7.79	L/m^3
Lubricants	30.6	40.9	L/hectare
	0.138	0.14	L/m^3
Fertilizer consumption			
Nitrogen	189	547	kg/hectare
	0.852	1.878	kg/m^3
Phosphate	32.5	97.8	kg /hectare
	0.146	0.336	kg /m^3
Potassium	0.084	0.084	kg /hectare
	0.000	0.000	kg /m^3

As can be seen, the difference between the base case and the alternate case is relatively large when compared using hectares of forest as the functional unit. With the exception of fertilizer, these differences disappear when using cubic meters of wood as the functional unit. This makes sense because the level of effort in forestry is more related to the amount of wood produced than to the area of land managed.

For the impact analysis, four methods were used to compare the effect of different methods on the analysis outcomes. Among the four, TRACI and BEES are U.S.-based methods, while IMPACT+ is European based and IPCC is based on global data yet is a single impact assessment. The results and discussion of the base case analysis is discussed below.

The potentials for five different environmental impact categories for different materials at different life-cycle stages are shown in **Figures 5 through 8**. The data used to create these figures are tabulated in Appendix III. Forest management activities account for approximately 5% of the total impact for all products. It is much less than the manufacturing stage, but comparable to the construction-stage impacts.

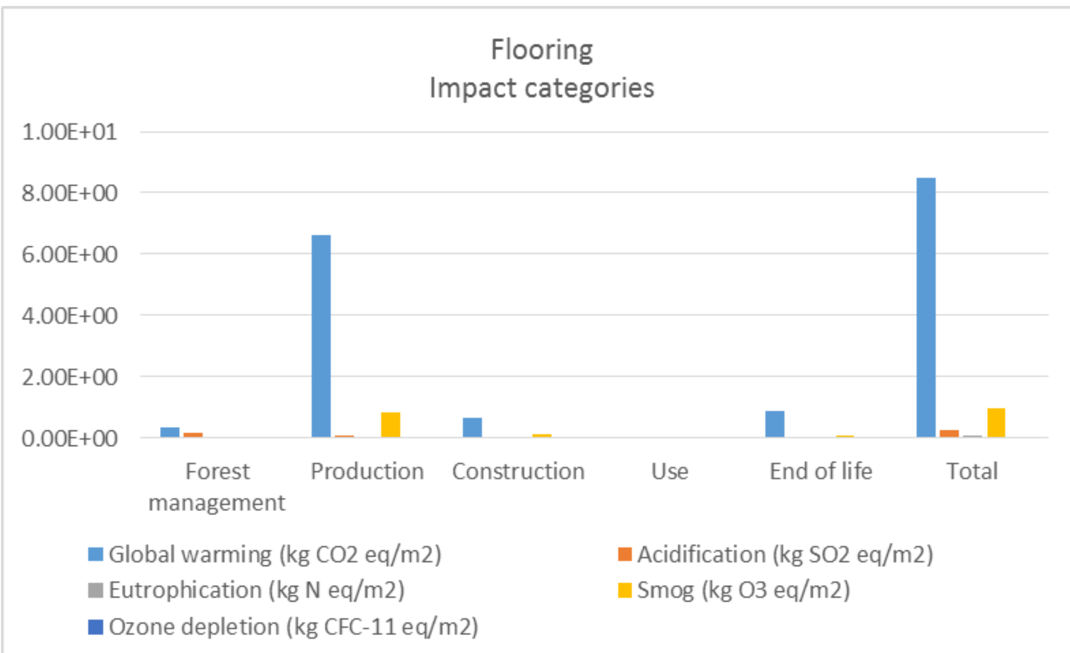

Figure 5. Potentials for five different environmental impact categories for flooring at different life-cycle stages.

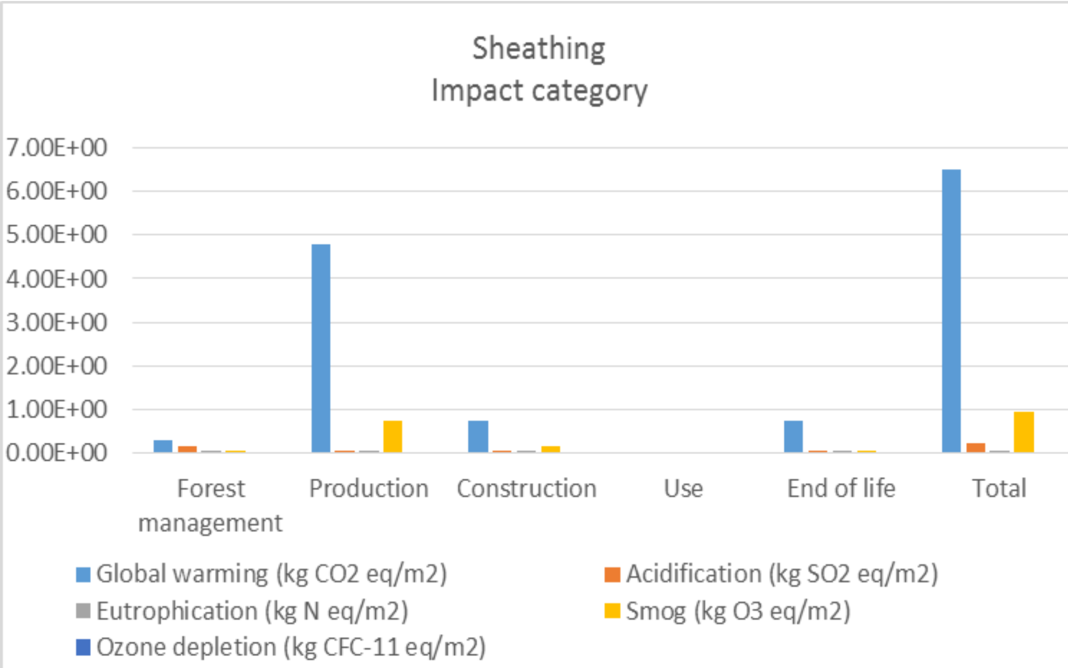

Figure 6. Potentials for five different environmental impact categories for sheathing at different life-cycle stages.

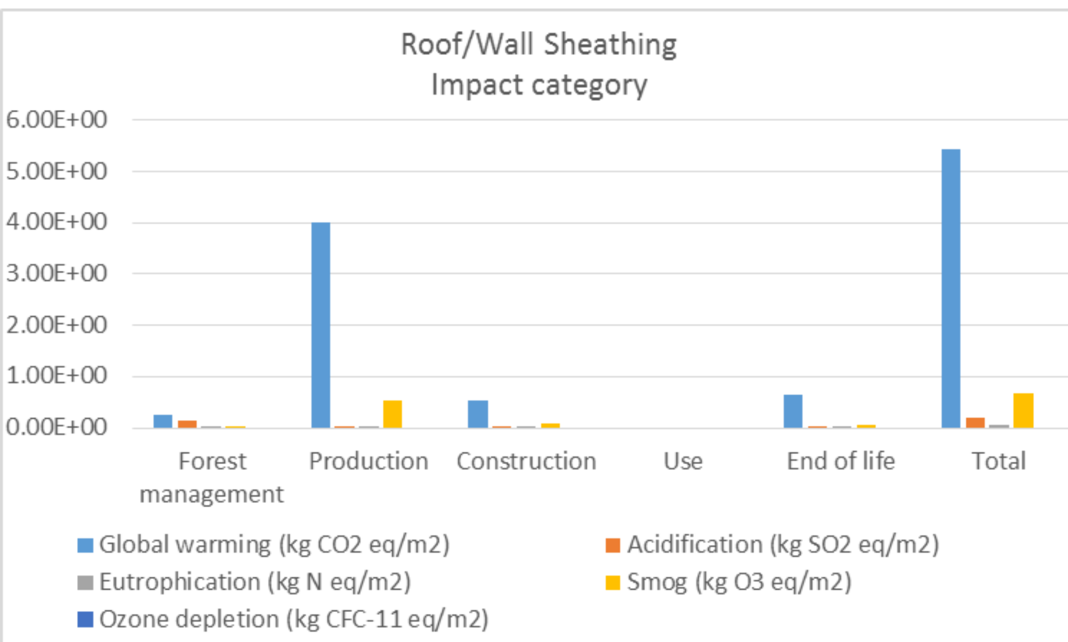

Figure 7. Potentials for five different environmental impact categories for roof/wall sheathing at different life-cycle stages.

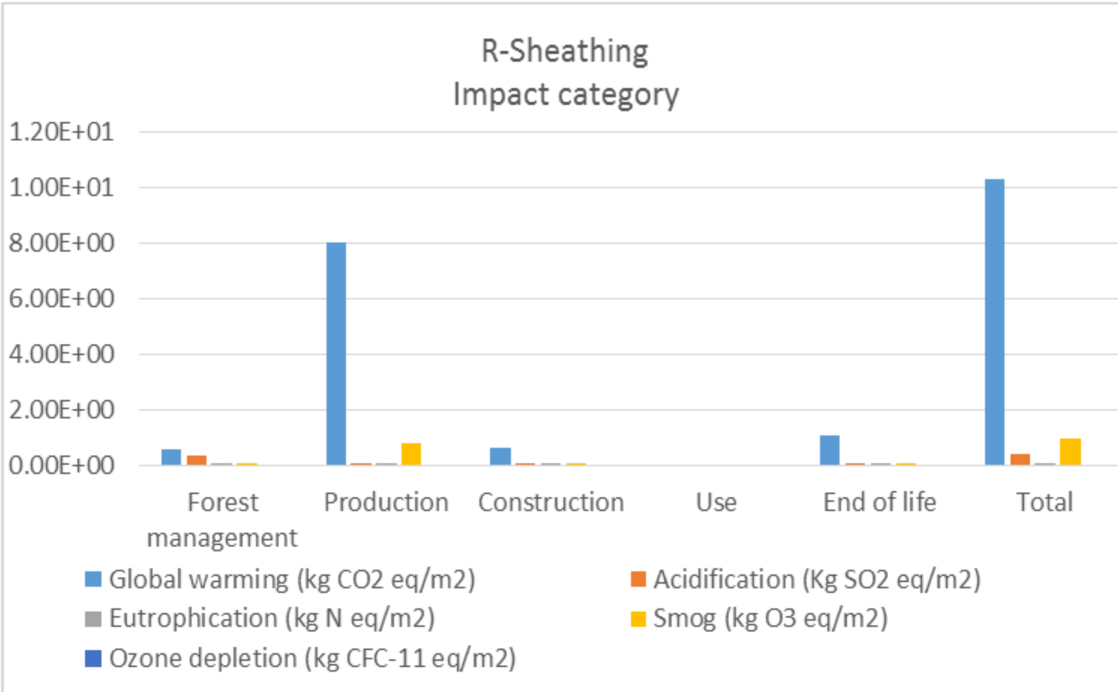

Figure 8. Potentials for five different environmental impact categories for R-sheathing at different life-cycle stages.

Impact assessment methods.

The comparisons of different impact assessment methods are shown in **Figures 9 through 12**.

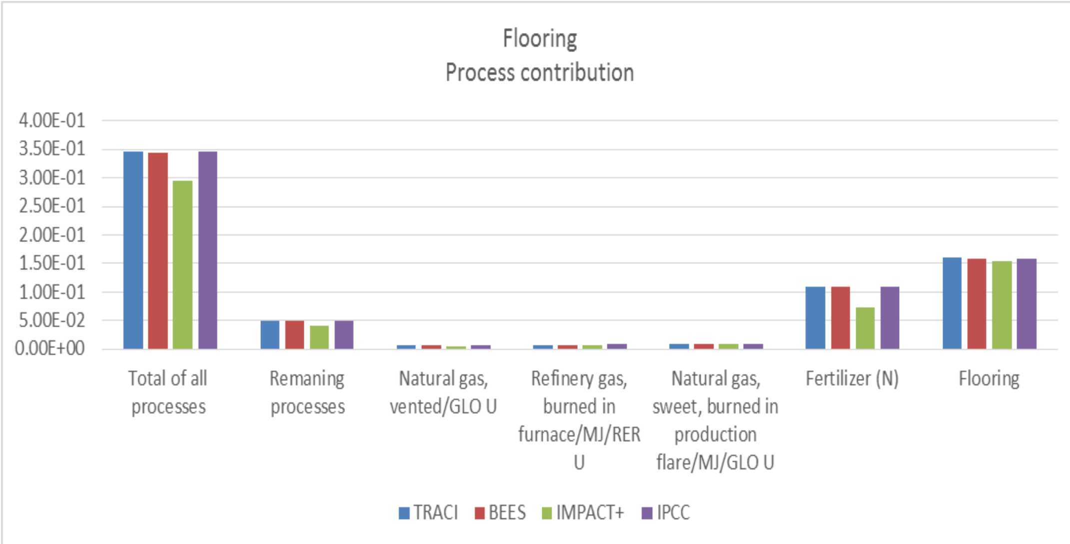

Figure 9. Process contributions to global warming potential of flooring for four different characterization methods.

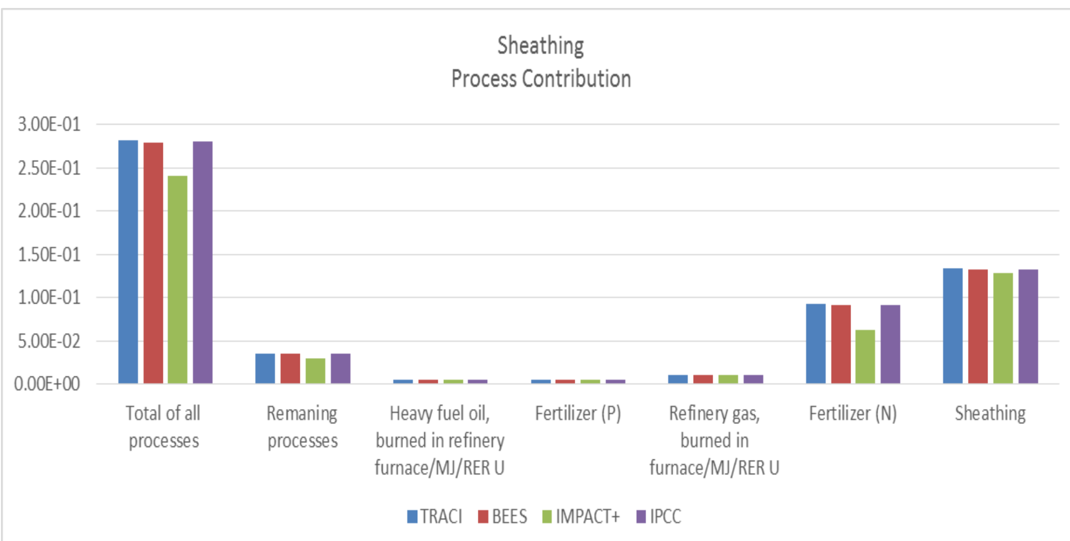

Figure 10. Process contributions to global warming potential of sheathing for four different characterization methods.

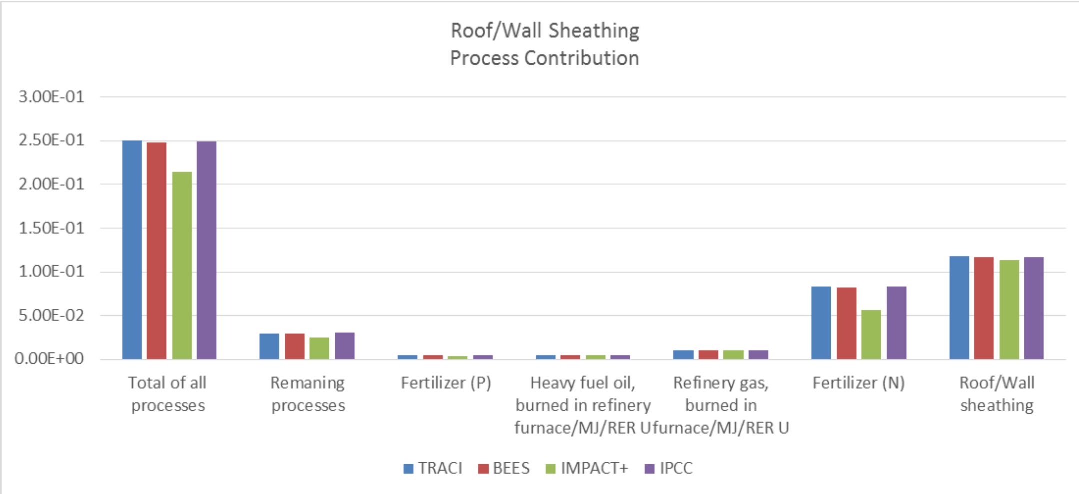

Figure 11. Process contributions to global warming potential of roof/wall sheathing for four different characterization methods.

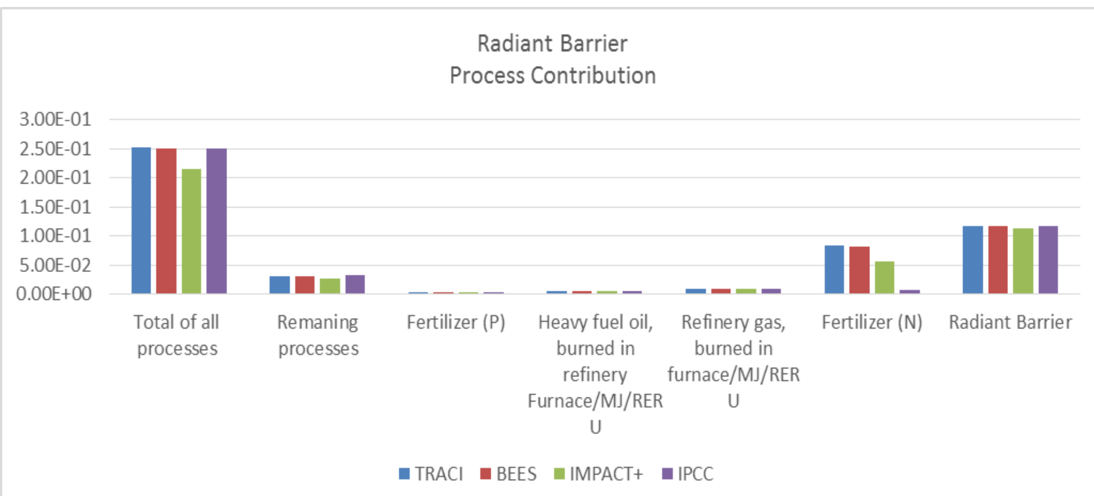

Figure 12. Process contributions to global warming potential of radiant barrier for four different characterization methods.

The impact results are comparable for TRACI, BEES and IPCC. This is not surprising since the TRACI and BEES methods are based on the IPCC model. The analysis by IMPACT+ shows a 20% lower GWP than that by the other three. This is a significant difference that should be considered when interpreting the results using this method. Overall, **none of the analyses shows a zero carbon footprint** because the substitution of other products was not considered in the analyses. In addition, the analyses did not consider the carbon stock in the wood product itself. According to the Wood PCR, this quantity should be subtracted from the calculated GHG emissions. Using this method, a negative carbon emission could be calculated.

However, from a full life cycle perspective, the carbon stored in the wood will eventually decompose into either CO_2 or CH_4. The treatment of the end-of-life stage is still a debatable topic that beyond the scope of this paper.

SEVERAL LIFE-CYCLE ASSESSMENTS OF WOOD PRODUCTS

Several studies of wood products have been reviewed in the process of writing this paper. In order to provide a transparent summary, it was necessary to standardize the terms and definitions used throughout this paper as well as develop a template for disclosing the system boundary of each study. Each study will be presented with an accompanying table that summarizes the life-cycle stages included in the study, any processes explicitly excluded from the study, assumptions made by the researchers, and the main conclusions or outcomes of the study. An example of the table is as follows:

Table. Example table summarizing pertinent information from wood-product studies

STUDY SUMMARY	REFERENCE:
Life-cycle stages included	A1-A4
Life-cycle stages excluded	A5, B1-B7, C1-C4
Assumptions	• Forest residue was left on site • All waste was burned
Main conclusions	• Transportation was significant

It is important for the reader to note that the studies presented herein do not include all forest management issues, which can be complex, and do not include all of the carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon.

LCA results are commonly presented in SI units, and that is the practice in this section.

Case Study: Life-cycle Inventory of Residential Wood Building Materials

Table. Summary of pertinent information from the Puettmann and Wilson (2005) study

STUDY SUMMARY	REFERENCE: (Puettmann and Wilson 2005)
Carbon cycle considered	Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• CO_2 emitted from biomass combustion is carbon neutral.
Main conclusions	• Manufacturing life-cycle module consumed the most energy. • Two-thirds of energy consumption is from fossil-based resources.

Commissioners. U.S. Department of Agriculture Forest Service, Forest Products Laboratory; U.S. Department of Energy; CORRIM; and private companies.

Scope. An LCI of forest and timber operations to manufacture glued-laminated timbers, kiln-dried and green softwood lumber, laminated veneer lumber, softwood plywood, and oriented strandboard in both the Pacific Northwest and Southeast United States (Puettmann and Wilson 2005). The LCA practitioners studied flows in the product stage of the life cycle—harvest, transportation, and manufacture. The functional unit is 1 m^3 of product.

Source location of wood for dimension lumber. The analysis was performed on the wood products industry as represented by the Pacific Northwest and the Southeast United States. A majority of the supply to the timber industry in the United States comes from these two regions.

Data. Forest regeneration, growth, and log production data were taking from growth and yield models of trees and recent studies. Primary data were obtained for wood production processes. Secondary data were collected from available databases for energy generation, transportation, and resin production.

Characterization. No characterization method was used in this study.

Results. The greatest use of energy is in the manufacturing module due to drying. The greatest CO_2 emissions were from the burning of biomass. However, the U.S. EPA does not count CO_2 emissions from burning biomass as a contributor to global warming potential (USEPA 2003).

Projected Emissions	Southeast Lumber, kg/m^3	Pacific Northwest Lumber, kiln-dried, kg/m^3	Pacific Northwest Lumber, green, kg/m^3
CO_2 (biomass)	248	160	230
CO_2 (fossil)	62	92	27.13
CH_4	0.10	0.19	0.02
N_2O	0.64	0.67	0.31

Case Study: Life-cycle Assessment of Rough-sawn Kiln-dried Hardwood Lumber

Table. Summary of pertinent information from the study by PE International (2012)

STUDY SUMMARY	REFERENCE: (PE International 2012)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A4
Life-cycle stages excluded	A5, B1-B7, C1-C4
Assumptions	• Biogenic carbon dioxide emissions are offset by the uptake in biomass (carbon neutral with no impact of the global warming potential).
Main conclusions	• Kiln drying is the greatest contributor to global warming potential at the timber-manufacturing gate. • Transportation-related activities can be a greater contributor to GWP than kiln drying. • GWP varies greatly depending on tree species and thickness.

Commissioner. American Hardwood Export Council (AHEC).

Scope. An LCA for United States hardwood lumber products that are rough sawn and dried in a kiln (PE International 2012). The LCA practitioners only studied flows due to the product stage and representative travel stage of the life cycle.

Source location of wood for dimension lumber. Hardwood forests that supply the U.S. timber industry are located primarily in the eastern United States.

Data. This study uses average forestry upstream data from CORRIM, with some primary data from AHEC members for timber activities. CORRIM data assumes that hardwood forests are naturally grown in the U.S. so that management is not required until harvest (Oneil, et al. 2010). Thus, forestry operations data do not include fertilization, irrigation, or planting. A commercial thinning was assumed at a stand age between 70 and 72 years, with the final harvest occurring at 82 to 120 years. Data on harvesting activities and fuel consumption rates were taken from existing studies typical of equipment and sites in the region. These studies were based on personal interviews and published information.

Economic allocation was performed for the forestry operations between saw logs and pulp logs. Wood species and wood grade allocations were not performed. It was assumed that the average yield of saw logs was between 33.5 to 44.8% of the total harvest volume (Oneil, et al. 2010).

CORRIM data were used for timber operations, with some secondary data from literature (Bergman and Bowe 2008, Bergman and Bowe 2010). Primary data provided by AHEC members on saw-mill energy requirements were used to verify that the CORRIM data were appropriate and conservative. Economic allocation was also used for the timber operations for the different co-products.

The energy mix for lumber drying was assumed to be 90% from biomass burned onsite and 10% from natural gas combustion. USDA data for kiln efficiencies and daily energy consumption were adopted for the base scenario (USDA 2000).

Average transportation distances and modes were provided by AHEC companies. Transportation to Europe was used as the base scenario with a shipping distance of 7753 km.

Carbon stored in the final timber product was listed as a separate line item in the report and was not subtracted from the total GWP.

Characterization. CML 2001, updated in 2010, and TRACI were used as the characterization methods within GaBi 5.

Table. Global warming potential for different rough sawn, kiln-dried lumber due to life-cycle modules A1-A4 (cradle-to-gate plus transportation)

Product	Global Warming Potential kg CO_2eq. per m^3	Carbon Storage kg CO_2eq. per m^3
Base scenario: 1-in.-thick white oak	556	-1114
2-in.-thick white oak	845	-1114
1-in.-thick ash	407	-974
1-in.-thick aspen	325	-603
1-in.-thick basswood	330	-603
1-in.-thick beech	377	-1073
1-in.-thick birch	385	-997
1-in.-thick cherry	301	-812
1-in.-thick cottonwood	373	-650
1-in.-thick elm	357	-857
1-in.-thick sap gum	368	-789
1-in.-thick hackberry	340	-857
1-in.-thick hickory	463	-1208
1-in.-thick hard maple	394	-1020
1-in.-thick soft maple	390	-1125
1-in.-thick red oak	496	-1020
1-in.-thick pecan	386	-1067
1-in.-thick American tulipwood	270	-650
1-in.-thick walnut	427	-882
1-in.-thick willow	310	-603

Results. The greatest contributor to the GWP at the timber gate is kiln-drying process. Depending on the wood species, timber thickness, wood moisture content, and kiln efficiency, the kiln-drying process contribution to GWP can vary greatly. Another significant contributor to the GWP is the transportation to the customer. This contribution varies depending on the thickness of the timber product. The greatest primary energy demand occurs due to forestry operation.

Case Study: Natural Tropical Forest in Ghana

Table. Summary of pertinent information from the study by Eshun, Potting, and Leemans (2010)

STUDY SUMMARY	REFERENCE: (Eshun, Potting and Leemans 2010)
Carbon cycle considered	Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• Changes in carbon storage due to land-use change were not included. • Average distance between forest site and wood-production facility is 500 km.
Main conclusions	• Total energy consumed by lumber industry 7.54 x 10^8 MJ/year • Total CO_2 emissions consumed by industry 754,000 tonne/year

Commissioners. Ghana government and Wageningen University.

Scope. An LCIA of five wood products. air-dried lumber, kiln-dried lumber, plywood, veneer, and furniture parts, which constitute approximately 90% of the total timber product export from Ghana (Eshun, Potting and Leemans 2010). This summary will focus on the results related to the lumber flows.

The LCA practitioners studied flows during the product stages of the life cycle—harvest, transportation, and manufacturing.

Source location of wood for dimension lumber. About 80% of the supply to the timber industry in Ghana comes from natural, tropical forests. A majority of forests are subject to illegal logging and Ghana deforestation rates in 2003 were 65,000 ha/year (The World Bank 2005). The authors estimate that complete deforestation could be achieved by year 2023 if current rates are maintained.

Data. Data were collected from 30 producers representing the forestry industry in Ghana (Eshun, Potting and Leemans 2010). Primary data were supplied on material and energy use, as well as waste production for calendar years 2000 to 2007. Data represent national average data in Ghana. Emissions due to timber manufacturing were calculated.

Characterization. CML-2000 was applied to determine the global warming potential, acidification potential, eutrophication potential, photochemical oxidant formation potential, and human toxicity potential. Only global warming potential results will be presented in this summary.

Results. For the years 2000 to 2007, an average of 760,000 m^3 of wood is harvested to produce 270,000 m^3 of air- and kiln-dried lumber.

Product	CO_2 ktonne/yr	CH_4 tonne/yr	N_2O tonne/yr	SO_2 tonne/yr	NO_x tonne/yr	NMVOC tonne/yr	CO ktonne/yr
Air-dried lumber	8	3	0	53	165	128	0
Kiln-dried lumber	219	263	10	76	451	286	9

Product	CO_2 ktonne/yr	CH_4 in CO_2eq.-ktonne/yr	N_2O in CO_2eq.-ktonne/yr	TOTAL CO_2eq.-ktonne/yr
Air-dried lumber	8	0	0	8
Kiln-dried lumber	219	6	0	225

Typically, the CO_2 emissions from burning biomass is excluded from GHG inventories. However, in the case of tropical forests, "IPCC recommends…to specifically flag these emissions as an indicator for deforestation (IPCC 2006)." Biomass was used as fuel in the kilns to dry the wood products, and it was the greatest contributor of energy use. Timber harvesting and transportation were the second greatest users of energy in the study.

Case Study: Dimension Lumber for Home Improvement Store

Table. Summary of pertinent information from the Gower, et al. (2006) study

STUDY SUMMARY	REFERENCE: (Gower, et al. 2006)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A5, C1-C4
Life-cycle stages excluded	B1-B7
Assumptions	• Harvesting did not significantly affect soil carbon content
Main conclusions	• Greenhouse gas emissions due to transportation are significant

Commissioners. Canfor, The Home Depot, Stora Enso in North America, and Time Inc.

Scope. A greenhouse gas LCA study of two magazine chains and a dimensional lumber chain. This summary will focus on the flow of Canfor wood (as dimension lumber) to The Home Depot, which is a large home-improvement retailer. The LCA practitioners studied direct and indirect greenhouse gas emissions created during all stages of the life cycle except the use phase—harvest, transportation, manufacturing, and end-of-life (recovery, recycling, or disposal). The Greenhouse Gas Protocol was employed to classify greenhouse gas emissions into categories of indirect or direct (WRI and WBCSD 2011). Most transportation-related emissions were classified as indirect, except those that occurred at the harvest or manufacturing sites. Direct emissions were those from forest harvest activities, and dimensional lumber production.

Source location of wood for dimension lumber. Chetwynd Forest, British Columbia, Canada, which is owned by Canfor, the largest producer of softwood lumber in Canada. This forest is certified to Canadian Standards Association Sustainable Forest Management standard.

Data. Primary data were collected for harvest, transportation, and manufacturing life-cycle modules.

Characterization. Intergovernmental Panel on Climate Change method for converting greenhouse gases to global warming potential was employed (IPCC 1996).

Results. Researchers emphasized the distinction between the biological and the industrial carbon cycle. According to their literature review, most LCA studies have focused on the biological component of the forest carbon cycle. They state, "Many scientists who have studied forest product carbon budgets have suggested that forest products store carbon. However, their conclusions are based on gross carbon storage in the products and do not account for GHG released to produce and transport wood and paper products (Gower, et al. 2006)."

By accounting for the GHG releases due to forestry and timber industry operations, as well as transportation, they determined that this dimension-lumber product chain was a net carbon and

GHG source to the atmosphere. "The life-cycle analysis of the dimensional lumber chain revealed that 0.22 tonnes of carbon, or 0.83 tonne CO_2-eq, were emitted per ton of dimensional lumber (Gower, et al. 2006)." Indirect emissions were 98% of emissions for dimensional lumber.

Case Study: An Assessment of Carbon Pools, Storage, and Wood Products Market Substitution Using Life-cycle Analysis Results

Table. Summary of pertinent information from the study by Perez-Garcia, Lippke, et al. (2005)

STUDY SUMMARY	REFERENCE: (Perez-Garcia, Lippke, et al. 2005)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A5-A5, B1-B7
Life-cycle stages excluded	A1-A3, C1-C4
Assumptions	• Long-term products were assumed to decompose at the end of the useful life of a house, which was set at 80 years, within the range estimated by CORRIM. • The transporting and manufacturing emissions associated with non-biofuel co-products were not tracked so as to be consistent with the assumption that their use would carry their own burden.
Main conclusions	• When carbon stocks accounted only for forest sequestration, the longer the harvest cycle, the greater the amount of carbon removed from the atmosphere. • Forest products can be associated with fewer emissions than fossil fuel products.

Commissioners. U.S. Department of Agriculture Forest Service, Forest Products Laboratory, U.S. Department of Energy support for developing the research plan, and CORRIM's University Membership.

Scope. The movement of carbon and energy from forests to forest products was the object of this study. The study created three different carbon pools to be analyzed: forests, forest products, and fossil fuel substitution.

Source location of wood for dimension lumber. The study did not specified.

Data. The products module was based on LCA data produced by CORRIM. The module tracked carbon pools associated with production of forest products from the forest through to end use in the housing sector. Products that were exported from the forest as commercial volume were first converted into biomass and then into carbon using species-dependent density factors. An accounting model was made to make the calculations of the carbon from forests to end-use markets.

Characterization. No characterization was made.

Results. The study showed that shorter rotations lead to fewer carbon emissions, associated with less fossil fuels use. As an alternative, any portion of the short-lived products can be used for energy production, which would reduce purchased energy needs of sawmilling. The substitution of the wood for concrete does increase the carbon emissions in the residential housing market. The study indicated an inverse relationship between harvest age and sequestered carbon with the least amount of carbon stored with the no-harvest scenario. No specific data about CO_2 emissions were reported.

Case Study: Greenhouse Gas and Energy Based Life-cycle Analysis of Products from the Irish Wood Processing Industry

Table. Summary of pertinent information from the study by Murphy, Devlin, and McDonnell (2015)

STUDY SUMMARY	REFERENCE: (Murphy, Devlin and McDonnell 2015)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A2-A3,
Life-cycle stages excluded	A1, B1-B7, C1-C4
Assumptions	• No assumption was specified.
Main conclusions	• Forest operations and transportation of the raw material for sawnwood production had the greatest impact. • The synthetic resin usage was responsible for 62% of GHG emissions from MDF production. • GHG emissions are lower in the scenario 2, where sawmill is integrated with a CHP plant, which uses sawmill by-products to meet the electricity and heating requirements.

Commissioners. Charles Parsons Energy Research Programme of Science Foundation Ireland.

Scope. The intention of this study was to provide a broad knowledge of the environmental impacts caused by the Irish biomass supply chains incorporating the wood processing supply stage. This study is a cradle-to-gate LCA.

Source location of wood for dimension lumber. The study was based on Ireland conditions and industry.

Data. Foreground data for each of the scenarios described was provided by company records for the year 2012. Included from an earlier study are the environmental impacts of forestry operations in Ireland, including; seedling production, site establishment, harvesting, and haulage. The study examined different scenarios for the wood processing industry: scenario 1: conventional sawmill; scenario 2: sawmill with integrated CHP; scenario 3: sawmill integrated with pellet plant; scenario 4: sawmill integrated with CHP and pellet manufacture; scenario 5: pellet production from pulpwood; scenario 6: medium density fiberboard (MDF) production; scenario 7: oriented strand board (OSB) production.

Data. EcoInvent was used as the data source within SimaPro.

Results. The overall results of the study showed that electricity is responsible for the majority of GHG emissions in the wood processes. The GHG emissions associated with the manufacture of wood products utilizing the forecasted national grid mix for 2020 can be seen on the table below.

	Product	GWP, kg CO_2eq.	
		2012	2020
Scenario 1	Sawnwood (m^3)	40.2	36.3
	Chip (odt)	86.7	78.5
Scenario 2	Powered by CHP	—	—
Scenario 3	Sawnwood (m^3)	31.7	29.5
	Chip (odt)	68.6	63.6
	Wood Pellets (odt)	327.8	266.1
Scenario 4	Powered by CHP	—	—
Scenario 5	Wood Pellets (odt)	1102.5	881.5
Scenario 6	MDF (m^3)	896.7	856.8
Scenario 7	OSB (m^3)	235.6	217.4

Case Study: Life-cycle Assessment and Life-cycle Cost Implications for Roofing and Floor Designs in Residential Buildings

Table. Summary of pertinent information from the study by Islam, et al. (2015)

STUDY SUMMARY	REFERENCE: (Islam, et al. 2015)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A4-A5, B1-B7
Life-cycle stages excluded	A1-A3, C1-C4
Assumptions	• Where the data have not yet been collected from Australian sources, data from the European EcoInvent database were used, after being adjusted for Australian electricity and transportation. • The inflation rate used was 3%, which was the average in Australia for the past 10 years. • The year of 2011 was considered as the base of the study.
Main conclusions	• The construction and operation phases were responsible for the majority of the environmental impacts and costs.

Commissioners. Forest and Wood Products Australia.

Scope. A typical Australian residential townhouse was selected to be studied. The functional unit of this LCA is a house over its 50-year lifetime, including construction, operation (heating and cooling energy), maintenance and disposal.

Source location of wood for dimension lumber. Unknown.

Data. A complete list of all the components and amounts used to construct a building was provided by builder's Bill of Quantity (BOQ). The original BOQ was converted into units suitable for input into AccuRate, LCA and life-cycle costing. Data for operational energy (heating and cooling only) were calculated in AccuRate, and the values were converted into units suitable for LCA. Data from the Australian region specific database (AusLCI) were used wherever possible.

Characterization. AusLCI was used as the characterization method within SimaPro.

Results. The 13 houses studied, including the base house, showed that cumulative energy demand (CED) and GHG were the biggest environmental impacts for construction and operation phases. Water use was the biggest impact on the construction and maintenance, and solid waste generation was the biggest impact at disposal phase. The costs varied between phases. Construction and maintenance had 86 to 91% of total costs, and operation and disposal were relatively small. No specific data about CO_2 emissions were reported.

Case Study: Life-cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-efficiency Improvement Potential

Table. Summary of pertinent information from the study by Bribian, Capilla, and Uson (2011)

STUDY SUMMARY	REFERENCE: (Bribián, Capilla and Usón 2011)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• In the manufacture stage, the supply of materials, the associated transport needs and the factory manufacturing processes of the different construction materials are considered. • Regarding transport from the production plant to the building site, a 20e28 t lorry covering an average distance of 100 km has been considered.
Main conclusions	• Improvements on the production plants is necessary. • To facilitate recycling, demolition should be limited, because it makes the separation of the materials more complicated. • It is important to adjust the inventory database for each country because there was a difference in GWP of 23% when comparing studies of ordinary brick.

Commissioners. CIRCE - Centre of Research for Energy Resources and Consumption, Campus Río Ebro - University of Zaragoza, European Commission's Intelligent Energy for Europe Program, and the "PSE CICLOPE Project" co-financed by the Spanish Ministry of Science and Technology and the European Regional Development Fund.

Scope. LCA study is to evaluate certain energy and environmental specifications of different building materials, analyzing their possibilities for improvement and providing guidelines for materials selection.

Source location of wood for dimension lumber. The impact categories analyzed in this study were selected considering the current energy and environmental issues in the European area.

Data. The European averages of the EcoInvent v2.0 database (2007) inventories were selected for all analyzed stages. The study considered average data; its applicability to each European country depends on the level to which its specific characteristics (energy mix, manufacture technology, origin of the starting materials, etc.) are adapted to these averages.

Characterization. Eco-indicator 99 was used as the characterization method within SimaPro.

Results. The brick and tile LCA results are that ceramic floor tiles have the greatest primary demand per unit weight due to high consumption of natural gas in its manufacturer stage. The demand for water is also large because of the cooling process in the manufacturing process. Mixing cement with lower-impact materials such as gravel, sand or water helps to reduce the environmental impact. Wood can have a net absorption of emissions if it is recycled or reused instead of incinerated. Note that different weights of materials may be needed to cover a square area of surface. Also note that cement is shown for reference purposes only as cement is not a building product and typically is less than 14 percent of concrete.

Product	Global Warming Potential, kg CO_2eq./kg	Product	Global Warming Potential, kg CO_2eq./kg
Ordinary brick	0.271	Cement	0.819
Light clay brick	-0.004	Cement mortar	0.241
Sand-lime brick	0.120	Reinforced concrete	0.179
Ceramic tile	0.857	Concrete	0.137
Quarry tile	0.290	Sawn timber, softwood, planed, kiln dried	0.300
Ceramic roof tile	0.406	Sawn timber, softwood, planed, air dried	0.267
Concrete roof tile	0.270	Glued laminated timber, indoor use	0.541
Fibre cement roof slate	1.392	Oriented strand board	0.620
EPS foam slab	7.336	Reinforced steel	1.526
Rock wool	1.511	Aluminium	8.571
Polyurethane rigid foam	6.788	Polyvinylchloride	4.267
Cork slab	0.807	Flat glass	1.136
Cellulose fibre	1.831	Copper	1.999
Wood wool	0.124		

Case Study: Using Life-cycle Assessment to Derive an Environmental Index for Light-frame Wood Wall Assemblies

Table. Summary of pertinent information from the study by Frenette, et al. (2010)

STUDY SUMMARY	REFERENCE: (Frenette, et al. 2010)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A5, B1-B7, C1-C4
Life-cycle stages excluded	None
Assumptions	• Site development issues, such as land disturbance, ecosystem alteration and destruction of vegetation, associated with the construction are not included in the analysis. • Materials not available in the Athena database were replaced with the most similar products available.
Main conclusions	• The LCA showed how sensitive it is for different sources of energy, so is important to select the more accurate energy used as possible. • The results showed the small impact of the wood framing and other wood-based products on the total embodied impact.

Commissioners. Département des sciences du bois et de la forêt, Université Laval, Québec, Canada; CIRAIG, École Polytechnique de Montréal, Québec, Canada; Wood Laboratory, EMPA, Dübendorf, Switzerland.

Scope. Explore the possibility of using LCA principles to define an appropriate environmental index to include in the framework comparing factory-built wood-frame exterior wall alternatives. The first phase of this study is an LCA of the case study following the four phases recommended by ISO 14040 standards (ISO 2006b, ISO 2006c). The second is the Life Cycle Inventory (LCI) calculation for each alternative using the Athena™ Environmental Impact Estimator software that includes North-American databases. The third phase is the aggregation of the results, with different LCI approaches. The last phase is the interpretation.

Source location of wood for dimension lumber. The geographical source of each product is determined according to regional market share analyses, although all off shore products are treated as though they were manufactured in North America. The methodology of the study was based on a case study, comparing the environmental performance of five alternative wall assemblies for the exterior walls of a residential building in Quebec City, Canada.

Data. The LCI was performed using Athena software, which integrates LCI databases and general processes providing a cradle-to-grave analysis for this context.

Characterization. Eco-indicator 99, IMPACT 2002+, and TRACI were used as the characterization method within Athena software.

Results. Some external claddings (brick and vinyl) and insulation materials (glass fiber and extruded polystyrene) have the biggest influence on the final embodied impact of the wall assemblies, and the wood frame has a small environmental impact compared to other building materials. The difference based on the energy used illustrates how the consideration of the American electricity grid mix for the operation energy increases considerably the environmental impacts. A visible result is that even the fact that LCA takes into account the operation energy, the results actually depend on the energy source. Even though some insulation materials have, in general, more environmental impacts than others, these impacts are relatively small compared to the saving of operation energy. Furthermore, the aggregation of the damage indicators into a single environmental index is controversial, since it implies a subjective weighting of these impacts. No specific data about CO_2 emissions were reported.

Case Study: Wood as a Building Material in the Light of Environmental Assessment of Full Life Cycle of Four Buildings

Table. Summary of pertinent information from the study by Pajchrowski, et al. (2014)

STUDY SUMMARY	REFERENCE: (Pajchrowski, et al. 2014)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A5, B1-B7, C1-C4
Life-cycle stages excluded	None
Assumptions	• The study was made for a 100 years use stage, so the difference in the environmental impacts came from the production of the different materials, and final disposal of demolition waste. • The study assumed that the fact that wood can be considered a renewable and carbon neutral material, decreasing these differences in the environmental impacts.
Main conclusions	• Wooden buildings were the ones that used less energy. • Using wood material for construction has carbon neutral balance, and makes possible the recovery of the energy by incineration. • Wood requires more maintenance, and two times more use of materials considered harmful for environment as impregnates, resins, and paints.

Commissioners. Polish Ministry of Science and Higher Education and the Wood Technology Institute in Poznan, Poland.

Scope. An LCA of building materials in Europe, comparing the energy used.

Source location of wood for dimension lumber. Four single-family residential buildings—meeting the European requirements with the usable area of 98.04 m^2 for a four-person family—were analyzed for the study. These buildings differed in material structure, building technology, and the energy standard.

Data. The goal of this study was to analyze and assess the potential environmental advantages of using wood in construction for houses. Having one group of researchers perform a comparison between four functionally equivalent houses can be recognized as a strong point of the study, because the initial assumptions, data quality, system boundaries were similar for all analyzed objects. These buildings were assumed to have the same energy requirements for a 100-year use stage.

Characterization. Impact 2002+ was used as the characterization method within SimaPro and EcoInvent was used as the database.

Results. The results show that the wooden buildings have a lower environmental impact than the masonry buildings in the majority of life-cycle stages. Wooden buildings have the most advantage for the environment due to the photosynthesis that occurs during the “cradle” step. No specific data about CO_2 emissions were reported.

Case Study: Cradle-to-Gate Life-Cycle Inventory and Impact Assessment of Wood Fuel Pellet Manufacturing from Hardwood Flooring Residues in the Southeastern United States

Table. Summary of pertinent information from the study by Reed, et al. (2012)

STUDY SUMMARY	REFERENCE: (Reed, et al. 2012)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A3,
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• All data from the survey were weighted average for the six plants based on each mill's production for 1 year. • Environmental impacts associated with the pellet mill equipment and any replacement parts were not included. • Product transportation was beyond the scope of the study.
Main conclusions	• The most significant inputs for pellet operations are wood residues and electricity. • The electricity required during pelletization contributes significantly. • Applying the mass allocation procedure for wood flooring manufacturing, the production of wood residues from hardwood lumber contributes the most to the total environmental impacts of wood pellets products. • The plastic bag used for bagging pellets represents a smaller, but still significant, impact in some categories.

Commissioners. University of Tennessee, U.S. Department of Agriculture Forest Service, Nisus Corporation, Mississippi State University, Oregon State University, WoodLife Environmental Consulting, and commercial pellet manufactures

Scope. An LCI of the use of dry hardwood flooring residues for bagged pellet production in the Southeast region of the United States. The LCI did not consider the product transportation. The system boundary includes inputs from the technosphere as well as the pelletization process.

Source location of wood for dimension lumber. This study focused a particular type of pellet operation (operations that use hardwood flooring residues) in the U.S. Southeast.

Data. Twenty-four (24) mills for the Southeast region in operation at the time of survey were contacted and sent an LCI survey from October to December 2009. Just six of them (about 25%) responded with complete data. The inputs are wood waste from wood flooring manufacturing, energy, lubricants, and water. The output is bagged wood fuel pellet. Life-cycle data for wood residue production were provided on a mass allocation basis.

Characterization. TRACI model was used as the characterization method within SimaPro.

Results. The most significant inputs for pellet operations are wood residues and electricity. The cumulative life-cycle emissions and wastes associated with wood pelletization are pregate (associated with wood flooring production and electricity production). The largest impact for each category is carried over from the wood residue material. The additional input of electricity for pelletization has an important impact on most categories. The electrical energy and other inputs were consistent with other reports. No specific data about CO_2 emissions were reported.

Case Study: Life-cycle Impacts of Forest Resource Activities in the Pacific Northwest and Southeast United States

Table. Summary of pertinent information from the Johnson, et al. (2005) study

STUDY SUMMARY	REFERENCE: (Johnson, et al. 2005)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A2
Life-cycle stages excluded	A3-A5, B1-B7, C1-C4
Assumptions	• Estimates of tree biomass by component were then used to estimate the standing and removed carbon pool over time. • The total cost and fuel consumption over the life of the stand were calculated as the sum of all forest management activities, including commercial thinning and final harvest. • Fine roots grow and decompose at the same rate.
Main conclusions	• Transportation-related activities were the greatest contributor to emissions. • Primary direct emissions from forest operations are due to combustion of diesel and gasoline engines.

Commissioners. U.S. Department of Agriculture Forest Service, Forest Products Laboratory; U.S. Department of Energy; CORRIM; and private companies.

Scope. An LCA of forest operations in both the Pacific Northwest and Southeast United States. The LCA practitioners only studied flows due to the first module of the product stage of the life cycle—harvest.

Source location of wood for dimension lumber. The amount of biomass that was yield from the Pacific Northwest and the Southeast United States were calculated using three separate scenarios for each region. The three different scenarios included varying intensity of forest management and site productivity and were used to calculate the amount of vegetation growth using a vegetation simulator that was developed for each region. A majority of the supply to the timber industry in the United States comes from these two regions.

Data. Data on management intensities and site class of forests were collected from the Resource Planning Assessment database from the U.S. Forest Service. Site preparation and stand establishment data were taken from existing studies. Stand treatment options were developed by the North Carolina Tree Nutrition Cooperative and the University of Washington for the Southeast and Pacific Northwest regions, respectively. Data on harvesting activities were gathered from personal interviews and published information. Carbon production estimates were developed with the NUTREM2 model, which is used in the Southeast United States. For the Pacific Northwest, the amount of carbon was calculated by the authors.

Characterization. Eco-indicator 99 was used as the characterization method within SimaPro.

Results. The greatest contributor to the emissions is the combustion of diesel in the forestry equipment. The higher factors for the Southeast region generally reflect the increased use of mechanized site preparation and the higher levels of fertilization intensity.

Projected Emissions	Southeast Base, kg/m^3 harvested log	Southeast Alternate, kg/m^3 harvested log	Pacific Northwest Base, kg/m^3 harvested log	Pacific Northwest Alternate, kg/m^3 harvested log
CO_2 (fossil)	9.25	9.71	8.02	8.12
CH_4	6.29 x 10^{-3}	1.27 x 10^{-2}	1.71 x 10^{-3}	2.47 x 10^{-3}
N_2O	7.63 x 10^{-4}	1.88 x 10^{-3}	6.21 x 10^{-5}	1.84 x 10^{-4}

Case Study: Cradle-to-Gate Life-cycle Assessment of Softwood Lumber Production from the Southeast

Table. Summary of pertinent information from the study by Puettmann, et al. (2013)

STUDY SUMMARY	REFERENCE: (Puettmann, Oneil and Milota, et al. 2013)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• This LCA report is for planed (surfaced), dry, dimension lumber produced from logs.
Main conclusions	• Emission from forest resources is relatively smaller than that from manufacturing stage. • Using wood residue for drying process during the production makes the process favorable with respect to energy use. • Using TRACI impact method, which does not count the contribution of emissions from burning wood fuel, a net storage of 861 kg CO_2eq. was calculated for each cubic meter of lumber production.

Commissioner. CORRIM, the Consortium for Research on Renewable Industrial Materials.

Scope. A cradle-to-gate LCA of planed dry softwood lumber production in the southeast with a scope that covers forest regeneration through the final product at the mill gate.

Source location of logs for lumber. The logs are obtained from the forest resource base located in Georgia, Alabama, Mississippi, and Louisiana as representative of the region.

Data. Life cycle inventory data was based on the CORRIM LCI reports by Milota, West and Hartley (2005 and 2004) and Johnson, et al. (2005) with updates according to SE forest operations and boiler, and electrical grid data. Detailed primary data were collected from four large production pine mills in the southeast. These data include the material and energy inputs and outputs for each unit process for either calendar year 1999 or 2000. Data for packaging was collected from sampling and personal communications with manufactures. Secondary data on electrical grid inputs was adopted from the U.S. LCI database (Goemans 2010). Use phase data is not within the scope of the study.

Characterization. TRACI was used as the characterization method within SimaPro.

Results. To produce a cubic meter of lumber, 1.16 m^3 roundwood is needed from southeast forest. Emissions from forestry operation and manufacturing stage are 11.32 and 60.65 kg CO_2eq./m^3 of products, respectively. The CO_2eq. stored in product is 933.17 kg CO_2eq./m^3 of products.

Case Study: Cradle-to-Gate Life-cycle Assessment of Softwood Lumber Production from the Inland Northwest

Table. Summary of pertinent information from the study by Puettmann and Oneil (2013)

STUDY SUMMARY	REFERENCE: (Puettmann and Oneil 2013)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• This LCA report is for planed (surfaced), dry, dimension lumber produced from logs.
Main conclusions	• Emission from forest resources is relatively smaller than that from manufacturing stage. • Using wood residue for drying process during the production makes the process favorable with respect to energy use. • Using TRACI impact method, which does not count the contribution of emissions from burning wood fuel, a net storage of 676 kg CO_2eq. was calculated for each cubic meter of lumber production.

Commissioners. CORRIM, the Consortium for Research on Renewable Industrial Materials.

Scope. A cradle-to-gate LCA of planed dry softwood lumber production in the Inland Northwest with a scope that covers forest regeneration through the final product at the mill gate.

Source location of logs for lumber. The logs are obtained from the forest resource base located in Inland Northwest.

Data. Logs are obtained from the forest resource base in the eastern Washington, eastern Oregon, Idaho and western Montana. The forest resources data is mainly based on secondary data that were derived using U.S. Forestry Service Forest Inventory and Analysis census data and applying harvest treatments and volume removals with the 30 years harvest rates for the region. The production inventory data is primary data collected from four large production pine mills in the region. Data for packaging was collected from sampling and personal communications with manufactures. Secondary data on electrical grid inputs were adopted from the U.S. LCI database (Goemans 2010). Use phase data is not within the scope of the study.

Characterization. TRACI was used as the characterization method within SimaPro.

Results. To produce a cubic meter of lumber, 1.11 m^3 roundwood is needed from northwest forest. Emissions from forestry operation and manufacturing stage are 10.14 and 113.27 kg CO_2eq./m^3 of products, respectively. The CO_2eq. stored in product is 799.33 kg CO_2eq./m^3 of products.

Case Study: Cradle-to-Gate Life-cycle Assessment of Softwood Lumber Production from the Northeast-North Central

Table. Summary of pertinent information from the study by Puettmann, Oneil, and Bergman (2013)

STUDY SUMMARY	REFERENCE: (Puettmann, Oneil and Bergman 2013)
Carbon cycle considered	Biological and Industrial
Life-cycle stages included	A1-A3
Life-cycle stages excluded	A4-A5, B1-B7, C1-C4
Assumptions	• This LCA report is for planed (surfaced), dry, dimension lumber produced from logs. • Cut off rules of less than 1% of cumulative mass/energy were applied.
Main conclusions	• Emissions from forest operations is relatively small compared to that from the manufacturing stage. • Using TRACI impact method, which does not count the contribution of emissions from burning wood fuel, a net storage of 585 kg CO_2eq. was calculated for each cubic meter of lumber production.

Commissioners. CORRIM, the Consortium for Research on Renewable Industrial Materials.

Scope. A cradle-to-gate LCA of planed dry softwood lumber production in the Northeast/North Central.

Source location of logs for lumber. The logs are obtained from the forest resource base located in Northeast/North Central.

Data. Primary data on forest operation and forest regeneration as well as secondary data on forest growth and harvesting were collected from sites in Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin. The input data of wood boiler and hazardous air pollutants in the manufacturing process were collected by survey while the combustion emissions were adopted from the U.S. LCI database.

Characterization. TRACI was used as the characterization method within SimaPro.

Results. To produce a cubic meter of lumber, 1.11 m^3 roundwood is needed from Northeast/North Central forest. Emissions from forestry operation and manufacturing stage are 14.52 and 78.38 kg CO_2eq./m^3 of products, respectively. The CO_2eq. stored in product is 678.32 kg CO_2eq./m^3 of products.

ASSESSMENT AND RECOMMENDATIONS

In reviewing the many LCAs conducted on wood products and wood structures, there was a lack of consistency and completeness in the studies. The LCAs varied greatly in carbon-pool accounting methods, assumptions of forestry management practices, and scopes, such as system boundaries, allocation procedures, and assumptions. PwC and the Forest Products Association of Canada warn that "carbon accounting methodologies are still evolving, therefore it is important to ensure that the assumptions made are fully understood when interpreting or using LCA results (PwC 2010)."

However, owners are consulting these studies when making decisions about how to lower the environmental footprint of structures. It is imperative, therefore, that the shortcomings revealed in this paper be recognized and addressed, and that future research be performed ensure better consistency and completeness of wood LCA studies in the future.

Inconsistencies or information lacking in the reviewed LCI and LCA studies can be grouped into four main categories. In general, these studies

- Did not account for carbon from all five carbon pools as identified by the IPCC (2003).
- Assumed that the global carbon pool is steady.
- Did not verify whether wood came from a sustainably managed forest.
- Varied scopes considerably.

Not All Carbon Pools Are Considered

A component that is missing from the reviewed studies is accounting of carbon from all carbon pools established by the IPCC. According to the *IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry*, **accounting of the forest stock include five carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon** (IPCC 2003)**. Most studies limited the scope to emissions related to above-ground biomass considering only the roundwood**, and occasionally considering other above-ground biomass, deadwood, and litter. Natural degradation of non-roundwood left at the logging site is likely to cause emissions of methane, which is not considered in most of these scenarios. **The environmental impact of above-ground biomass should include all carbon emissions released due to fertilizer use, road construction, landing sites, logging residue, wood processing, wood processing residue, and transportation.** Logging activities release a substantial amount of carbon into the atmosphere that is not captured in stored in wood products. An LCA of wood should account for all sources and sinks of carbon. Current forest ecosystems store more carbon than is present in the atmosphere (Ingerson 2009), and proper accounting of losses from that sink is necessary. In general, land plants (and the soil they grow on) contain about 10 times more carbon than all the anthropogenic carbon in the atmosphere (Heiken, Jelen and Stevens 2008).

Carbon that is stored in soil and below-ground biomass is significant and should be considered in an LCA of wood. One study calculated that forest degradation and land-use change are responsible for 20% of recent anthropogenic carbon emissions (Ingerson 2009). "Early research by Covington (1981) indicated that forest floor biomass decreased by half during the 15 years following clear-cutting of northern hardwood stands, presumably due to faster decomposition and reduced deposition of litter (Ingerson 2009)."

Although the ground biomass pool can be largely stored in product pool, **harvesting will cause reduction of soil carbon** by an average of 8% ± 3% with a 95% confidence interval (Nave, et al. 2010). The loss of these forests will cause the releasing of this carbon into the atmosphere as carbon dioxide. This process is irreversible.

Current LCA methodology is to consider the sequestered carbon as a net value in the LCI that is shown separately in the reporting of impacts. This sequestered carbon value does not consider the effect on soil, or carbon emissions from other above-ground biomass deadwood, litter, or below-ground biomass. The Wood PCR allows for the assumption that CO_2 emitted due to the burning of wood products is equal to the wood sequestered by forests during the growing process, that is, a neutral CO_2 balance. **The Wood PCR does not account for soil carbon changes due to forest growth or harvest, nor the effect on carbon pools due to below-ground biomass, other above-ground biomass, deadwood, or litter.**

Some guidance is given on accounting for other carbon pools. For example, according to the Product Standard (WRI and WBCSD 2011), analyses are required to report method used to calculate land-use change impacts in the GHG inventory. But to calculate the true carbon footprint of wood, all sources and sinks of carbon from the five carbon pools must be included in an LCA.

Not All Forests Have Equivalent Carbon Pools

A primary premise of carbon-neutrality of wood is based on a steady carbon pool in the forests. But there is a common misconception that steady deforestation rates equate to steady forest carbon pools. The global deforestation rate is falling with an annual average of deforestation of 0.13% (FAO 2010). However, the **net deforestation rate cannot be used as a sole indicator of the quality of forests**.

Between 2000 and 2010, the world total forest area lost is approximately 130 million hectares (321 million acres), which was 3.2% of the total forest area in 2000. According to a recent report from Global Forest Watch, **Canada and Russia have become leaders in deforestation**, overtaking more tropical countries like Brazil. The study found that Russia and Canada combined to make up about one-third of global tree cover loss between 2011 and 2013, averaging a combined 67,337 km^2 (26,000 square miles) each year.

While many countries have been able to stabilize their forest area, nine countries are experiencing net deforestation rates of more than 2% (more than 10 times the global rate), which will result in the loss of most of their forests within the century. Worldwide, 39% of the frontier forests are under moderate or high threats that can cause declines in wildlife and plant populations or large-scale changes in the age of the forest.

The long growth period of wood makes a young forest much different than a mature one in terms of carbon sequestration. Planted reforesting usually favors monoculture forest, which decreases biodiversity, causes erosion and sediment pollution, and results in less attractive landscape (Gronow 2001). Although these modified forests provide important economic and ecological services, they may not support the complex and inimitable ecological communities and processes and cannot sustain themselves in the long term (Gronow 2001).

"For older forests with a low risk of major disturbances, conversion to young, fast-growing forest will cause large amounts of GHG emissions as the old stand is removed . . . and it may take decades or even centuries for a sustainable harvest regime to work off this initial carbon debt (Ingerson 2009)." The **afforestation practice does reduce the forest carbon stock in the long term**.

Yet there is rarely consideration of the age of a forest when conducting an LCA.

Not All Forests Are Sustainably Managed

Carbon neutrality of wood products is also based on the assumption that the wood comes from a sustainably managed forest. **While forest certification is generally growing, it is still a small portion of total acreage accounting for only 25% of the acreage in the U.S. and 10% globally** (ASTM 2015)**. For those forests that are certified to a forest standard, this does not ensure that the forest practices are sustainable**. In the U.S. and Canada, wood tends to be SFI and FSC certified, though wood from an SFI forest is not technically "sustainably managed," which is indicated below. An LCA of wood should verify that the wood comes from a sustainably managed forest, if such is the case. In addition, the true environmental impact of the forest management industry and timber processing industry should be accounted for in an LCA of wood.

Most wood ends up as waste or non-durable goods (paper and pallets). Logging activities release a lot of carbon into the atmosphere that is not captured in stored in wood products. Logging kills trees, which stops them from storing carbon and stops them from transferring carbon to the soil. Logging accelerates decomposition rates by removing forest canopy and raising soil temps. Logging debris is frequently burned, which immediately releases carbon to the atmosphere. Logging practices also increase the risk of forest fire, and logging roads are disruptive to the natural environment. Logging releases more carbon than forest fires (Heiken, Jelen and Stevens 2008).

For the 10% of forests that are managed by a sustainable forestry scheme, typically a chain-of-custody component is included to trace forest products from their sources. Because only 10% of forests are sustainably managed, many wood products come from sources that are not sustainably managed and quite possibly are from countries that have active deforestation ongoing.

There is potential to manage forests sustainably given the components of sustainable forestry schemes, but the current programs lack enforcement and geographical coverage to ensure all forest products should be considered carbon neutral. Comparisons of the FSC and SFI sustainable forestry schemes are available (Roberts 2015). In general, **SFI does not ensure a sustainably managed forest** because it:

- Allows large clear cuts
- Does not require protection of threatened or endangered species
- Allows timber companies to determine whether the use of toxic pesticides is allowable
- Does not require protection of old-growth stands within SFI-certified forests

These programs recognize that techniques and rate of harvesting, road and trail construction and maintenance, and the choice of species affect long-term soil degradation or adversely impact water quality, quantity or substantial deviation from stream course drainage patterns. FSC considers the diversity of species and age classes as well as wildlife corridors and streamside zones. FSC also states that the choice of species shall not result in long-term soil degradation or adverse impacts on water quality, quantity, or substantial deviation from stream course drainage patterns. But the sustainable forestry management schemes currently only monitor, rather than enforce, these practices. **Even worse is that these factors are not included in any LCI or LCA rules, schemes, or best practices.** Thus the industry realizes that practices affect the environment but do not encourage their inclusion in an environmental assessment or LCA.

Inconsistent Scopes

The scopes of the life cycle assessments of wood harvesting, wood products, and wood structures have inconsistent scopes. Inconsistencies were most common in the life-cycle stages considered, the intermingling or confusion between biological and industrial carbon, the treatment of sequestered carbon dioxide, the intermingling or confusion between carbon dioxide and carbon dioxide equivalent, and the accounting of carbon offsets (wood material substitution or displacement factors).

In addition, **many studies assumed that the carbon flux related to the use of biogenic materials was carbon neutral.** But few full life-cycle assessments have been made of energy use and carbon emissions associated with wood products from harvest (including regrowth to preharvesting levels) to disposal that would support that assumption. "Several sources indicate that energy use and other emissions associated with these stages can be substantial, perhaps even greater than the CO_2-equivalent stored in the finished wood products (Ingerson 2009)."

Nonetheless, researchers frequently calculated the amount of carbon sequestered in the wood based on its species and average carbon content, then assumed that was the amount of carbon that would be released into the atmosphere once the wood product was burned or decayed at its end-of-life. However, the EPA *Framework for Assessing Biogenic CO_2 Emissions* warns against making this assumption. It states that **biomass should not be assumed to be carbon neutral a priori**. According to the framework, "there are circumstances in which biomass is grown, harvested and combusted in a carbon neutral fashion but carbon neutrality is not an appropriate a priori assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle (USEPA 2014)."

Upstream impacts. The consideration of the environmental impacts due to the extraction of wood products was inconsistently considered in the various LCA studies. **The boundary of an LCA of wood products should extend from the decision to harvest trees (including regrowth to preharvesting levels) to the disposal of wood products made with those trees** (Ingerson 2009).

When the carbon sequestration was considered, it was frequently double counted. Carbon-sequestration benefits were touted as an offset to the environmental impacts associated with upstream wood activities (extraction and harvesting). Then again at the end of the life cycle, the emissions due to end-of-life (burning or being buried in the landfill and decaying) were declared to be offset by the carbon sequestered in the original product. A consistent method is needed to account for the sequestered carbon. **Current LCA methodology is to consider the sequestered carbon as a net value in the LCI that is shown separately in the reporting of impacts.**

Use phase. When evaluating the environmental impact of a building, it is well known that, in locations where energy is primarily fossil fuel based, the use phase is responsible for the majority of the building's environmental impact. In fact, in LCAs where the energy use attributed to the use phase was modeled for the specific building being studied, the results of full, cradle-to-grave

LCA of buildings with various structural materials were similar. However, in comparative assertions where the use phase was not included, or where energy use in all buildings was considered the same, the wood structures were consistently reported to have the least environmental impact of all the structural materials considered.

While the former is allowed according to ISO 14044 (ISO 2006c), **it is misleading to claim environmental superiority based on a limited life cycle.** Likewise, the latter assumption of equal energy use among the different structures studied was not justified and is known to be a false assumption. Different structural materials contribute to the energy use of a building due to characteristics of the materials, such as thermal mass.

Biological versus industrial carbon. There are two sources of carbon dioxide that are associated with the growth, harvesting, manufacturing, use, and disposal of wood products. The biological carbon cycle begins with a tree that assimilates carbon dioxide from the atmosphere during its growth. About half of the carbon dioxide that is assimilated is stored as vegetation, and the other half is released back to the atmosphere via autotrophic respiration (Gower, et al. 2006). This carbon dioxide is transformed into carbon within the tree and makes up about half of the tree's biomass (Gower, et al. 2006). This carbon stays sequestered in the biomass of the wood until the wood is burned or decomposes, releasing the carbon back into the atmosphere as either carbon dioxide or methane.

The industrial carbon cycle associated with wood products is an accounting of all carbon dioxide emitted due to upstream processes, transportation, manufacturing, use, and disposal of the wood products from the technosphere. These two sources of carbon are frequently confused or not explicitly separated during LCA studies.

Treatment of sequestered carbon dioxide. Carbon sequestration only occurs in the forest as a result of photosynthesis. The amount of carbon (biological) that can be stored in wood depends largely on the species and can be calculated. There was no common practice among the reviewed LCA studies in either the individual reporting of biological and industrial carbon, or in the combination of the biological and industrial carbon regardless of the life-cycle stages included in the study. For example, an LCA performed for a cradle to gate scope, if the amount of carbon sequestered is subtracted from the amount of industrial GWP due to the cradle-to-gate scope, then it is not clear how much carbon is sequestered in the wood product itself. This means, that if a practitioner wishes to use that information as an upstream input to a full LCA, they will not know how much carbon dioxide is released at the end of the life cycle. PWC and the Forest Products Association of Canada recommend reporting separately the "carbon emission from biomass and from fossil origin (PwC 2010)." The authors agree that **sequestered carbon should be reported as a separate item for the greatest transparency**.

Carbon offsets. A standardized accounting method to properly account for all carbon emissions from wood products is needed. Although several areas of inconsistency have been identified for LCA conducted on wood, a few are related to increased transparency in reporting. LCA needs to account for all industrial emissions upstream (due to planting, growth to preharvesting conditions, and harvesting); treatment of sequestered carbon dioxide shown as a negative value in a separate column for GWP, not as subtracted from the total (this will facilitate treatment of carbon at end-of-life); and proper accounting of carbon emissions due to burning of biofuels (should not be shown as negative).

Increased transparency and standardized reporting of greenhouse gas emissions is needed for forest products including wood products. Given the many unit process steps involved in making wood products, it is important for researchers to clearly identify which part of the forest industry and timber industry unit process are included in a study. Standardized terminology for different process steps would improve transparency in reporting.

Second, **carbon neutrality of wood products should not be assumed a priori.** The amount of carbon stored in a final wood product can be calculated based on the wood species. This amount of carbon sequestered in the wood should be listed separately from the carbon emissions and GWP associated with the industrial components of the wood extraction, transportation, manufacturing, construction, use, and end-of-life. Transportation effects can be significant because most lumber is shipped large distances for projects that are not located in the Southeast United States where there are numerous tree farms or Northwest United States where there are numerous managed forests.

Finally, carbon dioxide emissions from the burning of biomass should not be reported as a negative carbon dioxide equivalent or GWP value. The burning of biomass on the forest floor and the use of biomass as fuel release CO_2 and other emissions to the atmosphere, similar or sometimes in greater quantity than fossil fuels. This is misleading. Instead, the emissions from burning of biomass should be reported separately from the carbon dioxide equivalent or GWP due to equivalent energy from other sources. More work is needed to report these emission values based on equivalent energy creation. In addition, particulate matter should be reported for both burning of biomass and burning of fossil-fuel sources.

Other Consequences

There can be drastic consequences of miscalculating the true carbon footprint of wood products. One consequence of assuming that all wood is carbon neutral is that wood waste is often treated as renewable energy. It is true that wood is renewable in that it can be regrown on a human timescale. But unfortunately, this is not synonymous with carbon neutrality. Europe requires 15% of total energy to come from renewable sources by 2020, and the UK is using wood pellets from the southern U.S. to meet this requirement (Dwivedi, et al. 2014). As a result, Europe allows biomass pellets to meet renewable energy standard even though woody biomass is actually an overall contributor to GHG emissions on a 20 to 30 year time scale.

This is largely due to a general misunderstanding that wood pellets would be made from scraps or waste products (with no subsequent processing), but that isn't the case. In some locations, whole forests are being clear-cut to keep up with demand (Phillips 2015). "**In order for wood pellets to burn 'carbon free' the carbon emitted into the atmosphere must be recaptured by regenerated forests, which take several decades to grow.** If these emissions aren't offset, then burning wood pellets releases as much or more carbon dioxide per unit of energy than coal (Phillips 2015)." Leaving forestry waste on the forest floor or composting would also delay the release of carbon emitted into the atmosphere.

In the United States, there has been strong pushback from scientists about the U.S. Environmental Protection Agency's (EPA's) claim that burning wood biomass reduces emissions. A memo from acting assistant administrator for the Office of Air and Radiation, Janet McCabe, on November 19, 2014 (McCabe memo) credits the use of woody biomass for energy as reducing emissions. In February 2015, **a group of 78 scientists sent a letter to the EPA rejecting the allowance of treating burned wood biomass as carbon-emissions free** (Aneja, et al. 2015)**.**

They state, "Burning biomass instead of fossil fuels does not reduce the carbon emitted by power plants. In fact, as EPA itself acknowledges, burning biomass degrades facility efficiency and increases day-to-day emissions over emissions when fossil fuels are burned alone (Aneja, et al. 2015)." They continue that this policy precedent may encourage additional harvest of forests, which leads to reduction in carbon storage pools. "**Numerous studies have shown that when whole trees are harvested to replace coal, the result is an increased transfer of carbon to the air for decades due to the lower carbon efficiency of using wood than fossil fuels** (Aneja, et al. 2015)." According to the Washington Post, the scientists' premonition is happening. Between 2012 and 2014, the United States has doubled its export of wood pellets as companies try to keep up with demand from Europe (Warrick 2015).

The IPCC notes that emissions due to converting forests to bioenergy production can create so many upfront emissions that it may take "decades or centuries before net emissions savings are achieved (IPCC 2012)."

According to the U.S. Energy Information Agency, to achieve a 4% increase of U.S. electricity production by biomass would require an increase of wood harvest equivalent to 70% of the U.S. timber harvest by 2035. This large amount of harvest to achieve small gains in electricity production is due to inefficiencies in converting biomass to energy (Aneja, et al. 2015; Phillips

2015). Demand for wood pellets could rise to as much as 50 million metric tons a year. Especially as countries with some of the largest forests assets in the world, such as Canada, South America, Southeast Asia, and even Russia, begin to consider woody biomass as a fuel option (Phillips 2015).

Missing Impacts

Although this paper focused on carbon footprint, there are huge environmental issues besides carbon dioxide emissions that should be evaluated when evaluating the environmental impact of wood. **While the sequestration of carbon makes it favorable to forest products to consider only the carbon footprint, a full assessment should include all significant impacts.** For example, it is evident that clearcuts cause huge loss of the mycorrhizae (soil fungi), and of subsequent generations of trees (Ferriel and Grenier 2010). Harvesting removes species and not all previous species can be supported in the lack of diversity in the replanted forests.

Another impact missing from LCI studies is human health impacts. Human health effects of burning wood and wood pellets are sometimes considered in terms of particulates. However, many more emissions to air are due to the combustion of wood and biomass including (USEPA 2015):

- Fine particulate matter (PM2.5)
- Carbon monoxide (CO)
- NO_x, VOCs, PAHs, black carbon
- Heavy metals (arsenic, lead, mercury)
- Air toxics such as benzene

An example of the emissions from burning wood is the San Francisco Bay Area Winter Spare the Air requirements (Spare the Air 2015). When a “Spare the Air” alert is in effect, it is illegal to burn wood, manufactured fire logs, pellets, or any other solid fuels in a residential fireplace, woodstove, or outdoor fire pit. These possible daily alerts are called because wood smoke is the largest source of harmful particulate pollution in area during the winter season. In another example, the use of wood to heat homes in Tacoma, Washington, has caused the ambient air quality standards for ozone to be exceeded.

Even though some impact categories, such as biodiversity or land use change, can have a large uncertainty so are not included in EPDs yet, it is important that they are included in LCI as best available information to assess the full environmental impact of wood (Grant 2015). **At a minimum, land occupation (in area-years) should be disclosed.**

Research Needs

Accounting for carbon from all five pools. To account for the true environmental impact of wood, all carbon that is affected by wood harvest and use should be accounted for in LCA studies. LCA practitioners, decision makers, and the forestry industry could all benefit from a best practice guide on how to account for carbon from all five carbon pools: (1) above-ground biomass, (2) below-ground biomass, (3) deadwood, (4) litter and (5) organic soil carbon.

Disclose wood source and deforestation rate. There should be a requirement to disclose wood source and deforestation rate from source location in LCA. This would ensure the reader that the five carbon pools were considered in the study, and that the carbon emissions and sinks are calculated or estimated rather than assumed.

Consider age and rotation of trees. A requirement to consider age and rotation of trees in LCA would be useful. Different species and ages of trees sequester carbon dioxide at different rates, and older trees sequester much more than younger trees.

Model forest management activities. LCA practitioners would benefit from basic framework for modeling forest management activities in LCA. Understanding forest management activities may seem daunting, however a basic framework would facilitate the practitioner including these activities in LCA studies of wood.

Consider upstream impacts. Forest management activities should be included in life-cycle stage A1. Yet, full consideration of these impacts is rare in current LCA studies of wood. There should be a mandatory requirement to consider the upstream (Forest management) impacts.

Report sequestered carbon separately. Sequestered carbon should be reported separately in LCA studies. This should be considered a best practice and promoted among LCA practitioners. The sequestered amount needs to be shown separately from carbon emissions so that practitioners know how much carbon dioxide is released back to the atmosphere when the wood reaches the end-of-life stage.

Study of impact with and without harvesting. A study of impact with and without harvesting is needed with the do-nothing scenario as a base case. Sampson and Hair found that that the 25-year-old forest sequesters about 1.1 kg (2.5 lb) of CO_2 per tree per year, while the 120-year-old forest sequesters about 2.7 kg (6 lb) per tree per year (Sampson and Hair 1996). As a simple thought experiment, assuming the increase in sequestration is linear, harvesting at 25 years (which common practice in the Southeast) eliminates the opportunity for the tree to sequester an additional 170 kg (380 lb) of carbon if harvested at 120 years. If the tree were harvested at 220 years, which is well within the natural lifespan of the tree, an additional 430 kg

(940 lb) of carbon could be sequestered. Using this approach, each tree harvested causes a negative carbon sequestration of over one-half tonne (1/2 ton) of CO_2. Of course, this is a simplistic approach and more needs to be done to have better estimates of the foregone sequestration due to early harvest.

Create regional LCI data for forest products. The often-cited reason for not including using biodiversity, land use, and other forest management impacts has been that these vary regionally and the regional data are not available. Regional data is not available for much of other LCI—just consider the lack of data for manufacturing materials and products in China. **For forest products, as a start, regional data could be developed for the Pacific Northwest and the southeastern U.S. and for Canada.** Many of the studies referenced in this paper have some process data for these regions. Proxy data should be used and is generally better than no data at all. If proxy data or the regional data are not correct, it will motivate the development of more accurate data, as has been the case for many product manufacturers.

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APPENDIX I:

Forest Stewardship Council

FSC's mission is to promote environmentally sound socially beneficial, and economically prosperous management of the world's forests. One of the ways it meets its mission is by administering a Forest Management Certification Program. Through this program, forests can attain certification that ensures that it is managed according to FSC's 10 principles and 57 criteria. The 10 principles include:

- Compliance with laws and FSC principles
- Tenure and use rights and responsibilities
- Indigenous peoples' rights
- Community relations and worker's rights
- Benefits from the forest
- Environmental impact
- Management plan
- Monitoring and assessment
- Maintenance of high conservation value forests
- Plantations

For a forest to achieve FSC Forest Management certification in the United States, the forest is audited to the *FSC-US Forest Management Standard (v1.0)* (Forest Stewardship Council 2010). This standard outlines the 10 FSC principles and the requirements for demonstrating compliance with the principles. A list of the criteria under each principle is included in the following sections.

Compliance with laws and FSC principles. Criteria and indicators under this principle allow the forest managers to demonstrate that they meet the any applicable federal, state, or local laws and comply with any international treaties or agreements where the United States is a signatory. Requirements for demonstration of compliance with FSC principles and criteria are also included in this section. Criteria under this principle include (Forest Stewardship Council 2010):

- Forest management shall respect all national and local laws and administrative requirements.
- All applicable and legally prescribed fees, royalties, taxes and other charges shall be paid.

- In signatory countries, the provisions of all binding international agreements such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), International Labour Organization (ILO) Conventions, and Convention on Biological Diversity, shall be respected.
- Conflicts between laws, regulations and the FSC Principles and Criteria shall be evaluated for the purposes of certification on a case by case basis, by the certifiers and the involved or affected parties.
- Forest management areas should be protected from illegal harvesting, settlement and other unauthorized activities.
- Forest managers shall demonstrate a long-term commitment to adhere to the FSC Principles and Criteria.

Tenure and use rights and responsibilities. Through the criteria and indicators under this principle, forest managers must clearly define, document, and legally establish the long-term tenure and use rights to the land and forest resources. **In the U.S., 33% of forests are owned by the federal government, 11% are owned by state governments, 21% are family-owned, and 35% are owned by companies. This ownership profile is distinctly different from other countries** (ASTM 2015)**.** Criteria under this principle include (Forest Stewardship Council 2010):

- Clear evidence of long-term forest use rights to the land (for example, land title, customary rights, or lease agreements) shall be demonstrated.
- Local communities with legal or customary tenure or use rights shall maintain control, to the extent necessary to protect their rights or resources, over forest operations unless they delegate control with free and informed consent to other agencies.
- Appropriate mechanisms shall be employed to resolve disputes over tenure claims and use rights. The circumstances and status of any outstanding disputes will be explicitly considered in the certification evaluation. Disputes of substantial magnitude involving a significant number of interests will normally disqualify an operation from being certified.

Indigenous peoples' rights. Forest managers must recognize and respect the rights (legal and customary) of indigenous peoples to own, use, and manage their lands, territories, and resources. Criteria under this principle include (Forest Stewardship Council 2010):

- Indigenous peoples shall control forest management on their lands and territories unless they delegate control with free and informed consent to other agencies.

- Forest management shall not threaten or diminish, either directly or indirectly, the resources or tenure rights of indigenous peoples.
- Sites of special cultural, ecological, economic or religious significance to indigenous peoples shall be clearly identified in cooperation with such peoples, and recognized and protected by forest managers.
- Indigenous peoples shall be compensated for the application of their traditional knowledge regarding the use of forest species or management systems in forest operations. This compensation shall be formally agreed upon with their free and informed consent before forest operations commence.

Community relations and worker's rights. Forest operations that comply with the FSC Forest Management certification program must maintain or enhance the well being of forest workers and local communities. Criteria under this principle include (Forest Stewardship Council 2010):

- The communities within, or adjacent to, the forest management area should be given opportunities for employment, training, and other services.
- Forest management should meet or exceed all applicable laws and/or regulations covering health and safety of employees and their families.
- The rights of workers to organize and voluntarily negotiate with their employers shall be guaranteed as outlined in Conventions 87 and 98 of the International Labor Organization (ILO).
- Management planning and operations shall incorporate the results of evaluations of social impact. Consultations shall be maintained with people and groups (both men and women) directly affected by management operations.
- Appropriate mechanisms shall be employed for resolving grievances and for providing fair compensation in the case of loss or damage affecting the legal or customary rights, property, resources, or livelihoods of local peoples. Measures shall be taken to avoid such loss or damage.

Benefits from the forest. Criteria and indicators under this principle allow the forest managers to demonstrate that forest management operations encourage efficient use of forest products to ensure economic viability, environmental benefit, and social benefit. Criteria under this principle include (Forest Stewardship Council 2010):

- Forest management should strive toward economic viability, while taking into account the full environmental, social, and operational costs of production, and ensuring the investments necessary to maintain the ecological productivity of the forest.

- Forest management and marketing operations should encourage the optimal use and local processing of the forest's diversity of products.
- Forest management should minimize waste associated with harvesting and on-site processing operations and avoid damage to other forest resources.
- Forest management should strive to strengthen and diversify the local economy, avoiding dependence on a single forest product.
- Forest management operations shall recognize, maintain, and, where appropriate, enhance the value of forest services and resources such as watersheds and fisheries.
- The rate of harvest of forest products shall not exceed levels that can be permanently sustained.

Environmental impact. Through the criteria and indicators under this principle, forest managers must maintain the ecological function and integrity of the forest by conserving biodiversity, water and soil resources, and unique and fragile ecosystems and landscapes. Criteria under this principle include (Forest Stewardship Council 2010):

- Assessment of environmental impacts shall be completed—appropriate to the scale, intensity of forest management and the uniqueness of the affected resources—and adequately integrated into management systems. Assessments shall include landscape level considerations as well as the impacts of on-site processing facilities. Environmental impacts shall be assessed prior to commencement of site-disturbing operations.
- Safeguards shall exist which protect rare, threatened and endangered species and their habitats (for example, nesting and feeding areas). Conservation zones and protection areas shall be established, appropriate to the scale and intensity of forest management and the uniqueness of the affected resources. Inappropriate hunting, fishing, trapping and collecting shall be controlled.
- Ecological functions and values shall be maintained intact, enhanced, or restored, including:
  - Forest regeneration and succession.
  - Genetic, species, and ecosystem diversity.
  - Natural cycles that affect the productivity of the forest ecosystem.
- Representative samples of existing ecosystems within the landscape shall be protected in their natural state and recorded on maps, appropriate to the scale and intensity of operations and the uniqueness of the affected resources.

- Written guidelines shall be prepared and implemented to: control erosion; minimize forest damage during harvesting, road construction, and all other mechanical disturbances; and protect water resources.
- Management systems shall promote the development and adoption of environmentally friendly non-chemical methods of pest management and strive to avoid the use of chemical pesticides. World Health Organization (WHO) Type 1A and 1B and chlorinated hydrocarbon pesticides; pesticides that are persistent, toxic or whose derivatives remain biologically active and accumulate in the food chain beyond their intended use; as well as any pesticides banned by international agreement, shall be prohibited. If chemicals are used, proper equipment and training shall be provided to minimize health and environmental risks.
- Chemicals, containers, liquid and solid non-organic wastes including fuel and oil shall be disposed of in an environmentally appropriate manner at off-site locations.
- Use of biological control agents shall be documented, minimized, monitored and strictly controlled in accordance with national laws and internationally accepted scientific protocols. Use of genetically modified organisms shall be prohibited.
- The use of exotic species shall be carefully controlled and actively monitored to avoid adverse ecological impacts.
- Forest conversion to plantations or non-forest land uses shall not occur, except in circumstances where conversion:
  - Entails a very limited portion of the forest management unit; and
  - Does not occur on high conservation value forest areas; and
  - Will enable clear, substantial, additional, secure, long-term conservation benefits across the forest management unit.

Management plan. Forest managers must implement a management plan, including long-term objectives and the means for meeting the objectives. Criteria under this principle include (Forest Stewardship Council 2010):

- The management plan and supporting documents shall provide:
- Management objectives.
- Description of the forest resources to be managed, environmental limitations, land use and ownership status, socio-economic conditions, and a profile of adjacent lands.
- Description of silvicultural and/or other management system, based on the ecology of the forest in question and information gathered through resource inventories.
- Rationale for rate of annual harvest and species selection.
- Provisions for monitoring of forest growth and dynamics.
- Environmental safeguards based on environmental assessments.
- Plans for the identification and protection of rare, threatened and endangered species.

- Maps describing the forest resource base including protected areas, planned management activities and land ownership.
- Description and justification of harvesting techniques and equipment to be used.
- The management plan shall be periodically revised to incorporate the results of monitoring or new scientific and technical information, as well as to respond to changing environmental, social and economic circumstances.
- Forest workers shall receive adequate training and supervision to ensure proper implementation of the management plan.
- While respecting the confidentiality of information, forest managers shall make publicly available a summary of the primary elements of the management plan, including those listed in Criterion 7.1 (the first bullet in this section).

Monitoring and assessment. To comply with the FSC Forest Management certification program, forest managers must monitor and assess the forest condition, forest yield, chain of custody, operations management, and the environmental and social impacts of these activities. Criteria under this principle include (Forest Stewardship Council 2010):

- The frequency and intensity of monitoring should be determined by the scale and intensity of forest management operations as well as the relative complexity and fragility of the affected environment. Monitoring procedures should be consistent and replicable over time to allow comparison of results and assessment of change.
- Forest management should include the research and data collection needed to monitor, at a minimum, the following indicators:
- Yield of all forest products harvested.
- Growth rates, regeneration and condition of the forest.
- Composition and observed changes in the flora and fauna.
- Environmental and social impacts of harvesting and other operations.
- Costs, productivity, and efficiency of forest management.

- Documentation shall be provided by the forest manager to enable monitoring and certifying organizations to trace each forest product from its origin, a process known as the "chain of custody."
- The results of monitoring shall be incorporated into the implementation and revision of the management plan.
- While respecting the confidentiality of information, forest managers shall make publicly available a summary of the results of monitoring indicators, including those listed in Criterion 8.2 (the second bullet in this section).

Maintenance of high-conservation-value forests. Criteria and indicators under this principle require that forest managers maintain or enhance the attributes of high-conservation-value forests. Criteria under this principle include (Forest Stewardship Council 2010):

- Assessment to determine the presence of the attributes consistent with High Conservation Value Forests will be completed, appropriate to scale and intensity of forest management.
- The consultative portion of the certification process must place emphasis on the identified conservation attributes, and options for the maintenance thereof.
- The management plan shall include and implement specific measures that ensure the maintenance and/or enhancement of the applicable conservation attributes consistent with the precautionary approach. These measures shall be specifically included in the publicly available management plan summary.
- Annual monitoring shall be conducted to assess the effectiveness of the measures employed to maintain or enhance the applicable conservation attributes.

Plantations. Forest managers of plantations must implement a management plan that promotes the restoration and conservation of natural forests. Criteria under this principle include (Forest Stewardship Council 2010):

- The management objectives of the plantation, including natural forest conservation and restoration objectives, shall be explicitly stated in the management plan, and clearly demonstrated in the implementation of the plan.
- The design and layout of plantations should promote the protection, restoration and conservation of natural forests, and not increase pressures on natural forests. **Wildlife corridors, streamside zones and a mosaic of stands of different ages and rotation periods shall be used in the layout of the plantation**, consistent with the scale of the operation. The scale and layout of plantation blocks shall be consistent with the patterns of forest stands found within the natural landscape.
- Diversity in the composition of plantations is preferred, so as to enhance economic, ecological and social stability. Such diversity may include the size and spatial distribution of management units within the landscape, number and genetic composition of species, age classes and structures.
- The selection of species for planting shall be based on their overall suitability for the site and their appropriateness to the management objectives. In order to enhance the conservation of biological diversity, native species are preferred over exotic species in the establishment of plantations and the restoration of degraded ecosystems. Exotic species, which shall be used only when their performance is greater than that of native

species, shall be carefully monitored to detect unusual mortality, disease, or insect outbreaks and adverse ecological impacts.

- A proportion of the overall forest management area, appropriate to the scale of the plantation and to be determined in regional standards, shall be managed so as to restore the site to a natural forest cover.
- Measures shall be taken to maintain or improve soil structure, fertility, and biological activity. The techniques and rate of harvesting, road and trail construction and maintenance, and **the choice of species shall not result in long term soil degradation or adverse impacts on water quality, quantity or substantial deviation from stream course drainage patterns.**
- Measures shall be taken to prevent and minimize outbreaks of pests, diseases, fire and invasive plant introductions. Integrated pest management shall form an essential part of the management plan, with primary reliance on prevention and biological control methods rather than chemical pesticides and fertilizers. Plantation management should make every effort to move away from chemical pesticides and fertilizers, including their use in nurseries.
- Appropriate to the scale and diversity of the operation, monitoring of plantations shall include regular assessment of potential on-site and off-site ecological and social impacts, (for example, natural regeneration, effects on water resources and soil fertility, and impacts on local welfare and social well-being). No species should be planted on a large scale until local trials and/or experience have shown that they are ecologically well-adapted to the site, are not invasive, and do not have significant negative ecological impacts on other ecosystems. Special attention will be paid to social issues of land acquisition for plantations, especially the protection of local rights of ownership, use or access.
- Plantations established in areas converted from natural forests after November 1994 normally shall not qualify for certification. Certification may be allowed in circumstances where sufficient evidence is submitted to the certification body that the manager/owner is not responsible directly or indirectly of such conversion.

APPENDIX II:

Sustainable Forestry Initiative

For a forest to achieve SFI Forest Management certification in the United States, the forest is audited to the *SFI 2015-2019 Forest Management Standard* (Sustainble Forestry Initiative 2015). This standard outlines the 15 SFI objectives and the performance measures and indicators for demonstrating compliance with the objectives.

SFI promotes responsible forestry practices by certifying forests to its Forest Management standard. Through this program, forests can attain certification that ensures that it is managed according to SFI's 15 objectives, 37 performance measures, and 101 indicators. The 15 objectives include:

- Forest Management Planning
- Forest Health and Productivity
- Protection and Maintenance of Water Resources
- Conservation of Biological Diversity
- Management of Visual Quality and Recreational Benefits
- Protection of Special Sites
- Efficient Use of Fiber Resources
- Recognize and Respect Indigenous Peoples' Rights
- Legal and Regulatory Compliance
- Forestry Research, Science and Technology
- Training and Education
- Community Involvement and Landowner Outreach
- Public Land Management Responsibilities
- Communications and Public Reporting
- Management Review and Continual Improvement

Forest management planning. Performance measures and indicators under this objective ensure forest managers plan for long-term, sustainable harvest levels to avoid forest conversion. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Ensure that forest management plans include long-term harvest levels that are sustainable and consistent with appropriate growth-and-yield models.
- Not convert one forest cover type to another forest cover type, unless in justified circumstances.

- Not have within the scope of their certification to this *SFI 2015-2019 Forest Management Standard*, forestlands that have been converted to non-forestland use.

Forest health and productivity. The performance indicators and indicators under this objective are meant to ensure long-term forest productivity, carbon storage, and conservation of resources. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Reforest promptly after final harvest.
- Minimize chemical use required to achieve management objectives while protecting employees, neighbors, the public and the environment, including wildlife and aquatic habitats.
- Implement forest management practices to protect and maintain forest and soil productivity.
- Manage so as to protect forests from damaging agents, such as environmentally or economically undesirable wildfire, pests, diseases, and invasive exotic plants and animals, to maintain and improve long-term forest health, productivity and economic viability.
- Use best scientific methods when deploying improved planting stock, including varietal seedlings.

Protection and maintenance of water resources. Forest managers must protect water qualities through best management practices. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Meet or exceed all applicable federal, provincial, state and local water quality laws, and meet or exceed best management practices developed under Canadian or U.S. Environmental Protection Agency–approved water quality programs.
- Implement water, wetland and riparian protection measures based on soil type, terrain, vegetation, ecological function, harvesting system, state best management practices (BMPs), provincial guidelines and other applicable factors.

Conservation of biological diversity. Forest operations that contribute to conservation of biological diversity and forest plants and animals, and well as manage the quality and distribution of wildlife habitats, are contained in this section. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Conserve biological diversity.

- Protect threatened and endangered species, Forests with Exceptional Conservation Values (FECV) and old-growth forests.
- Manage ecologically important sites in a manner that takes into account their unique qualities.
- Apply knowledge gained through research, science, technology and field experience to manage wildlife habitat and contribute to the conservation of biological diversity.

Management of visual quality and recreational benefits. Performance measures and indicators under this objective ensure forest managers manage the visual impact of forest activities and provide recreational activities. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Manage the impact of harvesting on visual quality.
- Manage the size, shape and placement of clearcut harvests.
- Adopt a greenup requirement or alternative methods that provide for visual quality. Greenup requirements are the criteria for evaluating the relationship of a new harvest area with adjacent areas.
- Support and promote recreational opportunities for the public.

Protection of special sites. Through the performance indicators and indicators under this objective, forest managers must manage lands that are geologically or culturally important. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Identify special sites and manage them in a manner appropriate for their unique features.

Efficient use of fiber resources. Forest managers must minimize waste and use resources efficiently. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Employ appropriate forest harvesting technology and in-woods manufacturing processes and practices to minimize waste and ensure efficient utilization of harvested trees, where consistent with other *SFI 2015-2019 Forest Management Standard* objectives.

Recognize and respect indigenous peoples' rights. Forest operations that comply with the SFI Forest Management certification program must recognize and respect indigenous peoples. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Recognize and respect Indigenous Peoples' rights.

- Confer with affected Indigenous Peoples with respect to sustainable forest management practices when forest management activities occur on public lands.
- Respond to local Indigenous Peoples with respect to sustainable forest management practices on their private lands

Legal and regulatory compliance. Performance measures and indicators under this objective ensure forest managers comply with applicable laws and regulations. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Comply with applicable federal, provincial, state and local forestry and related social and environmental laws and regulations.
- Take appropriate steps to comply with all applicable social laws at the federal, provincial, state and local levels in the country in which the Program Participant operates.

Forestry research, science and technology. Through the performance indicators and indicators under this objective, forest managers must invest in forestry research. Under this objective, program participants shall individually and/or through cooperative efforts involving SFI Implementation Committees, associations or other partners (Sustainble Forestry Initiative 2015):

- Provide in-kind support or funding for forest research to improve forest health, productivity and sustainable management of forest resources, and the environmental benefits and performance of forest products.
- Develop or use state, provincial or regional analyses in support of their sustainable forestry programs.
- Broaden the awareness of climate change impacts on forests, wildlife and biological diversity.

Training and education. Forest managers must provide training and education to improve the implementation of sustainable forestry operations. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Require appropriate training of personnel and contractors so that they are competent to fulfill their responsibilities under the *SFI 2015-2019 Forest Management Standard*.
- Work—individually and/or with SFI Implementation Committees, logging or forestry associations, or appropriate agencies or others in the forestry community—to foster improvement in the professionalism of wood producers.

Community involvement and landowner outreach. Forest managers that comply with the SFI Forest Management certification program must provide public outreach and education to broaden the practice of sustainable forestry. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Support and promote efforts by consulting foresters, state, provincial and federal agencies, state or local groups, professional societies, conservation organizations, Indigenous Peoples and governments, community groups, sporting organizations, labor, universities, extension agencies, the American Tree Farm System® and/or other landowner cooperative programs to apply principles of sustainable forest management.
- Support and promote, at the state, provincial or other appropriate levels, mechanisms for public outreach, education and involvement related to sustainable forest management.
- Establish, at the state, provincial-or other appropriate levels, procedures to address concerns raised by loggers, consulting foresters, employees, unions, the public or other Program Participants regarding practices that appear inconsistent with the *SFI 2015-2019 Forest Management Standard* principles and objectives.

Public land management responsibilities. Performance measures and indicators under this objective ensure forest managers implement sustainable practice on public lands. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Participate in the development of public land planning and management processes.

Communications and public reporting. Through the performance indicators and indicators under this objective, forest managers must increase transparency by annually reporting progress. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Provide a summary audit report, prepared by the certification body, to SFI Inc. after the successful completion of a certification, recertification or surveillance audit to the *SFI 2015-2019 Forest Management Standard*.
- Report annually to SFI Inc. on their conformance with *the SFI 2015-2019 Forest Management Standard*.

Management review and continual improvement. Forest managers must conduct reviews and monitor performance to promote continual improvement. Under this objective, program participants shall (Sustainble Forestry Initiative 2015):

- Establish a management review system to examine findings and progress in implementing the *SFI 2015-2019 Forest Management Standard*, to make appropriate improvements in programs, and to inform their employees of changes.

APPENDIX III:

Summary of Life-cycle Assessment of Wood Products by Werner (Werner and Richter 2007)

Table IA. Evaluation of Relative Impacts of Wood Products Compared to Products Made of Conventional Materials.

	Energy			CML92/Eco indicator 95											Waste			Crit. Vol.	
	NonR	REN	CED	GWP	AP	EP	POP	ODP	ETW	ETS	HT	RA	CS	HM	Solid	Reac.	Haz.	Air	Water
Windows (Richter et al. 1996./Brunner et al. 1996l)																			
Wood/alu			+	+	+	+	+	+	+		-				+	++	-		
Wood/alu			+	+	++	+	+	+	+		-				+	++	--		
Aluminum			0	0	0	0	0	0	-		+				0	+	+		
Steel			-	0	0	-	-	-	-		0				-	0	--		
Stainless steel			+	+	0	0	0	+	+		+				+	+	+		
Non-ferrous steel			-	--	-	-	-	-	-		0				-	--	+		
PVC			+	+	0	0	0	+	+		+				+	+	+		
Insulation materials (Mötzl et al. 2000)																			
Wood fibre board	++	--		++	++	++	++		++		++								
Glass wool	-	+		--	--	--	-		+		-								
Cellulose fibres	++	++		++	++	++	++		++		++								
Perlite	++	++		+	++	++	++		++		++								
EPS	--	++		--	--	--	--		--		--								
Foamglass	--	+		--	--	--	+		0		--								
Mineral wool	+	++		0	+	+	++		+		+								
Vermiculite	++	++		++	+	+	++		+		+								
Floorings (Günther et al. 1997)																			
Parquet (3-layers)	+	--	-	--	++											++	++		
Linoleum	+	-	+	-	+											+	++		
Extruded PVC	0	++	+	+	0											+	--		
PVC	-	++	0	+	0											0	--		

Polyolefins	0	+	0	+	++										0	++		
Rubber	0	+	0	+	--										-	+		
Textile flooring	-	++	-	+	++										++	++		
Floorings (Jönsson 1999/Windsperger 1998)																			
Parquet	++			++	+	-	++								++	++	++		
Linoleum	-			+	+	0	--								++	-	--		
PVC	-			--	--	+	0								--	--	0		
Wall constructions (Werner et al. 1996)																			
Wood frame				++	+	++	++	++	+	++	+								
Laminated timber board				++	-	+	+	+	--	+	-								
Brick wall, 2-layered				--	--	--	-	-	-	-	-								
Porous cement bricks				-	0	0	0	-	0	-	0								
Doorframes (Werner et al. 1996)																			
Particleboard	+	--	0	0	0	0	0	0				0	+	++					
Solid wood	+	-	+	+	+	++	+	+				0	++	++					
Galvanized Steel	-	++	-	-	--	--	-	-				0	--	--					
Railway sleepers (Künniger et al.1998)																			
Beech wood			-	0	-	0		-							0	-	0		
Steel			+	0	0	0		0							0	0	0		
Concrete			+	0	+	0		0							+	+	0		
Utility poles (Künniger et al. 1997)																			
Roundwood CCF	++	--	+	++	++	+	+								++				
Concrete	+	++	+	+	+	0	+								--				
Tubular steel	--	++	--	--	--	-	--								+				
Elements of landscape architecture (Künniger et al. 2000)																			
Swings: wood			+	+	+	+	+	+	--	+	-								
Swings: steel			-	-	-	-	-	-	+	-	+								
Swings: steel (with duplex)			-	-	-	-	-	-	+	++	+								
Palisades: wood			-	+	++	+	+	+	--	0	--								
Palisades: concrete			+	--	-	-	-	-	++	++	++								

Blinds: wood (vertical filling)			+	++	++	++	++	++	-	-	++								
Blinds: wood (diagonal filling)			+	++	++	+	++	++	--	-	+								
Blinds: lime stone bricks			-	-	-	-	--	--	+	++	-								
Blinds: bricks			-	--	--	--	--	-	+	++	--								
Blinds: concrete			0	-	-	-	0	-	+	++	-								
Posts vineyard: roundwood			-	+	++	++	+	+	-	++	-								
Posts vineyard: quart. Roundw			+	+	++	++	+	+	--	++	-								
Posts vineyard: reinf.concrete			0	-	-	-	--	--	++	++	+								
Posts vineyard: galv. steel			-	-	--	--	0	-	+	--	+								
Posts fruit yard: roundwood			+	+	+	+	+	+	--	++	-								
Posts fruit yard: quart.roundw			+	+	+	+	+	+	--	++	-								
Posts fruit yard: PVC			+	0	0	+	-	+	++	++	+								
Posts fruit yard: galv.steel			--	--	--	--	-	-	+	--	+								
Residential houses (Boyer et al. 2004/Lippke et al. 2004)																			
Cold climate; wood			0	+											0			0	++
Cold climate; steel			0	-											0			0	--

Warm climate; wood			0	+											+			+	0
Warm climate; concrete			0	-											-			-	0

Evaluation: ++: very positive (, 50% of average impact); +: positive (50% to 90% of average impact); 0: average (90%-110% of average impact);-: negative (110%-150% of average impact); --: very negative (> 150% of average impact). Abbreviations: NonR: non-renewable energy; REN: renewable energy; CED: cumulated energy demand; GWP 100: global warming potential (100 years); AP: acidification potential; EP: eutrophication potential; POP: photochemical ozone formation potential (photosmog); ODP: (stratospheric) ozone depletion potential; ETW: eco-toxicity potential water; ETS: eco-toxicity potential soil; HT: human toxicity potential; RA: radioactivity; CS: carcinogenic substances; HM: heavy metals

APPENDIX IV:

Energy and Resource Consumption Used for the Analysis of Different Forest Management Intensity

Table IIA. Southeastern United States Scenarios: Specific Assumptions for Three Management Scenarios Applied to Private Forest Lands in the Southeastern United States

	Low intensity	Medium intensity	High intensity
Site index	58	67	80
Planting density (trees/acre)	726	726	726
Fertilization	none	Years 2, 16	Years 2,5,9,13,17,21
First thinning (m^3) at year	0	63	59
		17	13
Second thinning (m^3) at year	0	0	58
			19
Final harvest (m^3) at year	220	175	295
	30	25	25
Total yield/hectare (m^3)	220	238	323
Rotation age	30 years	25 years	25 years
% sawlog	3.20%	20.20%	42.70%
% chip-n-saw	34.90%	11.20%	8.90%
% pulpwood	61.90%	68.60%	48.40%
% area in class for base case	37%	58%	5%
% area in class for alternative case	0%	37%	63%
Seedling, site preparation, planting, and fertilizer consumption			
	Low intensity	Medium intensity	High intensity
	Fuel consumption (gal/acre)		
Greenhouse and seedling	5.46	5.46	5.46
Site preparation	2.16	7.86	14.18
Planting	0.71	0.71	0.71
Pre-commercial thin	0.00	0.00	0.00
Total	8.32	14.02	20.34
	Pounds / acre over rotation		
Nitrogen in seedlings	0.125	0.125	0.125
on site	0	236	636
Phosphate in seedlings	0.006	0.006	0.006
on site	0	40	115
Potassium in seedlings	0.075	0.075	0.075

on site	0	0	0

APPENDIX V:

Impact Analysis Results for Flooring, Sheathing, and Radiant Barriers

Flooring.

Impact category	Forest management	Production	Construction	Use	End of life	Total
Global warming (kg CO2 eq/m2)	3.46E-01	6.6E+00	6.7E-01	0	8.8E-01	8.5E+00
Acidification (kg SO2 eq/m2)	1.78E-01	7.1E-02	3.9E-03	0	2.3E-03	2.6E-01
Eutrophication (kg N eq/m2)	2.41E-04	4.4E-03	4.9E-03	0	4.8E-02	5.8E-02
Smog (kg O3 eq/m2)	2.84E-03	8.2E-01	1.0E-01	0	6.4E-02	9.9E-01
Ozone depletion (kg CFC-11 eq/m2)	5.73E-08	8.9E-08	4.6E-09	0	3.2E-08	1.8E-07
Total primary energy consumption	Forest management	Production	Construction	Use	End of life	Total
Non-renewable fossil (MJ)	6.20E+00	2.1E+02	8.8E+00	0	4.8E+00	2.3E+02
Non-renewable nuclear (MJ)	9.21E-02	7.8E-01	9.4E-02	0	1.3E-01	1.1E+00
Renewable (solar, wind, hydro, geothermal) (MJ)	1.25E-03	1.3E-01	3.1E-02	0	1.6E-02	1.8E-01
Renewable (biomass) (MJ)	3.06E-03	1.1E+02	9.6E-03	0	7.7E-03	1.1E+02

Sheathing.

Impact category	Forest management	Production	Construction	Use	End of life	Total
Global warming (kg CO2 eq/m2)	2.82E-01	4.8E+00	7.2E-01	0	7.2E-01	6.5E+00
Acidification (kg SO2 eq/m2)	1.61E-01	5.5E-02	5.7E-03	0	1.9E-03	2.2E-01
Eutrophication (kg N eq/m2)	2.49E-04	6.0E-03	4.2E-03	0	3.9E-02	4.9E-02
Smog (kg O3 eq/m2)	2.57E-03	7.2E-01	1.6E-01	0	5.3E-02	9.4E-01
Ozone depletion (kg CFC-11 eq/m2)	3.97E-08	7.7E-08	4.4E-09	0	2.6E-08	1.5E-07
Total primary energy consumption	Forest Management	Production	Construction	Use	End of life	Total
Non-renewable fossil (MJ)	5.16E+00	1.6E+02	9.5E+00	0	3.9E+00	1.8E+02
Non-renewable nuclear (MJ)	6.96E-02	7.0E-01	9.3E-02	0	1.0E-01	9.6E-01
Renewable (solar, wind, hydro, geothermal) (MJ)	1.03E-03	2.7E-01	3.1E-02	0	1.3E-02	3.2E-01
Renewable (biomass) (MJ)	2.29E-03	9.2E+01	9.6E-03	0	6.3E-03	9.2E+01

Roof/wall sheathing.

Impact category	Forest management	Production	Construction	Use	End of life	Total
Global warming (kg CO2 eq/m2)	2.50E-01	4.0E+00	5.4E-01	0	6.5E-01	5.4E+00
Acidification (kg SO2 eq/m2)	1.42E-01	4.1E-02	3.1E-03	0	1.7E-03	1.9E-01
Eutrophication (kg N eq/m2)	2.21E-04	5.1E-03	3.7E-03	0	3.5E-02	4.4E-02
Smog (kg O3 eq/m2)	2.25E-03	5.3E-01	8.3E-02	0	4.7E-02	6.6E-01
Ozone depletion (kg CFC-11 eq/m2)	3.43E-08	9.4E-08	5.3E-09	0	2.3E-08	1.6E-07
Total primary energy consumption	Forest management	Production	Construction	Use	End of life	Total
Non-renewable fossil (MJ)	4.54E+00	1.0E+02	7.1E+00	0	3.5E+00	1.2E+02
Non-renewable nuclear (MJ)	6.12E-02	1.4E+00	8.3E-02	0	9.3E-02	1.6E+00
Renewable (solar, wind, hydro, geothermal) (MJ)	9.16E-04	1.8E-01	3.0E-02	0	1.1E-02	2.2E-01
Renewable (biomass) (MJ)	2.01E-03	9.1E+01	9.0E-03	0	5.7E-03	9.1E+01

Radiant barrier.

Impact category	Forest management	Production	Construction	Use	End of life	Total
Global warming (kg CO2 eq/m2)	2.52E-01	4.8E+00	6.4E-01	0	7.4E-01	6.4E+00
Acidification (kg SO2 eq/m2)	1.43E-01	5.0E-02	3.9E-03	0	1.8E-03	2.0E-01
Eutrophication (kg N eq/m2)	2.24E-04	4.6E-03	3.7E-03	0	3.4E-02	4.3E-02
Smog (kg O3 eq/m2)	2.26E-03	6.8E-01	1.0E-01	0	4.9E-02	8.3E-01
Ozone depletion (kg CFC-11 eq/m2)	3.45E-08	1.4E-07	5.4E-09	0	2.4E-08	2.0E-07
Total primary energy consumption	Forest management	Production	Construction	Use	End of life	Total
Non-renewable fossil (MJ)	5.56E+00	1.2E+02	8.5E+00	0	3.6E+00	1.4E+02
Non-renewable nuclear (MJ)	6.87E-02	2.0E+00	8.3E-02	0	1.0E-01	2.3E+00
Renewable (solar, wind, hydro, geothermal) (MJ)	1.05E-03	2.7E-01	3.0E-02	0	1.2E-02	3.1E-01
Renewable (biomass) (MJ)	2.46E-03	1.1E+02	9.0E-03	0	6.1E-03	1.1E+02