Life-Cycle Assessment for the Cradle-to-Gate Production of Softwood Lumber in the Pacific Northwest and Southeast Regions*

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Abstract

A cradle-to-gate life-cycle inventory was done for 2 by 4 to 2 by 12 dimension lumber produced from logs in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States. Seven mills in the PNW and 11 mills in the SE provided data for 2012 lumber and coproduct production, raw material and fuel use, electricity consumption, and on-site emissions. The mills represented 17 and 11 percent of the production volumes in the regions, respectively. Five processes existed within the mill, log yard, sawing, drying, planing, and energy generation. Data for the first four processes came exclusively from the survey. The functional unit was 1 m^3 of planed dry wood. Data for energy generation were based on a nationwide wood boiler survey that included PNW lumber mills. The cradle-to-gate processing energy in the PNW region was 3,434 MJ/m^3 of planed, dry lumber, 96 percent of which is owing to log transport and wood processing. The value was higher, 5,151 MJ/m^3, for the SE region in part owing to a higher initial wood moisture content. In each region, more than 70 percent of the energy is from bio-based residuals with less than 30 percent from fossil sources. The global warming impact indicator is 58.7 kg CO_2 eq per m^3 in the PNW and 81.4 kg CO_2 eq per m^3 in the SE, of which 85 percent is a result of log transport and processing. Planed, dry lumber from the PNW region stores 856 kg CO_2 eq per m^3 compared with 935 kg CO_2 eq per m^3 for lumber from the SE region. The coproducts, emissions, and material and energy inputs are further discussed in this article.

The environmental consequences of extracting raw materials and producing a product, such as lumber, are carried forward into the life cycle of products, such as wooden structures. These consequences arise not only from wood growth and harvesting but also from electricity and fuel consumption, the use of ancillary materials such as lubricants and packaging, emissions to air and water, and disposal of waste and ash. The scope of the present work was to determine the energy and material inputs and outputs for producing dimension lumber in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States through a cradle-to-gate life-cycle inventory (LCI) on the manufacturing process. The data were obtained using guidelines established by the Consortium for Research on Renewable Industrial Materials (CORRIM) (Puettmann et al. 2014) based on ISO 14044 (International Organization for Standardization 2006). The environmental impacts, global warming, ozone depletion, acidification, smog, and eutrophication are discussed. CORRIM performed a gate-to-gate study with a similar goal and scope for lumber produced during the 1999 calendar year (Milota et al. 2005) that was later updated to a cradle-to-gate analysis (Puettmann et al. 2013).

Planed dried dimension lumber is important for structural framing in North America. This includes softwood lumber that is 38 mm in thickness and 89 to 286 mm in width,

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usually referred to as 2 by 4 to 2 by 12 lumber. In 2012, the survey year, about 40 percent was used for repair and remodeling and 39 percent for construction, both residential and nonresidential (Western Wood Products Association [WWPA] 2013). The functional unit for this study is 1 m^3 of planed, surfaced dry framing lumber produced in either the PNW or the SE region of the United States.

The PNW and SE regions accounted for 93 percent of the 45 million m^3 of US softwood lumber production in 2012. More than 95 percent of the PNW regional production is Douglas-fir (*Pseudotsuga menziesii*) and hem-fir. Hem-fir is a mix of western hemlock (*Tsuga heterophylla*) and true fir (*Abies* spp.) species. The PNW region includes areas of Oregon and Washington west of the Cascade Divide. The SE region produces southern pine (*Pinus* spp.) lumber and includes the states of (in order of decreasing 2012 production) Georgia, Arkansas, Alabama, Mississippi, North Carolina, South Carolina, Florida, Texas, Louisiana, Virginia, and Oklahoma. Within both regions, there is a range of mill sizes with much of the production volume coming from larger mills. In the SE region, for example, 60 percent of the mills produce 72 percent of the lumber, and 9 percent of the mills produce 14 percent of the lumber. Larger mills tend to produce dimension lumber, while smaller mills tend to make beams or appearance grades.

Methods

Seven (of eight contacted) mills in the PNW region and 11 (of 13 contacted) in the SE region were surveyed to determine their material use and energy consumption for the 2012 calendar year. This was much more extensive than the four mills surveyed in each region in 1999 and represented enough production to satisfy LCI requirements. Mills were selected so that they represented the range of mill sizes that produce dimension lumber in the regions.

Lumber manufacturing was divided into four unit processes: log yard, sawing, drying, and planing (Fig. 1). Together, these represent the system boundary, and materials and energy that enter or leave these processes cross the system boundary. Separation into processes is necessary because some coproducts (such as green chips or logs sold off-site) do not go through all processes and embody different environmental loads. The boiler unit process, which provides steam for drying at many facilities, was surveyed separately (Puettmann and Milota 2017). In addition to the wood inputs and outputs shown in Figure 1, there are other inputs to each process, such as fuels, electricity, and materials, or outputs, such as emissions. Other products may cross the system boundary in minor amounts. For example, rough green lumber might be sold off-site.

The log yard process receives logs with the attached bark and provides surge capacity so that the mill can operate if the delivery of logs is interrupted. This process includes transport of logs to the mill, unloading logs, grading, storing logs, and moving them to the merchandiser or debarker at the sawmill. The inputs to the log yard are logs on a truck at the harvest site and fuels, mostly diesel, used in the machinery to move logs within the process. The output from the log yard is logs with the attached bark, either at the sawmill or sold off-site.

The sawing process includes all debarking, sawing, and chipping required to convert logs with bark to rough green lumber and coproducts. The coproducts include chips, sawdust, bark, and hog fuel. The process starts with debarking, after which the logs are opened on a head rig. The head rig creates lumber, flitches, and cants. The flitches and cants pass through resaws and edgers and are cut into lumber that is then sorted and stacked. The bark and sawdust are either sold or used as fuel. The slabs and edgings that are not large enough to saw into lumber are chipped and sold to pulp mills.

The drying process includes the kilns that receive rough green lumber from the sawing process. It is stacked on carts with wood spacers (stickers) that allow air to flow between the layers in the dryer. The kilns are a batch process in the PNW and a combination of batch and continuous processes

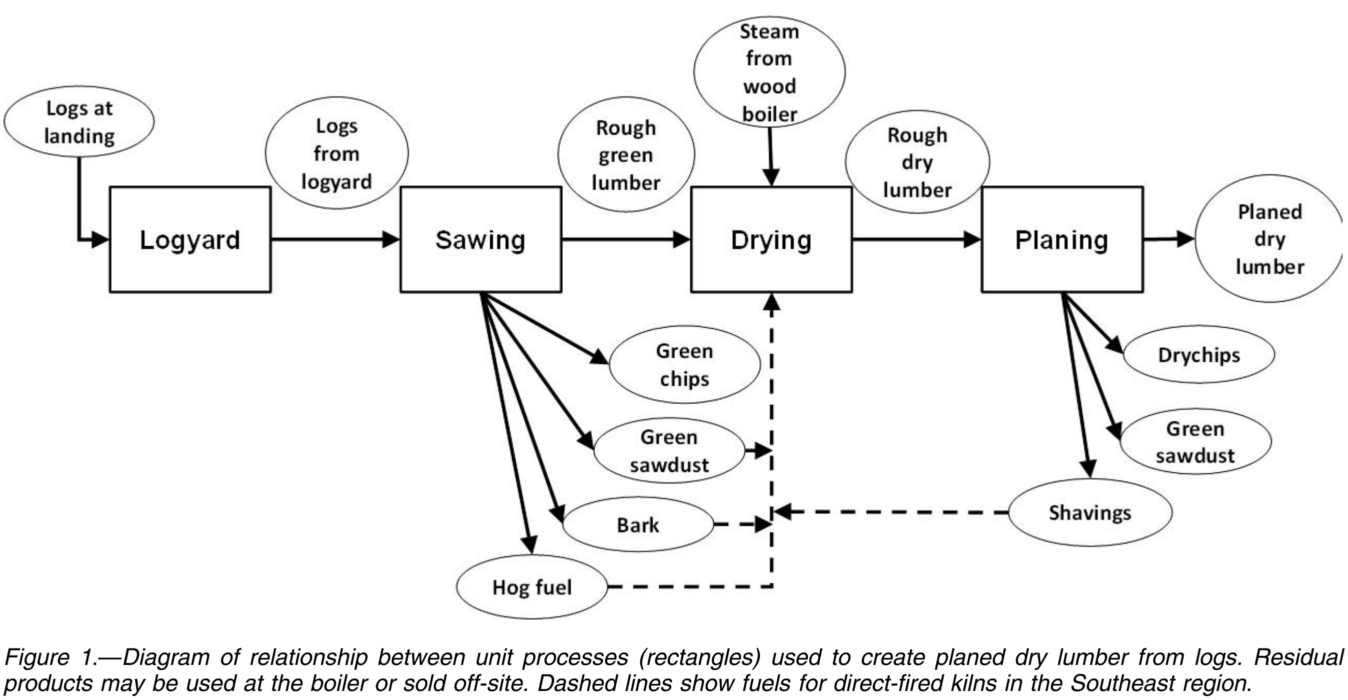

Figure 1.—Diagram of relationship between unit processes (rectangles) used to create planed dry lumber from logs. Residual products may be used at the boiler or sold off-site. Dashed lines show fuels for direct-fired kilns in the Southeast region.

in the SE. The wood is dried for 16 to 60 hours. The thermal energy is supplied by steam or the direct combustion of woody biomass. The rough dry lumber is then moved to a dry shed or planer in-feed.

The planing process produces planed dry lumber from rough dry lumber. Planed lumber is a uniform size and has a smooth surface. The process includes unstacking, planing, grading, end trimming, sorting, and packaging. Occasionally, some lengthwise sawing is done. The process also includes unitizing, moving the packages, and loading onto conveyance for shipment. The coproducts include chips, sawdust, planer shavings, and wood flour.

The values reported by each mill were for consumption and production during the 2012 calendar year. These were divided by the respective mill's 2012 production to obtain a production-based value: per cubic meter of log for the log yard, per cubic meter of rough green lumber for the sawmill, per cubic meter of rough dry lumber for drying, and per cubic meter of planed dry lumber for planing. These values from each mill were then compared to identify values for inputs or production that were outliers. Suspect values were resurveyed to verify accuracy. The production-based values for each mill were combined into a weighted average for each input and output (Tables 1 through 4). Weighting was based on the mills' 2012 production so that the values from mills with greater production received greater weight. If a value was not reported in a survey, plant personnel were contacted to determine whether it was unknown or zero. Zero values were averaged with the other data. Missing or unknown data were not included in the average, which was based on reduced lumber volume. These input and output values represent an average per cubic meter of lumber for the regional production. Only averaged values are reported to maintain the confidentiality of the survey participants. The previously reported (Johnson et al. 2005) life-cycle contributions of forest operations were used to extend the data to a cradle-to-gate analysis. Steam production from wood boilers was surveyed separately (Puettmann and Milota 2017).

Allocation was on the basis of bone dry mass. Lumber, reported in cubic meters, was converted to mass for allocation purposes using the specific gravity (SG) (Miles and Smith 2009) appropriate for the species mix and moisture content. Allocation causes, for example, some of the burdens from forest operations, the log yard, and sawing to be assigned to chips and other sawing coproducts instead of lumber.

The US Life-Cycle Inventory database was used to assess off-site impacts associated with the nonwood materials, fuels, and electricity. SimaPro 8.04 (Pré Consultants 2015) was used as the accounting program to track all of the materials. Environmental impacts were determined using the TRACI method (Bare 2011). The five impact categories presented, global warming potential (GWP), ozone depletion, acidification, smog, and eutrophication, are consistent with the requirement of the product category rules for wood products (FPInnovations 2013).

Results

The mills surveyed produced mainly dimension lumber and studs, 38 mm in thickness and from 89 to 286 mm in width (sold as nominal 2 by 4 to 2 by 12 lumber) after planing. Annual production for the mills surveyed averaged 170 million board feet (MMBF) in the PNW and 140 MMBF in the SE. The PNW survey included 1.97 million m^3 (1.21 billion board feet [BBF]), or about 17 percent of the regional production of dimension lumber for 2012. The SE survey included 2.44 million m^3 (1.53 BBF), or about 11 percent of the 2012 regional production.

The primary survey data for the PNW region included 94.2 percent dry and 5.8 percent green lumber. In 2012, 39 percent of the region's production was dried because Douglas-fir is often sold green. The survey was sent, however, to mills that produce mainly dry lumber, so this difference was expected. All the lumber in the SE was dry.

In the PNW region, 44.3 percent of the planed lumber in the survey was hem-fir, and 55.7 percent was Douglas-fir. Industry-wide production data (WWPA 2013) indicate that 41 percent of the dry dimension lumber in the region was hem-fir and 59 percent Douglas-fir. Thus, the survey results mimic the industry. The energy reported based on the survey may be slightly higher than actual because more water is removed from hem-fir during drying than from Douglas-fir. All the production in the SE region survey was southern pine.

The sawmills surveyed were of average technology. Most reported upgrades in the past 5 years. These were in the log yard, sawmill, and boiler. Half the mills in the PNW and two-thirds in the SE had at least one new kiln in the past 5 years with several continuous kilns included in the survey. Three-fourths of the mills had planer upgrades in the past 2 years, often automated grading equipment and/or multiclones and a baghouse.

There was no pollution control equipment in the log yard. The process of the sawing of green lumber had no pollution control except a baghouse on certain equipment in most cases. There were no emissions control devices on the dry kilns. Boilers and burners most commonly had an electrostatic precipitator (wet or dry) often followed by a baghouse. Emissions control at the planing process consisted of baghouses.

The wood inputs and outputs as well as the major ancillary materials will be presented for each process, log yard, sawing, drying, and planing. In some cases, a mill could report an amount only on a facility-wide basis, and a method was selected for dividing it among the processes. For example, a mill-wide value for lubricating oil in rolling stock was divided among the four processes in proportion to diesel use.

On-site process inputs and outputs

Log yard.—The logs arriving at the PNW mills were 54.2 percent hem-fir and 47.6 percent Douglas-fir with a weighted average basic SG of 0.434 (Miles and Smith 2009) and moisture content of 82.8 percent (weighted average from surveys). The logs arriving at the SE mills were all southern pine with an average SG of 0.470 (Miles and Smith 2009). The reported moisture contents varied from 66 to 122 percent with 100 percent being the mode. The average log diameter and length were 26.2 cm and 10.3 m in the PNW and 15.6 cm and 5.0 m in the SE.

Logs in the PNW were reported in Westside Scribner except one mill that reported in cubic feet. A conversion factor of 139.5 BF Scribner log scale per m^3 of log (3.95 BF/ft^3) was derived from Mann and Lysons (1972). Mills in the SE region reported logs by mass, and an SG of 0.47 and moisture content of 100 percent were used to convert mass to m^3 of wood after subtracting the bark mass. Bark mass for

Table 1.—On-site inputs and outputs to provide 1 m^3 of logs to sawmills from forest operations.[a]

	PNW	SE	Units, per m^3
Products			
Roundwood sawlogs (PNW or SE)	1.00 (99.4%)	1.00 (96.1%)	m^3
Roundwood sold off-site	0.00590 (0.6%)	0.0402 (3.9%)	m^3
Resources			
Water, process, surface	2.24	8.50	kg
Water, process, well	2.02	16.2	kg
Materials/fuels			
Softwood logs with bark, harvested at average-intensity site (PNW or SE)	1.0059	1.040	m^3
Transport, combination truck, diesel powered	98.9	97.4	t·km
Diesel, loaders and haulers	0.400	0.140	liters
Gasoline, loaders and haulers	0.00436	0.00370	liters
Propane, loaders and haulers[b]	0.00538	0.000789	liters
Organics (lubricants, etc.)[c]	0.00942	0.0305	liters
Solvents for cleaning[c]	0.0000019	0.0000376	kg
Antifreeze 50% solution, loaders and haulers	0.000364	0.000154	liters
Landfill, organics to[d]	0.00164	—	kg
Landfill, inorganics to[d]	0.00271	0.000492	kg
Recycle[d,e]	0.000235	—	kg
Electricity/heat			
Electricity, at grid (WECC [2008] or SERC [2008])	1.63	2.80	kWh
Electricity from turbine/wood boiler	0.450	—	
Emissions to air			
Wood (dust)	0.00599	0.00879	kg
Particulates, >10 μm	0.00550	0.00842	kg
Particulates, <2.5 μm	0.00230	0.000894	kg
VOCs	0.0000687	0.015	kg
Emissions to water			
Suspended solids, unspecified	0.000670	—	kg
BOD_5	0.00360	—	kg
Oils, unspecified	0.0000350	—	kg

[a] Allocations are shown in parentheses. PNW = Pacific Northwest; SE = Southeast; WECC = Western Electricity Coordinating Council; SERC = Southeast Electric Reliability Council; VOC = volatile organic compound; BOD = biological oxygen demand.
[b] Liquid petroleum gas, combusted in industrial boiler, was used as a surrogate.
[c] Gasoline at refinery was used as a surrogate.
[d] Denotes process with no off-site impacts.
[e] Includes metals, oil, antifreeze, bulbs, and batteries.

each region was estimated to be the bark plus half the hog fuel recovered in the sawing process.

Each cubic meter of wood leaving the log yard had a bone dry mass of 434 kg in the PNW region and 470 kg in the SE region. The bark on 1 m^3 of wood was calculated from the sawmill process: 116.8 kg in the PNW region and 26.7 kg in the SE region. The total mass (including moisture) of 1 m^3 of wood and its attached bark was 910.5 and 993.2 kg in the PNW and SE, respectively.

For each cubic meter of wood in log form entering the sawmill, 0.0059 m^3 of logs in the PNW and 0.0402 m^3 of logs in the SE were sold off-site because they were the wrong size or grade for the sawmill to process (Table 1). Thus, 915.9 and 1033.1 kg entered the log yard in the PNW and SE, respectively. The transportation distance from the harvest site (landing) to the log yard was 108 km in the PNW and 94 km in the SE for transportation efforts of 98.9 and 97.4 t·km/m^3, respectively. These changed little from the 113 and 92 km, respectively, in the 1999 survey. The logs that were sold off-site received a proportion of the allocation (Table 1).

In the PNW region, 2.2 kg/m^3 of process water was used in the log yard compared with 27.7 kg/m^3 in the SE region, probably because of differences in sprinkling practices. Diesel consumption was 0.40 liter/m^3 in the PNW region and 0.14 liter/m^3 in the SE region; however, electricity use in the SE region, 2.8 kW/h/m^3, was greater than in the PNW region, 2.1 kW/h/m^3, reflecting more use of cranes. It is difficult to make comparisons between the log yard process presented here and the 1999 survey because the log yard and sawmill processes were combined in the previous work.

Sawing.—The reported inputs and outputs associated with the production of 1 m^3 of rough green lumber are shown in Table 2. The mills reported production in board feet lumber scale. This was converted to cubic meters using the actual rough green lumber dimensions (target size) reported by all mills. Target thickness averaged 41.9 mm in the PNW region and 43.4 mm in the SE region, very similar to 41.3 and 43.1 mm in the 1999 survey. The inputs and outputs balance by mass to within 2.9 and 0.4 percent in the PNW and SE regions, respectively.

Table 2.—On-site inputs and outputs to produce 1 m³ of rough green lumber from logs from log yard.[a]

	PNW	SE	Units, per m³
Products			
Sawn lumber, softwood, green, rough, at sawmill	1.00 (50.1%)	1.00 (52.2%)	m³
Chips, softwood, green, at sawmill	212 (24.4%)	276 (30.7%)	kg
Sawdust, softwood, green, at sawmill	48.8 (5.6%)	87.8 (9.7%)	kg
Hogfuel, softwood, green, at sawmill	119 (13.8%)	43.5 (4.8%)	kg
Bark, softwood, green, at sawmill	52.4 (6.1%)	23.6 (2.6%)	kg
Resources			
Water, process, surface	37.9	39.0	kg
Water, process, well	12.2	41.0	kg
Materials/fuels			
Roundwood sawlogs (PNW or SE)	1.68	1.70	m³
Peeler core, softwood, plywood mill, SE	—	0.130	m³
Diesel, loaders and haulers	0.230	0.210	liters
Gasoline, loaders and haulers	0.0110	0.0180	liters
Propane, loaders and haulers[b]	0.0220	0.00210	liters
Organics (lubricants, etc.)[c]	0.180	0.151	liters
Antifreeze 50% solution, loaders and haulers	0.000394	0.000233	liters
Solvents for cleaning[c]	0.0000740	0.0000230	kg
Babbitt alloy[d]	0.000200	—	kg
Antistain for fungal growth[d]	0.000103	—	kg
Marking ink[d]	0.00557	—	kg
Softwood lumber, planed, dry (PNW or SE, runners)	0.0380	—	m³
Hot rolled sheet, steel, at plant (strapping)	0.00736	—	kg
Recycled postconsumer PET flake (plastic trapping)	0.00159	0.0000450	kg
Landfill, organics to[d]	0.00224	0.00459	kg
Landfill, inorganics to[d]	0.0360	—	kg
Recycle[d,e]	0.00161	—	kg
Electricity/heat			
Electricity, at grid (WECC [2008] or SERC [2008])	19.8	28.6	kW/h
Electricity from a turbine/wood boiler	6.06	—	kW/h
Emissions to air			
Wood (dust)	0.00403	0.00575	kg
Particulates, >10 μm	0.00617	0.0200	kg
Particulates, <2.5 μm	0.00179	0.00908	kg
VOCs	0.000115	0.0230	kg
Methanol	—	0.000287	kg
Formaldehyde	—	0.0000288	kg
Acetaldehyde	—	0.00000708	kg
l-Propanol	—	0.00000153	kg
Acrolein	—	0.00000921	kg
Phenol	—	0.000000136	kg
Emissions to water			
Suspended solids, unspecified	—	0.000244	kg
BOD_5	—	0.000614	kg

[a] Allocations are shown in parentheses. PNW = Pacific Northwest; SE = Southeast; WECC = Western Electricity Coordinating Council; SERC = Southeast Electric Reliability Council; VOC = volatile organic compound; BOD = biological oxygen demand.
[b] Liquid petroleum gas, combusted in industrial boiler, was used as a surrogate.
[c] Gasoline at refinery was used as a surrogate.
[d] Denotes process with no off-site impacts.
[e] Includes metals, oil, antifreeze, bulbs, and batteries.

The allocation to rough green lumber is lower compared with the 1999 survey, 50.1 versus 56.9 percent in the PNW region, and higher in the SE region, 52.2 versus 48.9 percent. The allocation to chips in each region was 1 to 2 percent lower than in the 1999 survey. The allocation to other coproducts is highly variable because, e.g., one mill might include sawdust or bark with hog fuel and another mill might list these separately. In the current survey, 1.68 and 1.83 m³/m³ of logs (see Table 2, roundwood sawlogs and peeler cores) were used compared with 1.59 and 1.99 m³/m³ in the 1999 survey in the PNW and the SE regions, respectively. The cubic recovery ratios were 0.60 and 0.55 in the PNW and SE regions, respectively.

The sawing process in the PNW region used 50.1 kg/m³ of process water compared with 80.0 kg/m³ in the SE region (Table 2). If the log yard and sawmill are combined adjusting for log use, these become 57.8 and 122.0 kg/m³, respectively. This is much less than reported in the 1999

Table 3.—On-site inputs and outputs to produce 1 m^3 of rough dry lumber from rough green lumber from sawmill.[a]

	PNW	SE	Units, per m^3
Products			
Sawn lumber, softwood, rough, dry, at kiln	1.00	1.00	m^3
Resources			
Water, process, surface	3.20	19.1	kg
Water, process, well	7.60	19.8	kg
Materials/fuels			
Softwood lumber from sawmill (PNW or SE)	1.00	1.00	m^3
Diesel, loaders and haulers	0.140	0.210	liters
Gasoline, loaders and haulers	0.00946	0.00773	liters
Propane, loaders and haulers[b]	0.00188	0.000928	liters
Organics (lubricants, etc.)[c]	0.00789	0.0243	liters
Antifreeze 50% solution, loaders and haulers	0.000262	0.000224	liters
Solvents for cleaning[c]	0.0000054	0.0000280	kg
Softwood lumber, planed, dry (PNW or SE, stickers)	0.000468	0.000240	m^3
Landfill, organics to[d]		0.00418	kg
Landfill, inorganics to[d,f]	0.0034	0.570	kg
Recycle, metals[d,e]	0.0000163		kg
Electricity/heat			
Electricity, at grid (WECC [2008] or SERC [2008])	8.90	8.50	kW/h
Electricity from turbine/wood boiler	2.60	—	kW/h
Wood combusted, at boiler	106.9	99.7	kg
Natural gas, combusted in industrial boiler	2.60	—	m^3
Shavings, softwood, kiln dried, at planer, SE	—	2.50	kg
Sawdust, softwood, green, at sawmill, SE	—	56.1	kg
Sawdust, softwood, green, at sawmill, SE[f]	—	0.150	kg
Transport, combination truck, diesel powered/United States	—	0.0300	t/km
Liquid petroleum gas, combusted in industrial boiler	—	0.0110	Liters
Emissions to air			
Wood (dust)	—	0.0180	kg
Particulates, >10 μm	0.00472	0.0460	kg
Particulates, <2.5 μm	0.00149	0.0290	kg
VOCs	0.106	0.700	kg
Methanol	0.0150	0.0380	kg
Formaldehyde	0.000313	0.00724	kg
Acetaldehyde	0.0200	0.00612	kg
l-Propanol	0.000146	0.000156	kg
Acrolein	0.000818	0.000894	kg
Phenol	—	0.000924	kg
Benzene	—	0.0000130	kg
Manganese	—	0.0000887	kg
Mercury	—	0.000000194	kg
Carbon disulfide	—	0.00000693	kg
Lead	—	0.00000260	kg
Trichloroethane	—	0.00000218	kg
Dioxins, unspecified	—	3.84×10^{-13}	kg
Hydrogen chloride	—	0.0000278	kg
Sulfur dioxide	—	0.0110	kg
Nitrogen oxides	—	0.0270	kg
Carbon dioxide, biogenic	—	33.0	kg
Carbon monoxide, biogenic	—	0.0550	kg
Benzo[*g,h,i*]perylene	—	8.66×10^{-14}	kg
Barium	—	2.50×10^{-8}	kg
Hexane	—	0.0000160	kg
Emissions to water			
Suspended solids, unspecified	—	0.00464	kg
BOD_5	—	0.00000618	kg

[a] Allocation is 100% to rough dry lumber. PNW = Pacific Northwest; SE = Southeast; WECC = Western Electricity Coordinating Council; SERC = Southeast Electric Reliability Council; VOC = volatile organic compound; BOD = biological oxygen demand.

[b] Liquid petroleum gas, combusted in industrial boiler, was used as a surrogate.

[c] Gasoline at refinery was used as a surrogate.

[d] Input that has no off-site impacts.

[e] Ash in SE.

[f] Transported from off-site, 94.7 km.

Table 4.—On-site inputs and outputs to produce 1 m^3 of planed dry lumber from rough dry lumber.[a]

	PNW	SE	Units, per m^3
Products			
Planed lumber, softwood, dry, packaged, at planer	1.00 (88.7%)	1.00 (90.1%)	m^3
Shavings, kiln dried, at planer	51.0 (9.7%)	54.0 (9.5%)	kg
Sawdust, softwood, kiln dried, at planer	1.96 (0.4%)	—	kg
Chips, softwood, kiln dried, at planer	6.60 (1.3%)	1.20 (0.2%)	kg
Flour, softwood, kiln dried, at planer	—	0.590 (0.1%)	kg
Resources			
Water, process, surface	5.20	21.2	kg
Water, process, well	1.80	7.90	kg
Materials/fuels			
Softwood lumber from dryer (PNW or SE)	1.14	1.21	m^3
Diesel, loaders and haulers	0.440	0.350	liters
Gasoline, loaders and haulers	0.00746	0.210	liters
Propane, loaders and haulers[b]	0.00660	0.0450	liters
Organics (lubricants, etc.)[c]	0.0684	0.141	liters
Antifreeze 50% solution, loaders and haulers	0.000869	0.000531	liters
Solvents for cleaning[c]	0.0000278	0.0000984	kg
Paint, end coat[d]	0.000580		kg
Marking ink[d]	0.000697	0.00371	kg
Packaging—wrapping material	0.380	0.0700	kg
Softwood lumber, planed, dry (PNW or SE, runners)	0.00298	0.00170	m^3
Softwood lumber, planer, dry (PNW or SE, lath)	0.000255	0.0000600	m^3
Recycled postconsumer PET flake[e]	0.140	0.0570	kg
Cardboard—AWC	0.00265	0.00803	kg
Antistain for fungal growth[d]	0.00250	0.00113	kg
Landfill, organics to[d]	0.003129	0.00403	kg
Landfill, inorganics to[d]	0.0330		kg
Recycle[f]	0.00275	0.00231	kg
Electricity/heat			
Electricity, at grid (WECC [2008] or SERC [2008])	9.80	22.0	kW/h
Electricity from a turbine/wood boiler	4.50		kW/h
Emissions to air			
Wood (dust)	0.000774	0.00674	kg
Particulates, >10 μm	0.00673	0.0210	kg
Particulates, <2.5 μm	0.00120	0.00705	kg
VOCs	0.00347	0.0190	kg
HAPs, unspecified	0.000227	—	kg
Methanol	—	0.000356	kg
Formaldehyde	—	0.0000357	kg
Acetaldehyde	—	0.00000876	kg
l-Propanol	—	0.00000190	kg
Acrolein	—	0.0000114	kg
Phenol	—	0.000000168	kg
Emissions to water			
Suspended solids, unspecified	—	0.000302	kg
BOD_5	—	0.000760	kg

[a] Rough dry lumber volume is based on dimensions when green. PNW = Pacific Northwest; SE = Southeast; WECC = Western Electricity Coordinating Council; SERC = Southeast Electric Reliability Council; VOC = volatile organic compound; HAP = hazardous air pollutant; BOD = biological oxygen demand.
[b] Liquid petroleum gas, combusted in industrial boiler, was used as a surrogate.
[c] Gasoline at refinery was used as a surrogate.
[d] Input that has no off-site impacts, input as dummy process.
[e] Surrogate for plastic strapping.
[f] Includes plastic strapping, metals, antifreeze, bulbs, and batteries.

study, 143.9 and 304.3 kg/m^3. Diesel use averaged 0.22 liter/m^3, mainly for rolling stock to move material from the sawmill to the kiln. Sometimes an intermediate holding area was used so that the packages of rough green lumber could be more optimally loaded into the kiln.

The sawmill was the greatest consumer of electricity among the four processes, 26.4 kW·h/m^3 in the PNW region and 28.6 kW·h/m^3 in the SE region. For the log yard and sawing processes combined, again adjusting for log use, these values are 29.9 and 33.4 kW·h/m^3, respectively. These compare with 45.3 and 34.4 kW·h/m^3 in the 1999 survey, suggesting that the value for the PNW region erred on the high side in 1999. Diesel use for the log yard and sawmill (adjusted for log use) was reduced from the 1999 survey (0.98 and 0.83 liter/m^3) to 0.90 and 0.52 liter/m^3 in the PNW and SE regions, respectively. This could reflect mechanical efficiency improvements or improved efficiencies in material handling. Other inputs included dunnage and chemicals necessary for lumber production.

Dry kilns.—The woody inputs are equal to the outputs at the kiln because there are no coproducts. Any mass calculations for rough dry lumber were performed using a green volume and the corresponding basic SG because bone dry mass does not change during drying.

The wood enters the kiln at a moisture content of approximately 65 to 70 percent for Douglas-fir and 100 percent for hemlock and southern pine. To meet the grade specification of 19 percent or less, the average moisture content ranges from 14 to 16 percent when dry owing to the piece-to-piece moisture content variability. A weighted average of 314.8 kg/m^3 water is removed in the PNW region and 399.5 kg/m^3 in the SE region. Thus, more energy is required in the SE.

Steam heat exchangers (heating coils) provided thermal energy to kilns in the PNW region and to about half the kilns in the SE region. The balance of the kilns in the SE region were direct fired, meaning that wood fuel is burned at the kiln and the combustion gases are admitted to the drying chamber. Several continuous kilns were reported in the SE region, whereas none were installed in the PNW region at the time of the survey. Steam use required 106.9 $kg_{WoodyFuel}/m^3$ (548.2 kg_{steam}/m^3) and 2.6 $m^3{}_{NaturalGas}/m^3$ (41.0 kg_{steam}/m^3) at the boilers in the PNW and 99.7 $kg_{WoodyFuel}/m^3$ (511 kg_{steam}/m^3) in the SE (no natural gas boilers in the SE survey). Kiln drying in the SE also required 58.7 kg/m^3 of wood fuel combusted at direct-fired kilns. Some of the fuel came from off-site and carried the same embodied impacts as the coproducts at surveyed mills plus 0.030 t/km/m^3 of transportation effort. A small amount of liquid petroleum gas was used in the burners, presumably for start-up.

The thermal efficiency is the energy required divided by the energy consumed. In the PNW region, the consumption is 589.2 kg of steam to remove 314.8 kg of water, and the efficiency is

$$55\% = 100 \times \frac{314.8\,\mathrm{kg_{water}} \times 2.26\,\frac{\mathrm{MJ}}{\mathrm{kg_{water}}}}{589.2\,\mathrm{kg_{steam}} \times 2.16\,\frac{\mathrm{MJ}}{\mathrm{kg_{steam}}}} \tag{1}$$

The kilns in the SE region are heated by a combination of steam and direct wood combustion, yielding 20.93 MJ/kg_{wood}. The efficiency in the SE then becomes

$$41\% = 100 \times \frac{399.5\ \mathrm{kg_{water}} \times 2.26\,\frac{\mathrm{MJ}}{\mathrm{kg_{water}}}}{511\,\mathrm{kg_{steam}} \times 2.16\,\frac{\mathrm{MJ}}{\mathrm{kg_{steam}}} + 58.65\ \mathrm{kg_{wood}} \times 20.93\,\frac{\mathrm{MJ}}{\mathrm{kg_{wood}}} \times 0.9_{\mathrm{burnereff}}} \tag{2}$$

The difference is partly because losses owing to the water in the green wood combustion are assigned to the boiler in the PNW region, whereas green wood is used as a fuel at the kiln in the SE region. The impacts of producing steam from woody fuels were obtained from the CORRIM boiler process (Puettmann and Milota 2017) and for natural gas and liquid petroleum gas from SimaPro library processes.

Dry kilns use water (Table 3) for a wet-bulb thermometer. Mills reported a weighted average water use of 10.8 kg/m^3 in the PNW region and 38.9 kg/m^3 in the SE region, each of which is higher than would be used only by the wet bulb. The authors of this article predict wet-bulb water use to be 2 to 4 kg/m^3, which is also in closer agreement with the 1999 survey results, and it is uncertain why the reported values are this high. Diesel use was 0.14 liter/m^3 in the PNW and 0.21 liter/m^3 in the SE. This is for forklifts and modified front-end loaders used for moving lumber into the kiln, out of the kiln, and to the planer.

Electricity use at kilns was 11.5 and 8.5 kW·h/m^3 for the PNW and the SE regions, respectively. The difference may be due to shorter drying times in the SE region. The values are considerably less than reported in the 1999 survey (14.5 and 19.1 kW·h/m^3). This could be due to more efficient kiln motors and variable-frequency drives being used more commonly to reduce airflow in the later stages of drying.

Planer.—The planed lumber produced in the PNW region was reported as 49.9 percent dry Douglas-fir (SG = 0.48), 44.3 percent dry hem-fir (SG = 0.45), and 5.8 percent green Douglas-fir (SG = 0.45). The nonwood inputs and outputs were not separable between planing green and dry lumber but should be similar. The wood inputs were made equivalent by assuming a green dimension (sawmill target size) and basic SG for the rough dry lumber. Thus, 1 m^3 of rough dry lumber entering the process has the same (or nearly the same) bone dry mass as 1 m^3 of rough green lumber. On the product side, planed green lumber has a slightly larger target size and slightly lower SG than planed dry lumber. These two factors nearly offset each other so that the bone dry masses of 1 m^3 of planed green and dry lumber are very similar for a given nominal dimension. All planed lumber was dry southern pine in the SE region.

The reported woody inputs and outputs associated with the production of 1 m^3 of planed dry lumber are shown in Table 4. The reported inputs and reported outputs balance by mass to within 5.4 percent in the PNW and 0.5 percent in the SE. The mills reported production in BF lumber scale. This was converted to cubic meters using the actual planed dry dimensions as presented in the grading rules.

Water, 7.0 kg/m^3 in the PNW region and 29.1 kg/m^3 in the SE region, was used for cooling machinery and dust control. In the PNW and SE regions, 0.44 and 0.35 liter/m^3 diesel were used, respectively. Electricity use was 14.3 and 22.0 kW/h/m^3 in the PNW and SE regions, respectively.

LCI results for planed dry lumber

LCI results for planed, dry, softwood, dimension lumber are presented in Tables 5 through 8. The forest operations columns represent the cradle-to-gate impacts of producing logs loaded on conveyance at the landing, including seedling production, planting, management, and harvest. The wood production columns represent the gate-to-gate impacts of lumber production. The total columns represent the cradle-to-gate impacts of producing lumber, packaged and loaded on conveyance at the plant gate. The values in each column include the on-site and off-site impacts.

Raw material energy consumption (Table 5) is the amount of resource extracted and used for energy. Almost all of the coal and uranium are used in electricity production. In each region, 91 percent of the oil is attributable to diesel burned in equipment such as trucks, skidders, and forklifts. In the PNW region, 65, 20, and 12 percent of the natural gas is used for off-site electricity, in boilers, and for chemical production, respectively. In the SE region, these values are similar, 59, 21, and 16 percent. Chemical production includes ammonia, urea, and ethylene, which are used in forest fertilization and product packaging. Wood is combusted for energy in on-site boilers or burners at lumber mills. Burners in the SE region consume 37.5 percent of the wood energy.

The major sources of on-site air emissions (Table 6) are dryers and boilers. Dryer emissions include volatile organic compounds (VOCs), such as terpenes, that come from the wood. In the PNW region, VOCs are approximately 47 percent from each the boiler and the dryer. A higher proportion, 82 percent, comes from the dryers in the SE region, partly because of combustion at direct-fired kilns instead of a boiler and partly because hemlock is a nonresinous species. The balance of the VOCs are from other on- and off-site processes. About half of the large particulate (>10 μm) emissions tend to come from the

Table 5.—Cradle-to-gate raw material energy consumption for production of planed dry softwood lumber in the Pacific Northwest (PNW) and Southeast (SE).

	kg/m^3 of planed dry lumber					
	PNW			SE		
Fuel	Total	Forestry operations	Wood production	Total	Forestry operations	Wood production
Coal	8.49E+00	1.49E−01	8.34E+00	2.09E+01	2.35E−01	2.07E+01
Gas	8.51E+00	1.92E−01	8.32E+00	3.95E+00	8.51E−01	3.10E+00
Oil	7.27E+00	2.54E+00	4.73E+00	8.81E+00	3.54E+00	5.27E+00
Uranium	1.85E−04	3.50E−06	1.82E−04	5.85E−04	5.37E−06	5.80E−04
Wood	1.17E+02	0.00E+00	1.17E+02	1.79E+02	0.00E+00	1.79E+02

Table 6.—Cradle-to-gate air emissions for production of planed dry softwood lumber in the Pacific Northwest (PNW) and Southeast (SE).[a]

	kg/m^3 of planed dry lumber					
	PNW			SE		
Substance	Total	Forestry operations	Wood production	Total	Forestry operations	Wood production
Acetaldehyde[b]	2.16E−02	3.44E−05	2.16E−02	7.16E−03	4.77E−05	7.11E−03
Acrolein[b]	9.79E−04	4.17E−06	9.74E−04	1.14E−03	5.78E−06	1.13E−03
Carbon dioxide[c]	6.81E−02	2.25E−02	4.57E−02	5.52E−01	5.18E−01	3.44E−02
Carbon dioxide[d]	2.06E+02	6.52E−03	2.06E+02	2.36E+02	1.00E−02	2.36E+02
Carbon dioxide[e]	5.38E+01	8.26E+00	4.56E+01	7.56E+01	1.17E+01	6.40E+01
Carbon monoxide[d]	3.77E−01	0.00E+00	3.77E−01	4.26E−01	0.00E+00	4.26E−01
Carbon monoxide[e]	1.91E−01	7.51E−02	1.16E−01	2.50E−01	1.04E−01	1.45E−01
Formaldehyde[b]	1.90E−03	5.33E−05	1.85E−03	9.82E−03	7.41E−05	9.75E−03
HAPs[c]	2.13E−04	0.00E+00	2.13E−04	0.00E+00	0.00E+00	0.00E+00
Hydrocarbons[c]	5.67E−05	1.07E−06	5.56E−05	1.79E−04	1.64E−06	1.78E−04
Methane	1.29E−01	1.11E−02	1.18E−01	1.52E−01	2.42E−02	1.28E−01
Methane[e]	1.38E−02	8.54E−04	1.29E−02	1.06E−02	2.47E−03	8.10E−03
Methanol[b]	1.70E−02	0.00E+00	1.70E−02	4.46E−02	0.00E+00	4.46E−02
Nitrogen oxides	4.88E−01	1.50E−01	3.38E−01	6.36E−01	2.09E−01	4.28E−01
Particulates, <10 μm	5.50E−02	0.00E+00	5.50E−02	5.32E−02	0.00E+00	5.32E−02
Particulates, <2.5 μm	2.29E−02	0.00E+00	2.29E−02	6.37E−02	0.00E+00	6.37E−02
Particulates, >10 μm	2.17E−02	0.00E+00	2.17E−02	9.81E−02	0.00E+00	9.81E−02
Particulates, >2.5, <10 μm	1.02E−02	4.59E−03	5.59E−03	1.23E−02	6.40E−03	5.89E−03
Particulates[c]	1.41E−02	8.19E−04	1.33E−02	3.27E−02	1.44E−03	3.13E−02
Phenol[b]	7.58E−05	3.25E−12	7.58E−05	1.12E−03	6.40E−11	1.12E−03
Propanal[b]	1.63E−04	7.71E−11	1.63E−04	1.86E−04	1.52E−09	1.86E−04
Sulfur dioxide	2.69E−01	5.39E−03	2.64E−01	3.99E−01	2.67E−02	3.72E−01
Sulfur oxides	1.25E−02	0.00E+00	1.25E−02	1.31E−02	0.00E+00	1.31E−02
VOC	2.34E−01	4.01E−03	2.30E−01	9.63E−01	6.14E−03	9.57E−01
Wood (dust)	7.56E−02	0.00E+00	7.56E−02	—	—	—

[a] Values greater than 10^{-2} kg/m^3 for either region are shown, as are volatile organic compounds (VOCs), particulates, and Maximum Achievable Control Technology (MACT) standard hazardous air pollutants (HAPs).
[b] HAP specified in MACT rule, Title 3.
[c] Unspecified.
[d] Biogenic.
[e] Fossil.

sawing and planing, while smaller particulates (<2.5 μm) tend to be from the boiler and burners. Particulates in the form of condensed hydrocarbon may also be present in dryer exhaust and tend to fall between these sizes. Under Title III of the Clean Air Act Amendments of 1990, the Environmental Protection Agency has designated six hazardous air pollutants that wood products facilities are required to report as surrogates for all hazardous air pollutants. These are methanol, acetaldehyde, formaldehyde, propionaldehyde (propanal), acrolein, and phenol. Methanol and acetaldehyde are 89 to 99 percent from the dryer with nearly all the balance from boilers. In the PNW region, formaldehyde was 79 percent from the boiler and 13 percent from the dryer compared with 88 and 12 percent in the SE region. Acrolein was reported mainly from the dryers in both regions. Propionaldehyde was approximately 10 percent owing to the boiler with most of the balance attributable to the dryer in the PNW region and 100 percent in the SE region. Phenol ($<10^{-4}$ kg/m^3) was nearly 100 percent attributable to the boiler in the PNW region. The reporting of phenol from the dryer in the SE is probably owing to the combustion because phenol is not released during wood drying based on nearly all research. Many of the compounds listed as air emissions are produced off-site.

On-site liquid emissions (Table 7) from the process are not common for sawmills as process water is captured. Because discharge is not permitted at most sites, only one mill in the PNW region and three in the SE region reported liquid emissions. Chloride, suspended solids, and solved solids, the highest emissions, were not reported from on-site at any mill. Reported on-site emissions included suspended solids and biological oxygen demand in both regions and chemical oxygen demand and oil in the PNW region.

Solid emissions (Table 8) included ash from the boilers or burners and small amounts of plastic strapping and wood debris going to landfills. The ash to landfills is lower in the PNW region because more (70%) is sold for agricultural application than in the SE region (16%). Gas boilers with no ash were reported in the PNW region. Also, more water is removed in the SE region per cubic meter of lumber produced, so more energy is required contributing to more ash. The woody debris is most likely bark from log yard cleanup. It contains dirt and is not suitable for use as a fuel

Table 7.—Cradle-to-gate liquid emissions for production of planed dry softwood lumber in the Pacific Northwest (PNW) and Southeast (SE).[a]

	kg/m^3 of planed dry lumber					
	PNW			SE		
Substance	Total	Forestry operations	Wood production	Total	Forestry operations	Wood production
Barium	3.94E−02	1.13E−02	2.81E−02	4.35E−02	1.65E−02	2.70E−02
BOD	1.50E−02	1.76E−03	1.32E−02	1.09E−02	2.98E−03	7.91E−03
Bromide	1.13E−02	2.07E−03	9.25E−03	1.05E−02	3.52E−03	7.02E−03
Calcium	9.44E−02	3.10E−02	6.35E−02	1.06E−01	5.28E−02	5.36E−02
Calcium, ion	7.53E−02	0.00E+00	7.53E−02	5.16E−02	0.00E+00	5.16E−02
Chloride	1.91E+00	3.48E−01	1.56E+00	1.78E+00	5.93E−01	1.18E+00
COD	2.10E−02	3.34E−03	1.77E−02	1.77E−02	5.51E−03	1.22E−02
Fluoride	7.18E−04	6.50E−04	6.85E−05	1.47E−02	1.49E−02	1.23E−04
Iron	6.36E−03	1.64E−03	4.71E−03	7.15E−03	2.46E−03	4.69E−03
Lithium	1.56E−02	6.62E−04	1.50E−02	1.55E−02	4.15E−03	1.13E−02
Lithium, ion	1.34E−02	0.00E+00	1.34E−02	3.74E−03	0.00E+00	3.74E−03
m−Xylene	1.60E−06	2.92E−07	1.31E−06	3.09E−02	1.03E−02	2.06E−02
Magnesium	3.32E−02	6.05E−03	2.71E−02	3.09E−02	1.03E−02	2.06E−02
Radioactive, nuclides[b]	3.05E+02	5.77E+00	2.99E+02	9.65E+02	8.84E+00	9.56E+02
Sodium	2.99E−01	9.82E−02	2.01E−01	3.37E−01	1.67E−01	1.70E−01
Sodium, ion	2.39E−01	0.00E+00	2.39E−01	1.64E−01	0.00E+00	1.64E−01
Solved solids	1.04E+00	0.00E+00	1.04E+00	7.15E−01	0.00E+00	7.15E−01
Sulfate	8.12E−03	7.82E−04	7.34E−03	1.71E−02	1.32E−03	1.57E−02
Suspended solids[b]	1.40E+00	4.55E−01	9.46E−01	1.58E+00	7.69E−01	8.13E−01

[a] Values greater than 10^{-2} kg/m^3 for either region are shown. BOD = biological oxygen demand; COD = chemical oxygen demand.
[b] Unspecified.

Table 8.—Cradle-to-gate solid emissions for production of planed dry softwood lumber in the Pacific Northwest (PNW) and Southeast (SE).

	kg/m^3 of planed dry lumber					
	PNW			SE		
Substance	Total	Forestry operations	Wood production	Total	Forestry operations	Wood production
Ash	1.12	0.00	1.11	2.069	0.006	2.063
Other inorganics	0.031	0.00	0.031	0.317	0.000	0.317
Other organics	0.0005	0.0000	0.0005	0.010	0.000	0.010
Waste, solid	2.97	0.13	2.84	6.493	0.205	6.288
Woody material	0.005	0.00	0.005	—	—	—

or product. Many materials were recycled, such as metals, plastic strapping, antifreeze, and batteries.

LCI assessment results

The total energy for producing 1 m^3 of softwood lumber from the PNW region changed only slightly from 3,532 MJ/m^3 (Milota et al. 2005) to 3,434 MJ/m^3 in the current study (Table 9). The total energy was 5,151 MJ/m^3 in the SE region, higher than the 3,363 MJ/m^3 previously reported (Milota et al. 2005). It is not clear why the energy use in the 2005 report was so low. Taking the current value for the PNW region and accounting for the additional water removed during drying in the SE region would suggest a value for the SE region on the order of 4,200 MJ/m^3, about midway between the value in the 2005 report and the value from the current survey. The energy from wood is almost all for drying in both regions. It is worth noting that mills in both regions are more than 70 percent energy self-sufficient. Fossil energy, 878 MJ/m^3 in the PNW region and 1,160 MJ/m^3 in the SE region, is used for machinery, transportation, electricity, and drying. It is lower in the PNW region than in the 2005 report (1,534 MJ/m^3) because fewer mills reported gas boilers. For the same reason, the biomass energy used in the PNW region, 2,449 MJ/m^3, is greater than in the previous work, 1,597 MJ/m^3 (Milota et al. 2005).

GWP is lower in the PNW region than in the SE region, mainly because of hydro in the electrical grid. This is somewhat offset by use of the gas boilers in the PNW region. For GWP, 83 to 85 percent of the CO_2 equivalent emissions come from producing lumber, with 15 to 17 percent assigned to forestry operations (not shown in table). The contribution of forestry operations to the other factors ranges from 7 to 32 percent in the PNW region and from 21 to 64 percent (eutrophication) in the SE region.

GWP and other indicators were not calculated by Milota et al. (2005), as it was not required under CORRIM protocol at the time. Puettmann et al. (2013) updated the 2005 report, included more recent electricity grid and wood boiler data, and calculated indicators. The updates were necessary to comply with the product category rules for North American Structural Wood Products so that an environmental product declaration on North American softwood lumber could be produced. Global warming impacts in the PNW region were reduced by 48 percent compared with the 2013 report, while acidification, eutrophication, and smog were lowered by 44, 14, and 10 percent, respectively (Table 9). The GWP increase in the SE region is due to increased energy use compared with the earlier study. Acidification, eutrophication, and smog were increased by 17, 15, and 17 percent, respectively (Table 9). Impact indicators for GWP, acidification, eutrophication, ozone depletion, and smog potential provide general but quantifiable indications of potential environmental impacts. No single indicator has more or less significance than another. Each is stated in units that are not comparable to others.

Nonrenewable materials consumed during the manufacturing of planed dry lumber include ink, wrapping, and strapping and total 0.180 and 0.113 kg/m^3 in the PNW and SE regions, respectively. Renewable materials include mainly the logs, but dunnage and stickers and other materials make up 0.4 percent. Water consumption was 354 and 474 liters/m^3 in the PNW and the SE, respectively. Water consumption is more than three times greater, and solid waste is less than one-third of that previously reported. No reasons were determined for these differences.

Using the TRACI impact assessment method for carbon releases, a carbon balance (Table 10) was constructed for each region. Emissions from wood combustion (e.g., methane or nitrogen oxides) are included in the GWP impact category, but CO_2 is not. Using this method, 57.8 kg CO_2 eq were released in the production of 1 m^3 of lumber in the PNW and 81.5 kg CO_2 eq in the SE. The 1 m^3 of lumber stores has a carbon content of 50 percent and stores 856 and

Table 9.—Life-cycle impact assessment results for softwood lumber production with comparison to Milota et al. (2005) or Puettmann et al. (2013).

		Pacific Northwest		Southeast	
	Unit	2012	1999	2012	1999
Primary energy consumption					
Fossil	MJ	878	1,765	1,160	846
Nuclear	MJ	70.50	97.	223	166
Renewable, nonbiomass	MJ	36.7	73	8.82	4.3
Renewable, biomass	MJ	2,449	1,597	3,759	2,347
Total	MJ	3,434	3,532	5,151	3,363
Impact potential					
Global warming	kg CO_2 eq	57.8	112.3	81.4	60.7
Acidification	kg SO_2 eq	0.646	1.16	0.892	0.76
Eutrophication	kg N eq	0.0256	0.0297	0.0569	0.0495
Ozone depletion	kg CFC-11 eq[a]	5.51E−09	0.00000	3.87E−09	0.00000
Smog	kg O_3 eq	13.20	14.63	19.5	16.7
Material consumption (nonfuel)					
Nonrenewable	kg	0.180	0.114	0.113	0.104
Renewable	kg	478.0	466.0	652	479.3
Fresh water	liters	354.0	105.7	474	186
Solid waste	kg	4.12	12.81	8.89	23.6

[a] CFC = chlorofluorocarbons.

Table 10.—Carbon per 1 m^3 of planed dry softwood lumber produced in the Pacific Northwest (PNW) and Southeast (SE).

	PNW	SE
Forestry operations	8.6	13.8
Lumber manufacturing	49.2	67.7
CO_2 eq stored in product	856	935
Net CO_2 eq	−798	−854

935 kg CO_2 eq in the PNW and the SE, respectively. The difference is the due to the mean SG of 0.467 being less than 0.51 in the SE.

Conclusions

In each region, the PNW and the SE, the survey data are representative of the lumber sizes and production volumes consistent with trade association production data. In the PNW region, the relative amounts of Douglas-fir and hemlock lumber in the survey were similar to what is reported as outputs for the region.

Emissions from the forestry operations LCI range from 0 to 2 percent of the emissions from manufacturing for most compounds; however, this can range up to 67 percent for some isolated minor compounds. At the mill site. emissions to land and water are small. Mill site airborne emissions originate mainly at the boiler and dryer and are a function of the fuel burned.

Manufacturing consumes 96 percent of the cradle-to-gate energy to produce planed dry softwood lumber, with the balance attributable to forestry operations. Forestry operations consumed almost exclusively fossil fuels. The energy for processing was about 71 to 73 percent from biomass. Overall, energy use in both regions is dominated by the drying process. Steam from wood fuel supplied 91.8 percent of the thermal energy used for drying with the balance from natural gas in the PNW. The thermal energy for drying in the SE was all from wood; however, many kilns are direct fired, and the mills lack boilers. The sawing process is the greatest consumer of electrical energy followed by planing.

The global warming impact indicator is 58.7 kg CO_2 eq per m^3 in the PNW region and 81.4 kg CO_2 eq per m^3 in the SE region, of which 85 percent is due to processing and transport. Planed, dry lumber from the PNW region stores 856 kg CO_2 eq per m^3 compared with 935 kg CO_2 eq per m^3 for lumber from the SE region, far more than emitted from cradle to gate (57.8 and 81.5 kg CO_2 eq per m^3, respectively).

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