The Carbon Impacts of Wood Products

Richard Bergman
Maureen Puettmann
Adam Taylor
Kenneth E. Skog

Abstract

Wood products have many environmental advantages over nonwood alternatives. Documenting and publicizing these merits helps the future competitiveness of wood when climate change impacts are being considered. The manufacture of wood products requires less fossil fuel than nonwood alternative building materials such as concrete, metals, or plastics. By nature, wood is composed of carbon that is captured from the atmosphere during tree growth. These two effects—substitution and sequestration—are why the carbon impact of wood products is favorable. This article shows greenhouse gas emission savings for a range of wood products by comparing (1) net wood product carbon emissions from forest cradle–to–mill output gate minus carbon storage over product use life with (2) cradle-to-gate carbon emissions for substitute nonwood products. The study assumes sustainable forest management practices will be used for the duration of the time for the forest to regrow completely from when the wood was removed for product production during harvesting. The article describes how the carbon impact factors were developed for wood products such as framing lumber, flooring, moulding, and utility poles. Estimates of carbon emissions saved per unit of wood product used are based on the following: (1) gross carbon dioxide (CO_2) emissions from wood product production, (2) CO_2 from biofuels combusted and used for energy during manufacturing, (3) carbon stored in the final product, and (4) fossil CO_2 emissions from the production of nonwood alternatives. The results show notable carbon emissions savings when wood products are used in constructing buildings in place of nonwood alternatives.

Evaluating the environmental impact of product choices is increasingly important to help address sustainability issues. Wood products have many environmental advantages over nonwood alternatives (Wegner et al. 2010, Lippke et al. 2011, Ritter et al. 2011, Eriksson et al. 2012). One advantage is a lower *global warming impact,* which refers to the impact on climate change of product production from emissions of greenhouse gases (GHGs) to the atmosphere. Although there are many GHGs, carbon dioxide (CO_2) gas released from burning fossil fuels is the main driver of global warming (Intergovernmental Panel on Climate Change [IPCC] 2013). To provide some context on the magnitude of the problem, we looked at global fossil fuel CO_2 emissions. The US Energy Information Agency (US EIA) reported that in 2011, global fossil fuel CO_2 emissions were about 35.9 billion tons,[1] an increase of 3.4 percent from 2010, with China contributing the most at 9.6 billion tons (US EIA 2014a). The increase in global carbon emissions occurred even though the United States, the second largest contributor at 6.1 billion tons, had lower emissions in 2011 than 2010.

An area of huge concern is fossil fuel and cement emissions because of their ties to building construction, particularly in Southeast Asia (i.e., China), where fossil fuel resources are consumed to build residential structures (Wang et al. 2013). For example, although global fossil fuel and cement emissions declined 1.4 percent in 2009

[1] The present article was written with the wood building products industry in mind. Therefore, English units will be used instead of metric units.

The authors are, respectively, Research Forest Products Technologist, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (rbergman@fs.fed.us [corresponding author]); Owner, WoodLife Environmental Consultants, LLC, Corvallis, Oregon (maureen.puettmann@woodlifeconsulting.com); Associate Professor and Wood Products Extension Specialist, Tennessee Forest Products Center, Univ. of Tennessee, Knoxville (AdamTaylor@utk.edu); and Supervisory Research Forester, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (kskog@fs.fed.us). This paper was received for publication in May 2014. Article no. 14-00047.

Forest Prod. J. 64(7/8):220–231.
doi:10.13073/FPJ-D-14-00047

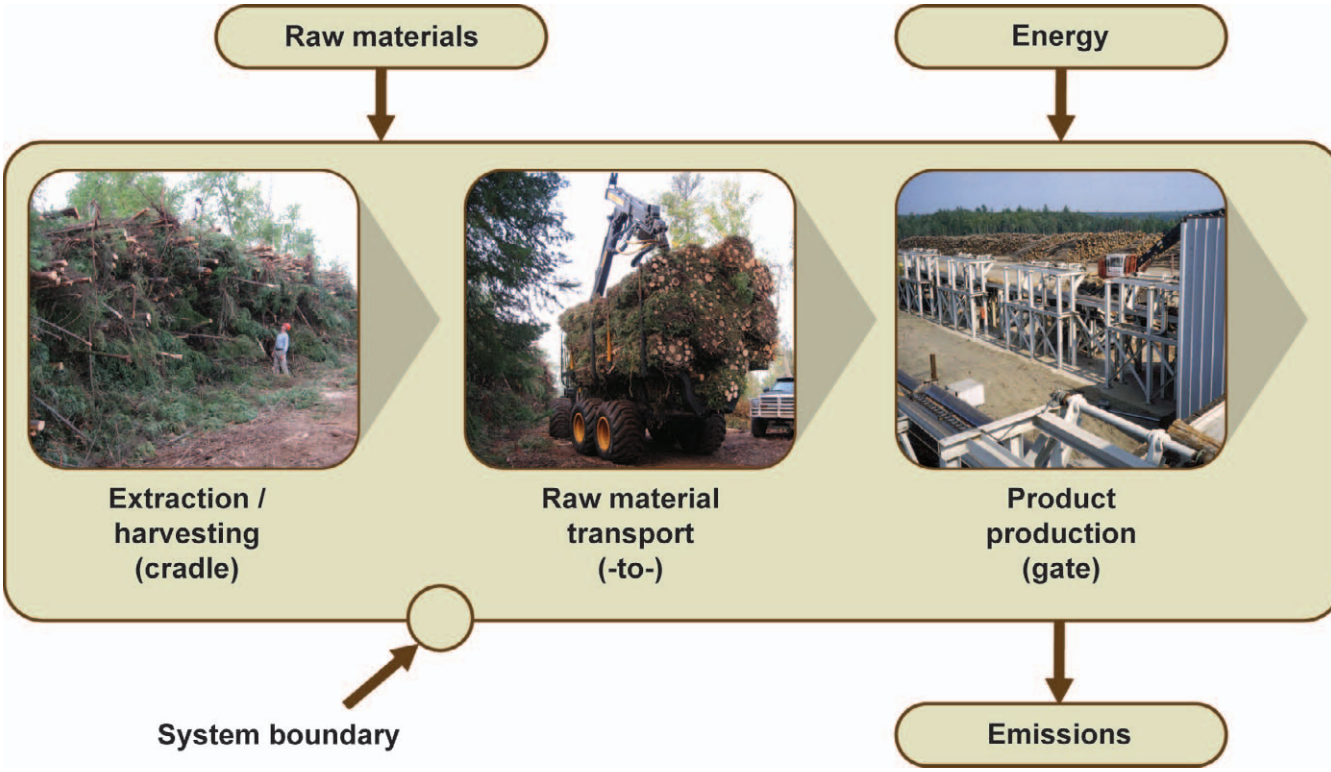

Figure 1.—Generic cradle-to-gate product production flow diagram.

because of the financial fallout from the Great Recession, this circumstance was quickly reversed with a substantial gain of 5.9 percent in 2010, which also exceeded the world 2010 gross domestic product (GDP) gain of 5.0 percent, a disturbing condition of increasing fossil carbon intensity per GDP when considering present and future impacts to climate change (Friedlingstein et al. 2010, Peters et al. 2012, British Petroleum [BP] 2014). Cement is an important component of concrete, which competes directly with wood in buildings.

Documenting the merits of wood will be important to the future competitiveness of the forest industry when selection of products will be made in part based on the climate change impacts associated with their production and use. In the United States, buildings consume roughly 40 percent of the energy generated; this includes the ''operating energy'' of buildings as well as the ''embodied energy'' (the energy required for manufacturing) of the building products produced (US Department of Energy [US DOE] 2012). To ensure that buildings incorporate products with low environmental impacts, it is important that information on the net carbon emissions associated with production and use be provided in a format that is clear, concise, and available to a wide range of building product specifiers and users, including architects, engineers, builders, and homeowners.

The environmental advantages of wood products are important and may be common sense to many; however, not everyone recognizes and understands these merits. Life-cycle assessment (LCA) is the internationally accepted and standardized method for evaluating the environmental impacts of products. LCA is a scientific approach to assessing the holistic environmental impacts of a product, including the resources consumed and the emissions released. An LCA can cover the life of a product from extraction of raw materials to production (i.e., ''cradle-to-gate''; Fig. 1), or from extraction through production to distribution, use, and final disposal (i.e., from ''cradle-to-grave''). LCA can identify unit processes of the manufacturing stage with higher environmental impact (''hot spots''), and companies can use this information to improve their product's environmental footprint. For cradle-to-gate manufacturing of wood products, the manufacturing stage typically outweighs the energy consumption and carbon emissions associated with the forest resource removal and regeneration stage and raw material transportation stage by at least a factor of 10 (Puettmann and Wilson 2005, Puettmann et al. 2010). For our analysis, we estimate net carbon emissions through product production and include carbon stored during the useful life of a wood product. We also include emissions from raw material transportation but not transport and installation of wood products (or nonwood substitutes) in end uses. This comparison implicitly assumes that transport and installation emissions are similar for wood products and nonwood substitutes.

Life-cycle assessment can be used to compare the environmental impacts of products; consumers can use this information to choose products with better environmental footprints (e.g., lower net GHG emissions). Many cradle-to-gate LCA studies have focused on wood products (www.CORRIM.org) and their nonwood alternatives. These analyses generally indicate that the manufacturing stage (rather than raw material extraction or transportation) accounts for greater environmental emissions then any stage of a wood products' life cycle. LCAs have shown a low emission environmental profile for wood compared with nonwood products that can serve the same function. Performing an LCA for a product is a detailed, data-intensive process, and the results may be difficult to interpret for nonexperts. Thus there is a need for simplified metrics from LCA studies, especially to enable users and specifiers of building products to choose materials with favorable environmental footprints.

In the present study and the Consortium for Research on Renewable Industrial Materials (CORRIM) research done so far, a distinction is made between logging and mill residues that are part of the sequestered carbon in the standing tree. Logging residues including branches, bark, and tops that are generated during harvesting, which make up approximately 30 to 50 percent of the tree harvested, are left behind in the forest to decay (Lippke et al. 2011, Ganguly et al. 2014, Hytönen and Moilanen 2014). However, Sathre and Gustavsson (2011) showed logging residues can be collected and used as fuel to generate electricity, thus replacing fossil-fuel based electricity, as reported by Bergman et al. (2013b) in the case of redwood logging in California. Most likely, though, logging residues will not be collected unless part of a forest management plan and thus will be left to decay in the forest, which is the assumption made in the present article. Therefore, assuming sustainable forest management practices will be followed from the time the forest was harvested for wood until the time the forest has completely regrown, the net carbon flux of the forest for logging residues is zero. This could be a conservative estimate because some of the carbon in the logging residues may become part of the soil organic carbon and be permanently sequestrated (Sathre and Gustavsson 2011, Skog et al. 2014). Concerning the impacts on soil carbon from forest harvesting, we assumed no lasting effect on soil carbon would occur during forest harvesting (Johnson and Curtis 2001, Lippke et al. 2011, Pacaldo et al. 2013), although there is some uncertainty around this assumption (Garten 2002, Nave et al. 2010). As for mill residues, the mill residues are a coproduct of the log brought to the production facility. Because mill residues are generated on-site, their use for energy or other purposes such as feedstock for other products is practically 100 percent. Mill residues not used for energy are not considered in calculating carbon impact factors for the same reason that logging residues (for which sustainable forest management practices will enable the forest to regrow to its original state before the next harvest) are not considered, and thus no net carbon flux from the forest for mill residues occurs. This may be a conservative estimate as well because some carbon from mill residues may be stored in various other wood products for several decades.

Carbon footprint

The quantity of CO_2 and other GHGs released per unit of product during a product's manufacturing and, in some cases, end use and disposal, is sometimes referred to as its ''carbon footprint'' (International Organization for Standardization [ISO] 2013). Coal, oil, natural gas, and wood all contain solid carbon that becomes CO_2 gas when the material is burned for energy. CO_2, methane (CH_4), nitrous oxide (N_2O), and water vapor are the primary GHGs of concern. Increases in GHGs in the atmosphere are considered the primary factor in global warming. Global warming impact is measured for each GHG in tons of CO_2 equivalent (CO_2 eq), where 1 ton of CO_2 emissions represents the global warming (radiative forcing [RF]) it causes over a specific time period, typically 100 years.

Because of the need to conserve energy resources and avoid GHG emissions, there is a global push to choose materials that have a low carbon footprint. The carbon footprint of a product can be calculated by measuring all the direct and indirect energy and material inputs to the manufacturing of a product and considering the carbon emissions associated with these inputs. Therefore, a carbon footprint can be determined through an LCA with the analysis limited to emissions that have an effect on climate.

During the production of wood materials, energy is used during harvesting to run equipment such as chainsaws and skidders, to fuel the transportation of logs to mills, and during manufacturing to power saws, planers, dryers, etc. Depending on the source of energy, the released emissions contribute to a variety of impact categories such as acidification (e.g., sulfur emissions), eutrophication (nitrogen), smog (particulates), and global warming (CO_2). Although many gases (e.g., methane) contribute to global warming and carbon footprint, CO_2 is by far the most important GHG in wood product life cycles from forest cradle–to–mill output gate (Puettmann and Wilson 2005, Puettmann et al. 2010).

Fossil versus biogenic carbon emissions

The production of energy from combustion sources results in CO_2 emissions. When coal, oil, natural gas, or wood are burned, water vapor and CO_2 are the primary atmospheric emissions. The resultant energy may be used directly in the production process, as heat or steam for wood dryers, or indirectly, as sources for electricity generation that can be used to power electric saw motors. For fossil fuels (coal, petroleum, and natural gas), the CO_2 emissions are commonly classified as ''fossil CO_2.'' This classification is in contrast to ''biogenic CO_2,'' which is emitted from the burning of biomass, such as wood. In the case of wood products, much of the process energy for manufacturing facilities is provided from burning wood-processing (mill) residues (Puettmann and Wilson 2005), thus primarily emitting biogenic CO_2.

In terms of the contribution of CO_2 to the greenhouse effect and the impact to climate change, there is no difference between the atmospheric chemistry and physics of biogenic and fossil CO_2. However, a distinction is commonly made between biogenic and fossil energy sources in life-cycle–based analyses because of the cycling of biogenic CO_2 from the atmosphere into wood resources and back to the atmosphere (i.e., natural carbon cycle) in comparison with the one-way flow of fossil CO_2 to the atmosphere. For attributional life-cycle analysis, which assesses the flux of emissions in the year a product is produced, biomass energy sources are considered to be offset when currently growing trees absorb CO_2 from the atmosphere as part of the photosynthesis process. Under an assumption of sustainable forest management, forests are sustained so annual carbon released does not exceed the annual carbon absorbed for the indefinite future. Therefore, the atmosphere does not see a net increase in CO_2 emissions (Beauchemin and Tampier 2008, Fernholz et al. 2009, Richter et al. 2009). Therefore, we use the attributional life-cycle analysis framework with a focus on current year net emissions as part of an assumed long-term forest carbon balance to count net zero emissions from wood energy emissions.

A number of alternate methods can be used to evaluate the impact of biogenic carbon emissions. One way is to use attributional life-cycle analysis but to estimate net emissions over a specific period of years by explicitly tracking carbon fluxes that include harvest and regrowth of the forest (i.e., temporal effects). A second method involves consequential life-cycle analysis, where a case of harvest and regrowth is compared with a case without harvest and continued forest growth over a specific time horizon. Features of these approaches can vary depending on the time frame of analysis, the extent of geographic area evaluated, and other factors. For each of these types of evaluation, the degree to which biogenic emissions are offset within a certain time frame can depend on many potential factors including (1) the types of biomass (e.g., logging residue, roundwood, new plantations, mill residue), (2) the age of forests at harvest, (3) forest growth rates, and (4) the extent to which increased wood prices lead landowners to hold or increase land in forest or intensify management (Brander et al. 2009, Brandão and Levasseur 2011, Cherubini et al. 2011, Bergman et al. 2012, Agostini et al. 2013, Guest et al. 2013, Helin et al. 2013). Regardless of the framework, forest growth from sustainable forestry can offset biogenic emissions over time. It could take a shorter time (a decade or less), or a longer time (many decades), depending on the wood source and circumstances. The extent of the offset can also be influenced by the GHG metric that is used (global warming potential [GWP] vs. time-zero equivalent [TIZE]; Salazar and Bergman 2013, Nepal and Skog 2014). For instance, the method used to estimate the impact to climate change for the delay of wood decay while in storage either as a product or in a landfill can provide different results. This happens because the TIZE approach quantifies the RF effects as they occur from GHG emissions, while the more common GHG metric, GWP, quantifies RF effects from the time of analysis out to the end of the selected time horizon, typically 100 years for the GHG regardless of when the emission occurred. The end result is that the TIZE approach better estimates the impact to climate change for temporary carbon sequestration in products and wood decay than GWP (Salazar and Bergman 2013). However, if the additional variables listed above had been included in the analysis, this would have increased the complexity, thus generating more uncertainty. Consequentially, attributional life-cycle analysis as is done in our analysis is best used because it is more robust for estimating the emissions directly linked with the life cycle of a product and for emissions accounting.

Carbon storage

Wood can store carbon in trees and long-term wood products for long time periods. A typical new 2,062-ft^2 home could contain 13,500 pounds of lumber, 3,160 pounds of plywood, 6,470 pounds of oriented strandboard (OSB), and 892 pounds of laminated veneer lumber, totaling 24,000 pounds of wood at 12 percent moisture content (MC) or 21,000 pounds of wood at 0 percent MC (Meil et al. 2004, Wood Products Council [WPC] 2009). On average, OD wood contains about 50 percent carbon by weight. Therefore a 2,062-ft^2 home could store 10,500 pounds of carbon or sequester 38,500 pounds of CO_2 eq,[2] assuming wood MC is 12 percent. This value does not include nonstructural wood products, which may have a shorter service life. Service life of structural wood products tends to match the service life of the structure itself. Therefore, assuming an expected median life of 80 years for a single-family home (Skog 2008), its stored carbon may last from two to three forest rotation cycles of intensely managed, highly productive forests (O'Connor 2004, Smith et al. 2005). This article considers carbon stored with products installed in a building but not emissions that occur after the service life of products.

As mentioned previously, carbon in wood products may continue to be stored after its service (i.e., use) life in a building, or it may be emitted by burning or decay. Wood products may end up in landfills where most of the wood does not decompose, it may be recycled into new engineered products, it may be burned for its energy values, or it may be reused as is in new construction (Skog 2008, Bergman et al. 2013a). Specifically, for wood to be used in new construction, Bergman et al. (2013a) show fossil CO_2 emitted for new framing lumber and new hardwood flooring are about four times greater than for recovered softwood framing lumber and recovered hardwood flooring. Additionally, end-of-life (i.e., after first product use) scenarios for old wood products can result in large cumulative energy savings and fossil CO_2 emission reductions when discarded wood is used to displace coal or natural gas in producing electric power. In fact, for the base case end-of-life scenario developed by Bergman et al. (2013a), these energy savings would offset 53 and 75 percent of biomass energy consumed to make new softwood framing lumber and new hardwood flooring, respectively.

Avoided emissions

For this analysis, the ''avoided emissions'' are the fossil carbon dioxide emissions from production of a nonwood product alternative that are avoided when a wood product is used instead (Fig. 2). The CO_2 emissions are estimated for the production of the in-use equivalent amounts of the two products. In the present study, product substitution is assumed to be one-to-one. We assume the two products have the same service life. This means that durability and the long-term functionality of the structural wood product and its nonwood substitute was considered to be equal in the analysis, an assumption consistent with the findings of O'Connor (2004). However, the life expectancy of all products used in buildings varies depending upon the quality of construction and owner preferences.

This study first estimates net carbon emission footprint values per unit of product for a number of US-produced wood products and for their nonwood product alternatives. We estimate the carbon footprint for each wood product by using fluxes shown for the wood product system in Figure 3. The carbon flux for each nonwood product alternative (Fig. 2) is simply based on fossil fuel emissions. Second, we estimate the savings in emissions by use of each wood product instead of its nonwood product alternative as the difference between the two carbon footprint estimates. In essence, the system boundary for the present study is set to analyze empirical data provided from raw material extraction to production through the LCA method for all products that could be considered a partial analysis. The reason is that although we assume sustainable forestry will be practiced in the future, an underlying assumption exists that any

[2] Using molecular weights of CO_2 and carbon, 38,500 pounds of $CO_2 = 10{,}500$ pounds of carbon $\times$ 44 kg of CO_2/12 kg of carbon.

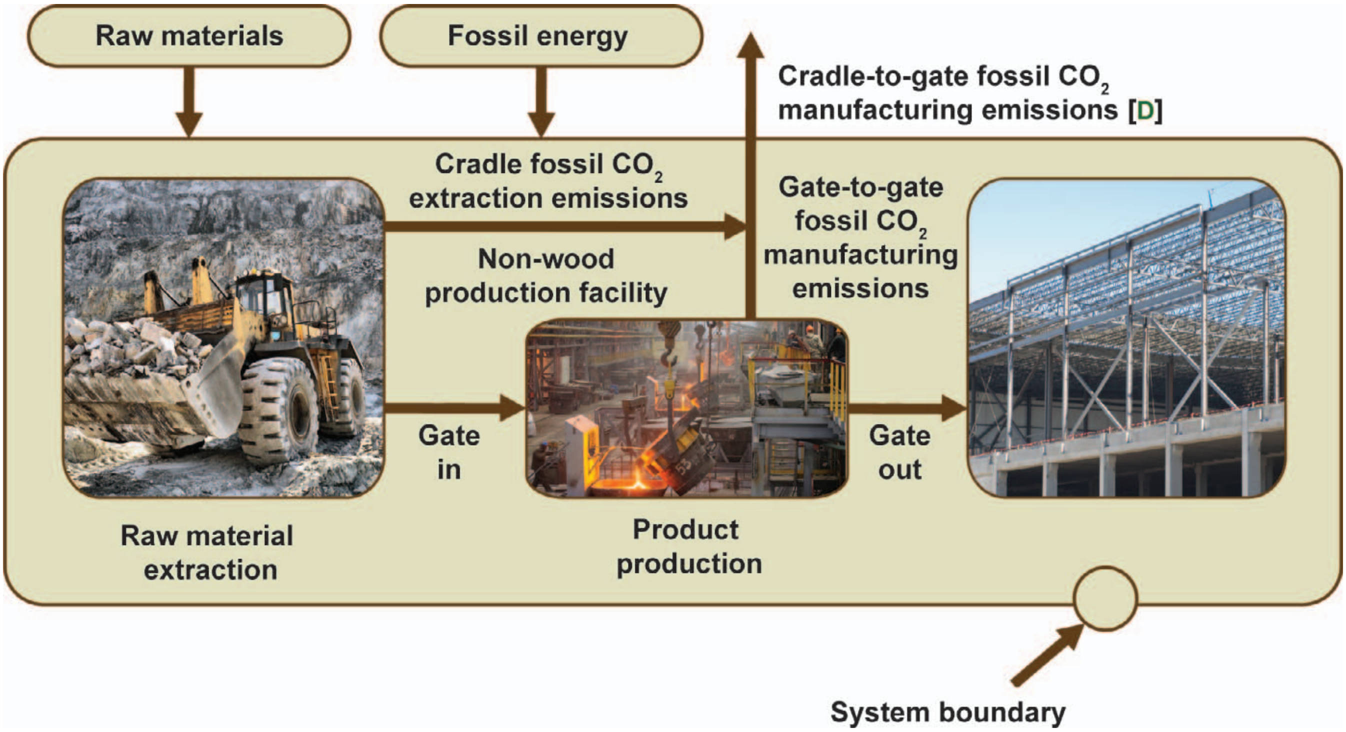

Figure 2.—System boundary and carbon fluxes for nonwood product production (Net emissions = D).

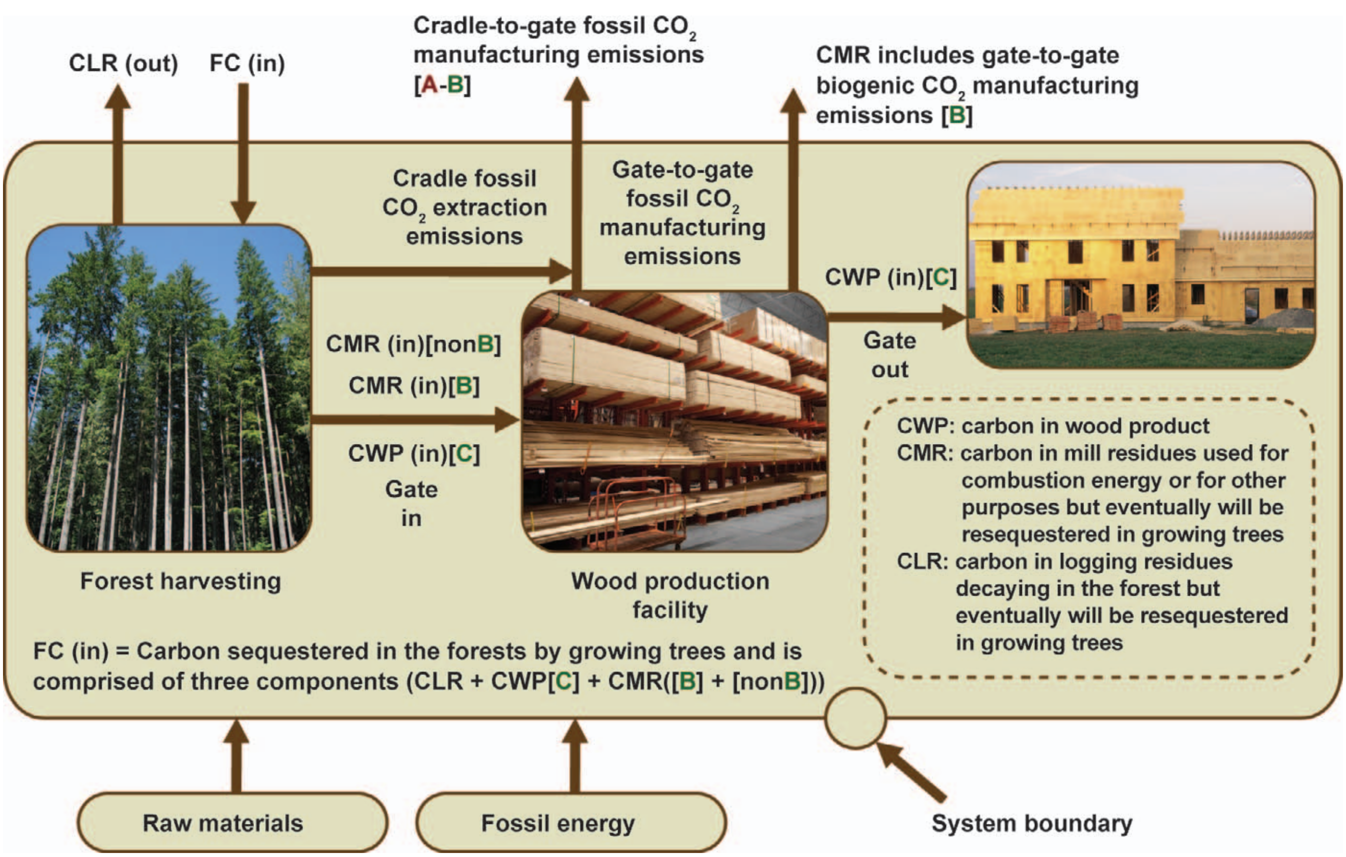

Figure 3.—System boundary and carbon fluxes for wood product production and carbon storage in end-use [Net emissions = (A – B) + B – C – B = A – B – C].

Table 1.—Data sources used to develop the net carbon footprint for each wood product and its substitutes.[a]

Wood product	Notes	Wood data source reference	Substitution product	Alternative data source reference
Hardwood lumber	Northeast/North Central region	Bergman and Bowe (2008)	Polyvinyl chloride (plastic) moulding	Mahalle and O'Connor (2009)
	Southeast region	Bergman and Bowe (2010b)		
Softwood lumber	Northeast/North Central region	Bergman and Bowe (2010a)	Steel stud	Rowlett (2004); Studs Unlimited, Inc. (2013)
	Southeast region	Milota et al. (2004)		
Hardwood flooring	Solid strip flooring	Hubbard and Bowe (2008)	Vinyl flooring	Potting and Blok (1995)
	Engineered wood	Bergman and Bowe (2011)		
Doors	Solid wood	Knight et al. (2005)	Steel door	Knight et al. (2005)
Softwood decking	ACQ-treated pine	Bolin and Smith (2011a)	Wood–plastic composite	Bolin and Smith (2011a)
Siding	Western red cedar	Mahalle and O'Connor (2009)	Vinyl siding	Mahalle and O'Connor (2009)
Softwood pole	Pentachlorophenol-treated wood	Bolin and Smith (2011b)	Concrete pole	Bolin and Smith (2011b)
OSB[b]	Southeast region	Kline (2004)	NA	NA
Plywood[b]	Pacific Northwest region	Wilson and Sakimoto (2004)	NA	NA
	Southeast region	Wilson and Sakimoto (2004)	NA	NA
I-joist	Pacific Northwest region	Wilson and Dancer (2005)	Steel joist	DiBernardo (2013); SSMA (2013)
	Southeast region	Wilson and Dancer (2005)		
Hardwood railroad tie	United States	Bolin and Smith (2013)	Concrete railroad tie	Bolin and Smith (2013)

[a] ACQ = alkaline copper quaternary; NA = not applicable; SSMA = Steel Stud Manufacturer's Association.
[b] No direct nonwood substitution products for oriented strandboard (OSB) or plywood were identified.

additional forest harvesting for product substitution would result in no net loss of forest carbon based on today's forestland levels. However, this is an unlikely scenario if product choices are made based on the current carbon impacts presented in this article. Therefore, this additional harvesting carbon impact will need to be analyzed and quantified when additional wood product substitution occurs and then included in carbon impact factors for wood products.

Methods

Product data sources and descriptions

We used the existing wood product life-cycle inventory (LCI) data sets to determine the net carbon emission

Table 2.—Mass and carbon content of some US wood products and their substitutes.[a]

Product	Material	Unit	Mass (lb/unit)[b]	Biogenic carbon content (%)
Moulding	Northeast/North Central hardwood lumber	1 bd ft (12 × 12 × 1 in.)	2.22	50
	Southeast hardwood lumber		2.22	48
	Polyvinyl chloride (plastic)		2.65	0
Stud	Northeast/North Central softwood lumber	One 2 × 4 stud	7.65	52
	Southeast softwood lumber		9.54	53
	Steel[c]		5.92	0
Flooring	Engineered hardwood	1 ft^2	1.28	52
	Solid hardwood		2.55	50
	Vinyl		0.52	0
Doors	Solid wood[d]	One door	55.0	50
	Steel[c]		84.0	0
Decking	Alkaline copper quaternary–treated	One deck board	18.2	53
	Wood–plastic composite		36.8	27
Siding	Western red cedar	100 ft^2	93.4	50
	Vinyl		55.6	0
Utility pole	Pentachlorophenol–treated wood	One 45-ft pole	1,315	53
	Concrete		4,000	0
Oriented strandboard (OSB)	Southeast OSB	One 4 × 8-ft sheet @ 3/8 in.	34.8	51
Plywood	Southeast plywood	One 4 × 8-ft sheet @ 3/8 in.	33.8	54
	Pacific Northwest plywood		29.3	51
I-joist	Southeast wood	One 16-ft-long, 10-in.-deep joist	76.2	50
	Pacific Northwest wood		95.5	50
	Steel joist[c]		57.2	0
Railroad tie	US wood	One 7 in. high × 9 in. wide × 8.5 ft long	139	48
	US concrete		700	0

[a] All comparisons are cradle-to-gate (production gate). Therefore, no product use or disposal was considered.
[b] Mass is listed at 0 percent moisture content.
[c] Galvanized steel processes were used for steel studs, steel doors, and steel I-joists.
[d] Solid wood door used Northeast/North Central hardwood lumber as input.

Table 3.—Carbon emission savings from use of US wood products in place of nonwood product alternatives (pounds of CO_2 per unit of product).[a]

Product	Units	Notes	A Gross carbon released during wood product manufacturing	B Biofuel used during wood product manufacturing[b]
Hardwood lumber	1 bd ft (12 × 12 × 1 in.)	Northeast/North Central region	2.0	1.3
		Southeast region	2.4	1.8
Softwood lumber	One 2 × 4 stud	Northeast/North Central region	4.0	2.6
		Southeast region	5.5	4.2
Hardwood flooring	1 ft^2	Solid strip flooring	2.4	1.5
		Engineered wood	2.2	1.1
Doors	One door	Solid wood	102.5	64.8
Decking	One deck board	ACQ-treated pine	11.5	3.7
Siding	100 ft^2	Western red cedar	83.1	13.2
Utility poles	One 45-ft pole	Pentachlorophenol-treated wood	1,002	950
OSB	One 4 × 8-ft sheet @ 3/8 in.	Southeast region	41.9	23.6
Plywood	One 4 × 8-ft sheet @ 3/8 in.	Pacific Northwest region	12.6	9.0
		Southeast region	22.3	14.3
I-joist	One 16-ft-long, 10-in.-deep joist	Pacific Northwest region	50.3	41.7
		Southeast region	72.8	50.5
Railroad ties	One 7 in. high × 9 in. wide × 8.5 ft long	United States	113.6	6.6

[a] ACQ = alkaline copper quaternary; OSB = oriented strandboard.
[b] Woody biomass energy.
[c] Negative values represent a carbon credit.

footprint for a range of wood products from cradle-to-gate (Table 1; Fig. 3). Many LCI data sets for wood product manufacturing and nonwood alternatives are publically available through Web-based sources including the US LCI Database (National Renewable Energy Laboratory [NREL] 2014). In the US LCI Database, which was used in this analysis, carbon emissions for the wood product LCI data are allocated by mass. Internationally accepted LCA software was used for modeling wood product production to obtain carbon emissions from wood products and alternative materials (PRé Consultants 2014). As shown herein, much LCI data exist for US wood and nonwood products, and the list of sources will grow with continued interest in environmental issues and LCA. Some wood products are specified by geographical areas. For example, softwood lumber is typically produced in four areas, the Southeast (SE), the Northeast/North Central (NE/NC), the Pacific Northwest, and the Inland West.

Carbon content

To calculate carbon stored in various products, we calculated the mass and biogenic carbon content of each wood product and the nonwood substitute alternatives (Table 2). Some of the nonwood materials (e.g., vinyl flooring) contain carbon, but in those cases, the carbon is from fossil (e.g., petroleum) sources. We do not consider fossil carbon content, because unlike wood products, the carbon transferred from fossil fuel to nonwood products is not being replaced as wood carbon is by continuing forest regrowth. As shown in Figure 3, forests are actively reabsorbing carbon removed by harvest and which then is transferred to wood products. In Figure 2, there is no equivalent reabsorption of fossil carbon emissions by the source of the fossil fuel. Birdsey (1992) provided the carbon content values for the various wood products.

Difference between wood and nonwood product carbon footprints (net carbon emission savings)

The net carbon emission footprints for the wood product and nonwood product, respectively, are

$$\text{Wood product net carbon emissions footprint} = A - B - C$$

(see Fig. 3)

$$\text{Nonwood product net carbon emissions footprint} = D$$

(see Fig. 2). The difference between the two carbon footprints for the 11 wood products and corresponding nonwood substitutes indicates the emissions savings from use of a wood product rather than the nonwood alternative and is calculated using this formula

$$A - B - C - D = E \quad (1)$$

where

A = *Gross* carbon emissions during wood production = (fossil CO_2 + biogenic CO_2). Cradle-to-gate product manufacturing consumes various energy sources, and almost all energy production results in CO_2 emissions. Energy sources used in wood manufacture include sources such as natural gas, diesel, gasoline, and electricity derived from fossil fuels that release fossil CO_2 when combusted. Biomass energy from burning wood processing (mill) residues is a major fuel source for energy that releases biogenic CO_2, not fossil CO_2, when combusted. Gross carbon emissions are also a reasonable proxy for energy consumption even though no carbon emissions are associated with hydroelectric and nuclear power emissions. This occurs because coal and natural gas are the primary energy sources for generating power in the United States (US EIA 2014b).

Table 3.—Extended.

C Carbon stored in the wood product	*D* Carbon released during nonwood product manufacturing	*A* − *B* − *C* − *D* = *E* Net carbon emission savings[c]	*E*/*A* Carbon emission savings per unit of gross wood emissions	*E*/*C* Carbon emission savings per unit of CO_2 eq of wood
4.0	6.5	−9.9	−5.0	−2.5
4.0	6.5	−9.8	−4.0	−2.5
14.6	16.7	−30.0	−7.6	−2.1
18.5	16.7	−34.0	−6.2	−1.8
4.6	0.8	−4.7	−1.9	−1.0
2.4	0.8	−2.1	−1.0	−0.9
221.4	540.8	−724.5	−7.1	−3.3
35.5	34.2	−62.1	−5.4	−1.7
171.3	116.0	−217.3	−2.6	−1.3
2,559	3,112	−5,618	−5.6	−2.2
76.5	—	−58.1	−1.4	−0.8
56.2	—	−52.8	−4.2	−0.9
68.1	—	−60.2	−2.7	−0.9
140.9	154.8	−286.9	−5.7	−2.0
176.4	154.8	−309.1	−4.2	−1.8
244.8	487.3	−625.0	−5.5	−2.6

B = Carbon emissions from *burning wood* residues = (biogenic CO_2). Biogenic CO_2 is released when wood is burned for energy. These biogenic carbon emissions are also being reabsorbed in forests and thus are deducted from the gross carbon emissions in this analysis (see emission and forest sequestration fluxes in Fig. 3).

C = *Carbon stored* in the wood product. CO_2 absorbed from the atmosphere during photosynthesis is converted to wood, bark, and other parts of the tree. On average, wood contains about 50 percent elemental carbon by dry weight of wood (Table 2). If the tree decays or burns, this solid carbon in the wood is released again to the atmosphere as CO_2 gas, and the carbon cycle continues. As long as the wood is ''locked-up'' in a product, the carbon is ''sequestered'' as a solid and does not contribute to climate warming through the atmospheric greenhouse effect. The carbon transferred to storage in a wood product is also being replaced by regrowth in a sustainably managed forest. This regrowth is equal to or greater than the amount of the carbon transfer to products and can be used to offset wood product production emissions for the period that the carbon remains stored in the wood product (see Fig. 3). The carbon stored in the product was calculated by multiplying the carbon content of a given wood product by the dry weight of the individual wood product (Table 2) and converting to CO_2 equivalents (Eq. 2).

$$\text{Carbon storage} = CS_i = CC_i \times W_i \times 3.67 \qquad (2)$$

where

CS_i = carbon storage for a unit of wood product *i* (lb/unit),

CC_i = carbon content for wood product *i* (% carbon/100),

W_i = weight of a unit of wood product *i* (lb), and

3.67 = ratio of the molecular weight of CO_2 to the molecular weight of carbon.

D = *Alternate product emissions avoided* = (Nonwood product fossil CO_2). When the fossil CO_2 releases associated with the manufacture of a nonwood product are not generated, this is considered ''avoided emissions'' (Fig. 2).

E = *Net carbon savings* = ($A - B - C - D$). The net carbon emissions savings obtained by use of each wood product is the difference between the carbon footprint for the wood product and for the nonwood products alternative. A negative value for *E* can be interpreted as a ''carbon credit'' or carbon savings, where using the wood product in place of a nonwood alternative results in a reduction in the net amount of CO_2 in the atmosphere.

E/*A* = *Net carbon emission savings per unit of gross wood emissions* = (Net carbon savings/gross carbon emissions during wood production).

E/*C* = *Net carbon emission savings per unit of carbon in wood* = (Net carbon savings/carbon contents of wood product).

Because wood product units are of varying mass, the absolute values for carbon footprints can be difficult to compare across products. Normalizing the net carbon savings by dividing by gross carbon emissions or by the carbon content of the wood can show the relative importance of the substitution and biogenic carbon effects for each product. Negative values for the emission savings per unit of wood emissions indicate that the gross carbon emissions are more than offset by the use of wood biofuel, carbon sequestration in wood products, and avoided fossil carbon emissions. The magnitude of these negative values for the emissions savings per unit of carbon in the wood product indicates how effective use of a unit of wood in the product is in offsetting emissions compared with use of a unit of wood in other products.

Results and Discussion

All of the wood products examined in this analysis provide a net emission savings when used in place of the selected nonwood alternative products (Table 3). The columns in Table 3 are labeled with letters corresponding to those in Equation 1. Using solid wood doors as an example,

$$\text{The net carbon savings for a single wood door} = 102.5\,(A) - 64.8\,(B) - 221.4\,(C) - 540.8\,(D) = -724.5\,(E)\,\text{kg CO}_2\,\text{eq}$$

For individual wood products, Column *E* (Table 3) shows the two lowest net carbon footprints for utility poles and solid wood doors (–5,618 and –724.5 kg CO_2 eq, respectively). This is because utility poles and solid wood doors are the two of the three largest wood products by mass. Wood studs, which are smaller in size, have a less negative net carbon footprint individually, but far more are used; thus, it doesn't make much sense to compare the carbon footprints of these different products. A more important comparison is the carbon footprint of the wood product with its nonwood alternative. As shown in Table 3, almost all of these nonwood alternatives require more energy for their manufacture, and the energy used is almost entirely fossil fuels containing carbon that has been stored in coal, oil, and natural gas for millions of years.

Normalizing the net emission savings to a unit of gross emissions for making wood products or a unit of carbon in the wood product helps when comparing various wood products. For example, utility poles result in –5,618 lb CO_2 eq net emission savings per pole. However, its normalized net emission savings per unit of gross emissions pole production is –5.6, which is near the value of –6.2 for the SE wood stud product. The normalized values per unit carbon in the wood product (*E*/*C*) are also similar, –2.2 and –1.8, respectively. The normalized values per unit carbon are consistent with the reported GHG displacement factor of –2.1 by Sathre and O'Connor (2009). For all 11 wood products studied including panel products, the values for normalized net carbon emissions per unit of gross emissions (*E*/*A*) range from –1.0 to –7.6, with a mean of –4.38 ± 1.99. One way to interpret this finding is that, on average, the use of wood building products avoids the use of about four times as much fossil fuel as the cradle-to-gate manufacture of the wood product requires.

The most effective ways to use a unit of wood to offset emissions is indicated by the normalized value of net emission savings per unit of carbon in the wood product (*E*/*C*). By this measure, wood use is most effective in use for solid wood doors, railroad ties, and hardwood lumber, followed by utility poles, softwood lumber, pine decking, cedar siding, and hardwood flooring.

Not all wood products have large substitution effects. In fact, solid wood flooring had a less energy-intensive nonwood alternative in this analysis, although the assumption that vinyl flooring provides a functional equivalent to wood flooring is debatable because of aesthetic considerations and the potentially short service life of vinyl. A better alternative for wood flooring might be ceramic or stone tile, but we are not aware of LCI data for these products. As such data becomes available, this type of comparative carbon emission analysis can be redone to more accurately reflect substitution scenarios.

Not all the products studied here have simple one-to-one, nonwood alternatives (i.e., plywood and OSB). Concrete block walls can be substituted for wood-framed walls that contain OSB or plywood; however, these walls also contain other products such as studs and nails. This type of more complicated substitution scenario was not attempted for this analysis but can be modeled using tools such as the Athena Impact Estimator for Buildings (AIE4B; Athena Sustainable Materials Institute [ASMI] 2014). For a demonstration of the AIE4B tool using cradle-to-gate manufacturing LCI data, see Lippke et al. (2004). Without considering the carbon stored in the wood and not differentiating between biogenic and fossil CO_2 emissions, Lippke et al. (2004) showed that building wood-framed structures in Minneapolis, Minnesota, and Atlanta, Georgia, instead of building steel- and concrete-framed structures reduced GHG emissions by 26 and 32 percent, respectively, reductions that were tempered by the fact all structures analyzed had common concrete foundations. Much larger differences were found when analyses were confined to assemblies that contained fewer or no common elements.

Carbon emission savings for some wood products vary by region. For hardwood lumber, the net carbon emission savings for the NE/NC region is slightly larger than for the SE region, about 1.0 percent more, whereas for wood studs for the NE/NC region, the net carbon emission savings is smaller than for the SE region, about 13 percent less. There are two reasons for higher net carbon emissions savings for wood studs in the SE. First, although more gross carbon is released in manufacturing of the SE wood stud (5.5 vs. 4.0), a greater amount of the gross carbon emissions come from woody biomass (4.2 vs. 2.6); thus, fossil CO_2 emissions per board foot are lower ($5.5 - 4.2 = 1.3$ vs. $4.0 - 2.6 = 1.4$). Second, the species composition for SE wood studs (southern pines) has a substantially higher density than species composition for the NE/NC wood stud, as noted in Column *C* in Table 3 (18.5 vs. 14.6; Milota et al. 2004, Bergman and Bowe 2010a). Denser wood contains more water than lighter wood at a specific MC. Therefore, denser wood requires more drying to reach the same final MC starting from the same initial MC as indicated by higher gross carbon emissions for the SE than the NE/NC studs (Bergman 2010). These density differences are not found in hardwood lumber, which is primarily produced in the eastern United States (Bergman and Bowe 2008, 2010b).

Conclusions

The reduced carbon emission impacts associated with woody biofuel use and storage of carbon in long-lived wood products result in lower net carbon emissions of wood products compared with nonwood product alternatives. For the cases we evaluated, the combined GHG emissions reductions due to biofuel usage, carbon storage, and avoided fossil emissions are always greater than the wood product manufacturing carbon emissions. Thus, use of wood products can help to reduce contributions to GHGs in the atmosphere that increase the greenhouse effect, with the caveat that sustainable forestry continues to occur from product substitution. However, more wood product substitution in the future would cause large removals of wood during forest harvesting and could violate our assumption of sustainable forestry. Therefore, this impact would increase the carbon emissions associated with wood products and thus lessen the effect of substitution.

For some wood products, such as wood flooring, the nonwood substitutes are not quite equivalent because the nonwood product is likely to have a substantially shorter use life. Structural products such as softwood (framing) lumber and their nonwood substitutes tend to have the same useful life of the structure, and LCI data are available for both of these products. The estimated net carbon emission savings for these secondary wood products would likely be even larger, e.g., if we used LCI data for more comparable nonwood flooring products.

Net carbon emission savings for wood products can differ among regions because of differences in species composition, and thus density, which influences the amount of drying energy and carbon emissions. However, these differences result in minor differences in net carbon emissions savings.

Our estimates of net carbon emission savings use an attributional, current period accounting framework to estimate the emission benefits associated with wood energy carbon emissions and wood product carbon storage. If we used an attributional or a consequential dynamic time framework, the level of carbon emission benefits of wood energy use and wood product carbon storage would have been lower but with higher uncertainty. Regardless of the framework used, these carbon emission benefits would still offset gross wood product manufacturing emissions. In addition, using wood products avoids using known energy-intensive producers of GHGs.

Acknowledgments

The work upon which this publication is based was funded in whole or in part through grant no. 10-DG-11420004-087 awarded by the Wood Education and Resource Center, Northeastern Area State and Private Forestry, US Forest Service.

Literature Cited

Agostini, A., J. Giuntoli, and A. Boulamanti. 2013. Carbon accounting of forest bioenergy. EUR 25354 EN. European Commission Joint Research Centre, Ispra, Italy. 88 pp.

Athena Sustainable Materials Institute (ASMI). 2014. Impact estimator for buildings. ASMI, Ottawa. http://www.athenasmi.org/our-software-data/impact-estimator/. Accessed September 16, 2014.

Beauchemin, P. A. and M. Tampier. 2008. Emission from wood-fired combustion equipment. http://www.env.gov.bc.ca/epd/industrial/pulp_paper_lumber/pdf/emissions_report_08.pdf. Accessed September 16, 2014.

Bergman, R. D. 2010. Drying and control of moisture content and dimensional changes. *In:* Wood Handbook—Wood as an Engineering Material. General Technical Report FPL-GTR-113. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 13-1–13-20.

Bergman, R. D. and S. A. Bowe. 2008. Life-cycle inventory of hardwood lumber manufacturing in the northeast and north central United States. CORRIM: Phase II Final Report: Module C. University of Washington, Seattle. 52 pp.

Bergman, R. D. and S. A. Bowe. 2010a. Environmental impact of manufacturing softwood lumber determined by life-cycle inventory. *Wood Fiber Sci.* 42(CORRIM Special Issue):67–78.

Bergman, R. D. and S. A. Bowe. 2010b. Life-cycle inventory of hardwood lumber manufacturing in the southeastern United States. CORRIM: Phase II Final Report: Module L. University of Washington, Seattle. 56 pp.

Bergman, R. D. and S. A. Bowe. 2011. Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States. CORRIM Phase II Final Report: Module N. University of Washington, Seattle. 56 pp.

Bergman, R. D., R. Falk, J. Salazar, H. Gu, T. Napier, and J. Meil. 2013a. Life cycle primary energy and carbon analysis of recovering softwood framing lumber and hardwood flooring for reuse. Research Paper FPL-RP-672. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 33 pp.

Bergman, R. D., H.-S. Han, E. Oneil, and I. L. Eastin. 2013b. Life-cycle assessment of redwood decking in the United States with a comparison to three other decking materials. CORRIM Final Report. University of Washington, Seattle. 101 pp.

Bergman R. D., J. Salazar, and S. A. Bowe. 2012. Developing a dynamic life cycle greenhouse gas emission inventory for wood construction for different end-of-life scenarios. *In:* Proceedings, International Symposium on LCA and Construction 2012. French Institute for Transports, Development and Networks (IFSTTAR), Nantes, France. pp. 318–325.

Birdsey, R. A. 1992. Carbon storage and accumulation in United States forest ecosystems. Table 1.2—Factors to convert tree volume (cubic feet) to carbon (pounds). USDA Forest Service, Washington, D.C. 55 pp. http://www.nrs.fs.fed.us/pubs/gtr/gtr_wo059.pdf. Accessed September 16, 2014.

Bolin, C. A. and S. T. Smith. 2011a. Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. *J. Clean. Prod.* 19(6–7):620–629.

Bolin, C. A. and S. T. Smith. 2011b. Life cycle assessment of pentachlorophenol-treated wooden utility poles with comparisons to steel and concrete utility poles. *Renew. Sust. Energ. Rev.* 15(5):2475–2486.

Bolin, C. A. and S. T. Smith. 2013. Life cycle assessment of creosote-treated wooden railroad crossties in the US with comparisons to concrete and plastic composite railroad crossties. *J. Transport. Technol.* 3(2):149–161.

Brandão, M. and A. Levasseur. 2011. Assessing temporary carbon storage in life-cycle assessment and carbon footprinting: Outcomes of an expert workshop, October 7–8, 2010, Ispra, Italy. Publications Office of the European Union, Luxembourg.

Brander, M., R. Tipper, C. Hutchison, and G. Davis. 2009. Consequential and attributional approaches to LCA: A guide to policy makers with specific reference to greenhouse gas LCA of biofuels. 14 pp. http://www.globalbioenergy.org/uploads/media/0804_Ecometrica_-_Consequential_and_attributional_approaches_to_LCA.pdf. Accessed September 16, 2014.

British Petroleum (BP). 2014. Statistical review of world energy June 2014. http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf. Accessed September 16, 2014.

Cherubini, F., G. P. Peters, T. Berntsen, A. H. Strmman, and E. Hertwich. 2011. CO_2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. *Global Change Biol.* 3(5):413–426.

DiBernardo, G. 2013. Framing decks with steel. *Professional Deck Builder* January/February 2013:18–32.

Eriksson, L. O., L. Gustavsson, R. Hänninen, M. Kallio, H. Lyhykäinen, K. Pingoud, J. Pohjola, R. Sathre, R. Solberg, J. Svanaes, and L. Valsta. 2012. Climate change mitigation through increased wood use in the European construction sector—Towards an integrated modelling framework. *Eur. J. Forest Res.* 131(1):131–144.

Fernholz, K., S. Bratkovich, J. Bowyer, and A. Lindburg. 2009. Energy from wood biomass: A review of harvesting guidelines and a discussion of related challenges. Dovetail Partners Inc. 14 pp. http://

www.dovetailinc.org/report_pdfs/2009/dovetailbioguides0709.pdf. Accessed September 16, 2014.
Friedlingstein, P., R. A. Houghton, G. Marland, J. Hackler, T. A. Boden, T. J. Conway, J. G. Canadell, M. R. Raupach, P. Ciais, and C. Le Quere. 2010. Update on CO2 emissions. *Nat. Geosci*. 3:811–812.
Ganguly, I., I. L. Eastin, T. Bowers, M. Huisenga, and F. Pierobon. 2014. Environmental assessments of woody biomass based jet-fuel. *CINTRAFOR News* Winter:3–10. http://www.cintrafor.org/publications/newsletter/C4news2014winter.pdf. Accessed July 10, 2014.
Garten, C. T. 2002. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. *Biomass Bioenergy* 23:93–102.
Guest, G., R. M. Bright, F. Cherubini, and A. H. Stromman. 2013. Consistent quantification of climate impacts due to biogenic carbon storage across a range of bio-products systems. *Environ. Impact Assess*. 43(2013):21–30.
Helin, T., L. Sokka, S. Soimakallio, K. Pingoud, and T. Pajula. 2013. Approaches for inclusion of forest carbon cycle in life cycle assessment—A review. *GCB Bioenergy* 5(5):475–486.
Hytönen, J. and M. Moilanen. 2014. Effect of harvesting method on the amount of logging residues in the thinning of Scots pine stands. *Biomass Bioenergy* 67:347–353
Hubbard, S. S. and S. A. Bowe. 2008. Life-cycle inventory of solid strip hardwood flooring in the eastern United States. CORRIM: Phase II Final Report: Module E. University of Washington, Seattle. 59 pp.
Intergovernmental Panel on Climate Change (IPCC). 2013. Summary for policymakers. *In:* Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (Eds.). Cambridge University Press, Cambridge, UK. 33 pp.
International Organization for Standardization (ISO). 2013. Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification and communication. ISO/TS 14067:2013. ISO, Geneva. 52 pp.
Johnson, D. W. and P. S. Curtis. 2001. Effects of forest management on soil C and N storage: Meta analysis. *Forest Ecol. Manag*. 140(2001):227–238.
Kline, D. E. 2004. Oriented strand board—Southeast. CORRIM: Phase I Final Report: Module E. University of Washington, Seattle. 79 pp.
Knight, L., M. Huff, J. I. Stockhausen, and R. J. Ross. 2005. Comparing energy use and environmental emissions of reinforced wood doors and steel doors. *Forest Prod. J*. 55(6):48–52.
Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, and R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. *Carbon Manag*. 2(3):303–333.
Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. *Forest Prod. J*. 54(6):7–19.
Mahalle, L. and J. O'Connor. 2009. Life cycle assessment of western red cedar siding, decking, and alternative products. FPInnovations—Forintek Division, Western Region, Vancouver, British Columbia, Canada. 126 pp.
Meil, J., B. Lippke, J. Perez-Garcia, J. Bowyer, and J. Wilson. 2004. Environmental impacts of a single family building shell—From harvest to construction. Table 3.1. Bill of materials for Minneapolis and Atlanta alternative house designs. CORRIM: Phase I Final Report: Module J. University of Washington, Seattle. 38 pp.
Milota, M. R., C. D. West, and I. D. Hartley. 2004. Softwood lumber—Southeast region. CORRIM: Phase I Final Report: Module C. University of Washington, Seattle. 77 pp.
National Renewable Energy Laboratory (NREL). 2014. US life cycle inventory database National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search. Accessed September 16, 2014.
Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. 2010. Harvest impacts on soil carbon storage in temperate forests. *Forest Ecol. Manag*. (259):857–866.
Nepal, P. and K. E. Skog. 2014. Estimating net greenhouse gas (GHG) emissions from wood energy use: Issues and the current state of knowledge: *In*: Wood Energy in Developed Economics: Resource Management, Economics and Policy. F. X. Aguilar (Ed.). Routledge, New York. 352 pp.
O'Connor, J. 2004. Survey on actual service lives for North American buildings. Presented at the Proceedings of Woodframe Housing Durability and Disaster Issues Conference, October 4–6, 2004, Las Vegas, Nevada; Forest Products Society, Madison, Wisconsin.
Pacaldo, R. S., T. A. Volk, and R. D. Briggs. 2013. No significant differences in soil organic carbon contents along a chronosequence of shrub willow biomass crop fields. *Biomass Bioenergy* 58(2013):136–142.
Peters, G. P., G. Marland, C. Le Quéré, T. Boden, J. G. Canadell, and M. R. Raupach. 2012. Global primary energy consumption accelerated in 2013 despite stagnant global economic growth. *Nature Climate Change* 2012(2):2–4.
Potting, J. and K. Blok. 1995. Life-cycle assessment of four types of floor covering. *J. Clean. Prod*. 3(4):201–213.
PRé Consultants. 2014. SimaPro 7 Life-cycle assessment software package, version 7. Amersfoort, The Netherlands. http://www.pre.nl/. Accessed September 16, 2014.
Puettmann, M. E., R. D. Bergman, S. S. Hubbard, L. Johnson, B. Lippke, and F. Wagner. 2010. Cradle-to-gate life-cycle inventories of US wood products production—CORRIM Phase I and Phase II products. *Wood Fiber Sci*. 42(CORRIM Special Issue):15–28.
Puettmann, M. E. and J. B. Wilson. 2005. Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. *Wood Fiber Sci*. 37(CORRIM Special Issue):18–29.
Richter, D., D. Jenkins, J. Karakash, J. Knight, L. McCreery, and K. Nemestothy. 2009. Wood energy in America. *Science* 323(5920):1432–1433.
Ritter, M., K. E. Skog, and R. D. Bergman. 2011. Science supporting the economic and environmental benefits of using wood and wood products in green building construction. General Technical Report FPL-GTR-206. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 9 pp.
Rowlett, R. 2004. How many? A dictionary of units of measurement: Sheet metal thickness gauges. University of North Carolina, Chapel Hill. http://www.unc.edu/~rowlett/units/scales/sheetmetal.html. Accessed September 16, 2014.
Salazar, J. and R. D. Bergman. 2013. Temporal considerations of carbon sequestration in LCA. Presented at the Proceedings of the LCA XIII International Conference, October 1–3, 2013, Orlando, Florida. pp. 136–142.
Sathre, R. and L. Gustavsson. 2011. Time-dependent climate benefits of using forest residues to substitute fossil fuels. *Biomass Bioenergy* 35(2011):2506–2516.
Sathre, R. and J. O'Connor. 2009. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Policy* 13(2010):104–114.
Skog, K. E. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Prod. J*. 58(6):56–72.
Skog, K. E., D. C. McKinley, R. A. Birdsey, S. J. Hines, C. W. Woodall, E. D. Reinhardt, and J. M. Vose. 2014. Managing carbon. USDA Forest Service/UNL Faculty Publications, Lincoln, Nebraska. 274 pp.
Smith, J. E., L. S. Heath, K. E. Skog, and R. A. Birdsey. 2005. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. General Technical Report NE-343. USDA Forest Service, Northeastern Research Station, Newtown Square, Pennsylvania. 216 pp.
Steel Stud Manufacturer's Association (SSMA). 2013. Product technical guide. SSMA, Chicago. http://www.ssma.com/filebin/pdf/SSMA_2012_Product_Tech_Catalog_Interactive_with_ICC.pdf. Accessed September 16, 2014.
Studs Unlimited, Inc. 2013. Studs Unlimited product literature, Oklahoma City. http://studsunlimited.com.temp.omnis.com/wp-content/uploads/2013/06/Studs-ProductLiterature.pdf. Accessed September 16, 2014.
US Department of Energy (US DOE). 2012. Chapter 1: Buildings sector. 1.1. Buildings sector energy consumption. *In:* 2011 Buildings Energy Data Book. US DOE, Washington, D.C. 286 pp. http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf. Accessed September 16, 2014.
US Energy Information Administration (US EIA). 2014a. International

energy statistics: Total carbon dioxide emissions from the consumption of energy. US EIA, Washington, D.C. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8. Accessed September 16, 2014.

US Energy Information Administration (US EIA). 2014b. Electric power annual. Table 1.1. Total electric power industry summary statistics, 2012 and 2011. US EIA, Washington, D.C. http://www.eia.gov/electricity/annual/html/epa_01_01.html. Accessed September 16, 2014.

Wang Y., Q. Zhu, and Y. Geng. 2013. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *J. Clean. Prod.* 53(2013):252–260.

Wegner, T., K. E. Skog, P. J. Ince, and C. J. Michler. 2010. Uses and desirable properties of wood in the 21st century. *J. Forestry* 108(4):165–173.

Wilson, J. and E. T. Sakimoto. 2004. Softwood plywood. CORRIM: Phase I Final Report: Module D. University of Washington, Seattle. 95 pp.

Wilson, J. B. and E. R. Dancer. 2005. Gate-to-gate life-cycle inventory of I-joist production. *Wood Fiber Sci*. 37(CORRIM Special Issue):85–98.

Wood Products Council (WPC). 2009. 2006 Wood used in new residential construction U.S. and Canada, with comparison to 1995, 1998 and 2003. WPC, Tacoma, Washington and APA—The Engineered Wood Association. 29 pp.