LIFE CYCLE INVENTORY OF SOFTWOOD LUMBER FROM THE INLAND NORTHWEST US

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Abstract. As part of CORRIM Phase II life-cycle inventory (LCI) studies on forestry and wood products, this study completed a gate-to-gate life LCI for the production of softwood lumber produced in the Inland Northwest region of the US. Data were collected by surveying representative softwood lumber producers. Raw material use, heat energy, fuels, electrical consumption, and associated wood production emissions represented input data into the LCI. The combined annual production of the representative softwood manufacturers was 16% of the total annual regional production of 755,852 m^3. Thermal energy requirements made a significant contribution to the total energy consumption for wood production. In this study, approximately 72% of the total energy was used for drying green lumber to 15% MC. Thermal energy was generated both from wood fuel and natural gas, representing 54 and 46% of the total, respectively.

Keywords: Life-cycle inventory, LCI, softwood lumber, CORRIM, energy, emissions, environmental impact, carbon.

INTRODUCTION

Over the past decade, life-cycle assessment (LCA) studies on forestry and wood products have generated international attention. In 2004, the Consortium for Research on Renewable Materials (CORRIM) published several wood product and forestry life-cycle inventories (LCIs) documenting the environmental performance of wood building materials from forestry operations through building construction and use (CORRIM 2005). Known as the CORRIM Reports, these extensive LCIs were the first publically available LCI studies covering US forestry and wood products production that followed international standards. The reports covered forestry operations and wood production for softwood lumber, softwood plywood, laminated veneer lumber, glued-laminated beams, and engineered I-joists from two major wood producing regions in the US, the Pacific Northwest and Southeast. In addition, oriented strandboard production was included using resources from the Southeast. In the interim, Australia has also completed an extensive LCI database on forestry and wood products following the model of CORRIM Phase I LCI. The Australian database consists of native and plantation hardwood and softwood forest types, hardwood and softwood

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timber production, glue-laminated beams, engineered I-joists, veneer and plywood production, laminated veneer lumber, particleboard, and medium-density fiberboard.

Beginning in 2004, CORRIM launched the second phase of LCI on forestry and wood products production (CORRIM 2004) that included two new resource and product production regions, Inland Northwest and Northeast–North Central. The products included in Phase II LCI were softwood lumber from both regions, hardwood flooring and lumber from the Northeast–North Central region, and nonstructural products such as medium-density fiberboard and particleboard and their associated resins.

At a time when the wood industry is rethinking how they grow, manage, and produce products originating from forests, LCA studies produce the scientific information that documents the quantitative environmental impacts of their operations and prepares the industry for future "green" marketing opportunities. This article is based on the CORRIM Phase II Final Report, Module B Life Cycle Inventory of Inland Northwest Softwood Lumber Manufacturing (Wagner et al 2009).

BACKGROUND

Life-Cycle Assessment

LCA, which began in the 1960s (Hunt et al 1992; Curran 1993, 1996), has evolved as an internationally accepted method for analyzing quantitative inputs and outputs of a product and corresponding effects on the environment. The environmental outcomes can accurately target the source of impacts such as where, when, and how impacts occur through a product's life. The most widely accepted methods for conducting LCA are set forth in the International Organization for Standardization (ISO) 14000 series of standards (ISO 2006). Figure 1 outlines the stages of product life as defined by ISO standards in which energy and resources are consumed and emissions and waste are released into the environment. ISO also defines a multiphase process consisting of four interrelated steps: 1) goal definition and scoping; 2) LCI; 3) life-cycle impact assessment (LCIA); and 4) improvement assessment (Fig 2).

These steps are interconnected with their outcomes based on the goals and purposes of a particular study. The goal definition and scoping step represents the purpose of the study in which the products and system boundaries are defined. The inventory portion, LCI, is an objective, data-based process of quantifying energy and raw material requirements, air and waterborne emissions, solid waste, and other environmental releases occurring within the system boundaries. The assessment portion, LCIA,

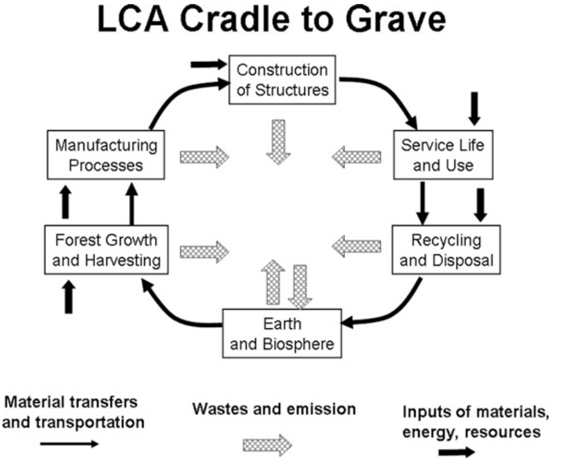

Figure 1. Life cycle of biological materials. (Adapted from Keoleian and Menerey 1993.)

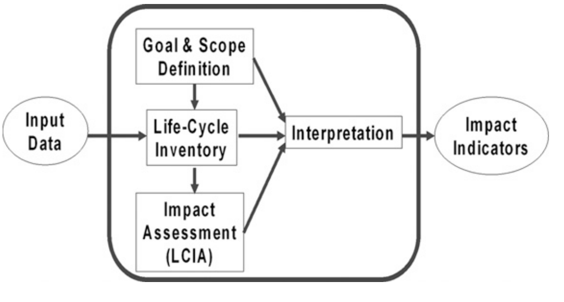

Figure 2. Steps in developing a life-cycle assessment. Picture extracted from http://www.nrel.gov/lci/assessments.html.

characterizes the effects of the environmental releases identified in the LCI and assesses their impact on categories such as global warming potential, habitat modification, acidification, or noise pollution.

One of the most useful outcomes of the LCA process is the ability to assess both direct and indirect effects of material consumption. Direct effects are generally easy to understand, and the public can usually comprehend the connection between cause and effect. For example, the direct effect of collecting newspapers for recycling is that disposal is avoided and therefore less material is deposited in a landfill. However, indirect effects are not always easily associated with consumption. Continuing with the previous example, it is not obvious that recycling operations use vast amounts of fossil fuel for collection of recyclables and can also require fossil fuels to generate electricity for sorting and processing materials. Therefore, fuel consumption related to recycling can result in the release of substantial amounts of carbon dioxide, a key contributor to global warming. Information provided in an LCA allows consumers to become more responsible in making purchase choices, manufacturers to reduce raw material use and environmental releases, and government agencies to guide the establishment of realistic regulations on environmental releases specific to a particular industry.

Loss or degradation of old-growth and/or tropical forests has fueled extensive public concern and debate surrounding the use of global forests. Harvest from federally owned forestland in the US has been hotly contested with resulting policy changes and sharp declines in harvests from those forests. Despite the controversies surrounding forestry, the renewability of wood means that it will continue to play a critical role in our society as a raw material for consumer products, industrial raw materials, and production and transportation infrastructure.

The goal of this study was to document the environmental impact of the production of softwood lumber produced in the Inland Northwest region of the US. Environmental impacts were measured based on emissions to air and water, solid waste, energy consumption, and resource use.

Softwood Lumber Production

Softwood lumber is produced in a variety of sizes and species[1] and is the primary material used for framing and finishing residential single family homes. In 2007, over one million new housing starts were reported for the US (NAHB 2009), although in 2008, housing starts decreased by nearly 33%. Approximately 13 m^3 of wood is needed for framing a single family home (Perez-Garcia et al 2005). Total US softwood lumber production in 2006 was 80 Mm^3 (Warren 2008). Domestic consumption of softwood lumber was 124.7 Mm^3 (USDA 2006).

The methods for producing kiln dry softwood lumber are consistent across all regions of the US, commonly consisting of log yard storage and systems for debarking logs; sawing logs into lumber of varying widths, thicknesses, and lengths; drying green lumber in dry kilns; planing dry or green lumber; grading planed lumber; and packaging graded lumber for shipment.

PROCEDURES

Scope of the Study

The scope of this study was to conduct a gate-to-gate LCI for softwood lumber from the Inland Northwest production region of the US considering those environmental releases and resource consumption associated solely with the manufacture of softwood lumber. Forestry operations and transportation of raw materials

[1] In the US, lumber length is recorded in actual dimensions, whereas width and thickness are traditionally recorded in nominal dimensions. Actual dimensions are defined either green (not dried) or after the wood has been dried to a desired MC of less than 30% MC on an oven-dry weight basis. Actual dimensions are smaller than nominal. Much softwood lumber is produced to actual thicknesses of 19 or 38 mm (nominal 1 or 2 in.), actual widths of 63 – 286 mm (nominal 3 – 12 in.), and lengths of 2.4 – 6.1 m.

to sawmills were excluded but are documented in other CORRIM Phase II projects (Johnson et al 2008; Puettmann et al 2010). This LCI includes log yard activities, sawing, drying, and planing softwood lumber. Mill surveys provided the primary data for the LCI analysis, whereas secondary data for the production and transportation of fuels and electricity were obtained from published databases (Franklin Associate 2004; Department of Energy 2007; PRé Consultants 2008).

The LCI of softwood lumber from the Inland Northwest is a continuation of LCI on softwood lumber conducted for the Pacific Northwest and Southeast (Milota et al 2005) as part of CORRIM Phase I product LCI. The project and the results can be used by LCI practitioners in addition to its use in LCA studies that document the use of wood products in building construction over its entire life cycle (cradle-to-grave). The data presented in the study are also available through the US LCI database (NREL 2004). Critical external reviews of this LCI process were conducted to ensure compliance with CORRIM guidelines and ISO 14044 standards (CORRIM 2001; ISO 2006).

Reference Unit

The reference unit was 1 m^3 of planed dry softwood lumber.[2] This is in compliance with CORRIM guidelines for using actual volume as a reference unit. All input and output data collected from manufacturers were allocated to the reference unit based on a mass allocation in accordance with CORRIM guidelines and ISO standards. A more specific functional unit such as an area of wall that is supported for a particular situation was not developed because it would require the use of the lumber to be defined in a particular situation over its full life cycle. A functional unit representing end-use is outside the scope of the study.

[2] For conversion of SI units to US industry units, 1 m^3 = 0.6164 thousand board feet based on actual lumber dimensions.

System Boundary

The system boundary encompasses the product manufacturing processes, including inputs of raw materials (logs) and electricity and fuels required to produce 1 m^3 of finished product. Transportation distances of raw materials to the production facilities were reported, but burdens associated with transportation were omitted from LCI analysis. Two system boundaries were evaluated: 1) a cumulative system boundary (gate-to-gate) that included all upstream flows of energy, fuel, and raw material production (Fig 3); and 2) an on-site system boundary that included only burdens generated at the manufacturing facility (Fig 3, dotted line). The on-site system boundary does not include production and transportation of electricity and fuels, but does include fuel combustion emissions and sawmill manufacturing emissions (including dryer and boiler emissions).

Excluded from both the cumulative and on-site LCI boundary were growing, management, harvesting, and log transportation. Both the separate analysis that was conducted of the forest management processes and a full cradle-to-gate LCI of wood products from CORRIM Phase II reports that includes harvesting and transportation are in other publications (Oneil et al 2010; Puettmann et al 2010).

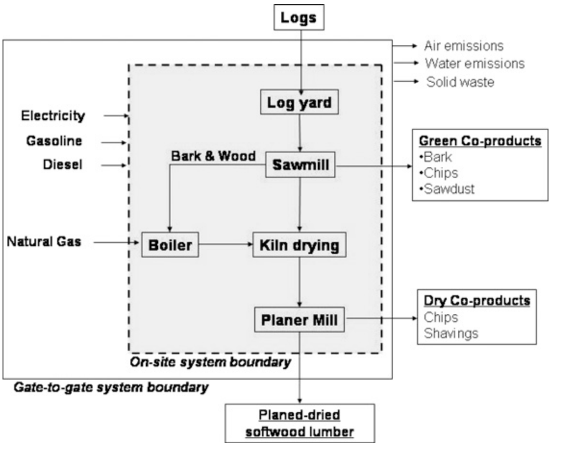

Figure 3. Gate-to-gate system boundary including unit processes used to model Inland Northwest softwood lumber production.

Data Collection and Quality

Primary softwood lumber production data were collected by written surveys and covered operations of the mills throughout one full calendar year, including summer and winter operations. A copy of the mill surveys can be found in the full report of this study (Wagner et al 2009). Total annual softwood lumber production for the Inland Northwest region in 2005 was 4,866,000 m^3 (WWPA 2006), which represent about 8% of the total US softwood lumber production. This study focused on production practices in the Inland Northwest region of the US that includes eastern Washington, eastern Oregon, Idaho, and western Montana. Four representative softwood lumber producers provided data for the LCI analysis. Their combined annual production was 755,852 m^3 in 2005/2006 or about 16% of the total production within the Inland Northwest region. Many species are used to produce softwood lumber from the Inland Northwest, including white fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), western redcedar (*Thuja plicata*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), and western hemlock (*Tsuga heterophylla*).

Two different log scales (Scribner Decimal C East Side and weight) used by the four mills gave log inputs in either thousand board feet (MBF) or short tons.[3] The wood materials considered in the LCI analysis include the main product, planed dry softwood lumber and the associated coproducts, chips, bark, sawdust, and wood fiber. All flow analyses of the product and coproducts in the process were determined on an oven-dry weight basis. Following CORRIM guidelines, an overall wood mass balance was determined from material input to material output and fell within 5% (Table 1). Log mass was calculated based on an average oven-dry density (wood only) of 436 kg/m^3.

[3] An average log conversion of 1.622 m^3/MBF was based on actual size of lumber (38 × 140 mm or 2 × 6 lumber, 1.5 × 5.5 in.).

Table 1. *Wood mass balance for lumber production in the Inland Northwest region*.[a]

Inputs		Outputs	
	kg/m^3		kg/m^3
Logs without bark	778	Lumber, planed dry	436
Bark	58	Pulp chips, green, sold	216
		Pulp chips, dry, sold	4
		Sawdust, green, sold	52
		Shavings, dry, sold	37
		Wood fiber, green, sold	3
		Bark, sold	29
		Wood fuel	60
Total outputs	837		837

[a] Values are per cubic meter of planed dry softwood lumber (not allocated).

Mill production data collected through surveys were in accordance with ISO standards (ISO 2006) and CORRIM research guidelines (CORRIM 2001). All data were weighted based on production of the individual mills. This produced a "composite" mill that was representative of the region. Missing values were not weight-averaged for that particular process, consistent with ISO standards. The LCI presented here covered one full calendar year during the period 2006/2007 depending on the operational (fiscal) year for each of the sampled softwood lumber companies. A single green and dry wood density was derived using published values and based on their weighted percentage of each species (FPL 1999). The weighted average green and dry (12% MC) densities were 410 and 436 kg/m^3, respectively. Whereas primary data for lumber production were collected through surveys, data for fuels and electricity were obtained from secondary sources available in publications or contained in LCA software, SimaPro (EIA 2007; Fal 2004; PRé Consultants 2008).

Moisture content. Wood MCs were used for calculating energy requirements needed for drying wood. Incoming logs and target kiln dry MCs were reported by manufacturers in the surveys. Average green MC (oven-dry basis) of 60% was used for the species mix representing the Inland Northwest lumber production region. The average MC after drying was reported to be approximately 15%. In accordance with

CORRIM guidelines, wood fuel values were entered using oven-dry weights. Log volume weights entering the sawmill were obtained directly from the Forest Resources module of the project and were entered into SimaPro on a green volume basis calculated from the green density of 410 kg/m^3. Wood fuel weights from industry surveys, following industry practice, were reported as green weight and assumed to be at 50% MC on a wet-weight basis.

Transportation. Delivery of the input materials was by truck. Environmental burdens for transporting logs to the lumber manufacturing facilities were not included. However, the average one-way haul distance was 129 km. Environmental burdens for hauling logs to the manufacturing facility and backhauling empty trucks to the woods is included in CORRIM cradle-to-gate analysis of building materials (Puettmann et al 2010).

Data assumptions.

1. Data quality was high based on comparisons to previous work (Milota et al 2005) and based on mass and heat balances.
2. Log inputs were in either thousands of board feet Scribner scale or tons and converted to m^3.
3. Lumber outputs were in m^3 based on the actual size of 38 × 140 mm (2 × 6 lumber).
4. The mass allocation procedure was used based on CORRIM guidelines. The sawmill process was divided into four unit processes. Therefore, in the drying process, in which much of the energy is consumed and emissions created, the inputs and outputs for drying were allocated directly to the dried lumber.
5. Higher heating values (HHVs) were used to convert volume or mass basis of a fuel to its energy value.
6. Water used on-site for sprinkling logs was both surface water and ground water. Two mills did not report water consumption and were not weight-averaged. No water use was reported for use in the boilers for steam generation.
7. The SimaPro 7.1.8 software package designed for analyzing the environmental impact of product production was used to perform LCA. Developed in The Netherlands by PRé Consultants, SimaPro7 + contains the Franklin database for the LCI process for a number of materials, including paper products, fuels, and chemicals. In this study, the Franklin database was used for the production of gasoline, diesel, natural gas, wood fired boilers, natural gas-fired boilers, and electrical generation.
8. Wood fuel MCs were assumed to be 100% oven-dry basis in the Franklin Boiler Database.

Lumber Process and Descriptions

Softwood lumber production was broken down into four unit processes, log yard activities, sawing (green lumber production), drying (including wood and natural gas boilers), and planing (Fig 3). The rationale for taking this approach was that a multiunit model would be most useful in analyzing ways to improve process efficiency, optimize operations, and reduce environmental impacts. Furthermore, data in this format can be used as a benchmark to document process improvements. In addition, multiunit approaches allow a subunit process developed for one product to be used for modeling other products. For example, if green planed lumber is the product of interest, then the drying unit process can be bypassed and lumber from the sawmill can be an input directly into the planing process. A multiunit process-type model also provides a realistic assignment of environmental burdens.

Inputs to lumber manufacturing (gate-to-gate) included logs with bark, fuel, electricity, and water. Outputs included planed dry lumber, coproducts (bark, chips, sawdust, and planer shavings), and emissions to air, land, and water (Tables 1 and 2). Natural gas and wood fuel (bark and wood waste) were used as fuel to fire boilers that supply heat to the dry kilns. The environmental emissions (air and water emissions and solid waste) associated with the wood and natural gas boilers were included in the cumulative and on-site system boundaries and were part of the drying process.

Table 2. *Gate-to-gate life-cycle inventory inputs to produce m³ of planed dry softwood lumber from the Inland Northwest region (allocated).*

Energy and fuel inputs		
Materials	Unit	Unit per m^3
Logs without bark	m^3	1.11
Bark	kg	34
Electrical use		
Electricity	MJ	222
Fuel use		
Hogged fuel	kg	55
Natural gas	m^3	26
Diesel	L	1.89
Gasoline	L	0.17
Feedstock		
Lubricants and oils	L	0.25
Water use		
Well water source	L	19.5

Unit Process Description

The four unit processes used to model softwood lumber production were developed from mill survey results. When manufacturers reported raw material use, energy consumption, and environmental data for a particular process in their production series, a unit process was created.

Log yard. The log yard process included unloading log trucks, scaling logs (measuring logs for volume), storing logs, spraying water on logs to prevent dry-out and blue stain, and transporting logs to the sawmill. Inputs included logs with bark, fuel and lubricants, electricity, and water. Outputs included logs with bark, dust, hydrocarbons, bark, and rock.

Sawing. The sawing process included debarking logs, sawing logs into rough-green lumber, chipping portions of logs that did not make lumber, sorting rough-green lumber into size classes, and stacking rough-green lumber for drying. Inputs included logs with bark, fuel and lubricants, and electricity. Outputs included rough-green lumber, pulp chips, green sawdust, and bark.

Kiln drying. The dry kiln process included loading rough-green stacked lumber into kilns, drying rough-green lumber, and unloading rough-dry stacked lumber from the kilns. Inputs included rough-green lumber, steam, electricity, and fuel and lubricants. Outputs included rough-dry lumber and kiln drying air emissions. The boiler processes included boiling water to produce steam for the dry kilns. Natural gas and wood boilers were used as energy inputs into the kiln drying process. Environmental data (emissions) for the boilers were obtained from the Franklin database. Outputs for the kiln drying process included rough kiln dry lumber, steam, boiler emissions, and ash and air emission associated with the dryers. During winter, logs were not thawed before sawing but are sawn with special teeth; therefore, additional boiler heat was reported to thaw the processed lumber.

Planing. The planer process included unstacking rough-dry lumber, planing rough lumber, grading planed lumber, sorting graded lumber, packaging graded lumber, and loading graded lumber for shipment. Inputs included rough-dry lumber, gasoline, and diesel. Outputs included planed dry lumber, shavings, and wood chips. No environmental data in the form of emissions were reported for the planing process.

LIFE-CYCLE INVENTORY RESULTS

Product Yields

The mass balance of the flow of wood and bark into and out of softwood lumber manufacturing facilities is presented in Table 1. The recovery efficiency was 52% for 1 m^3 of the primary product (bone-dry softwood lumber), 436 kg of lumber from 836 kg of oven-dry logs with bark (93% wood, 7% bark). Pulp chip production made up the largest segment of coproduct production with 221 kg (26%) and sawdust was next with 52 kg (6%).

Manufacturing Energy

Energy consumption for the production of Inland Northwest softwood lumber comes from electricity, diesel, gasoline, natural gas, and wood fuel (wood and bark) (Table 2). Electricity was used in all processes to operate debarkers, pneumatic and mechanical conveying equipment, fans, hydraulic pumps, saws, and dryer fans. Wood fuel and natural gas were used in boilers for heat input for lumber drying. On-site forklifts, loaders, and trucks used small amounts of gasoline and diesel fuel.

Cumulative energy is defined as the total fuel energy (production and combustion) allocated for the manufacture of 1 m^3 of Inland Northwest softwood lumber. This includes the cradle-to-gate burdens associated with the production of all fuels (coal, crude oil, natural gas, wood, and uranium) used in lumber production and electrical generation. Data for the extraction, production, transportation, and combustion of fuels were obtained from the Franklin database as part of the SimaPro LCA software (Franklin Associate 2004). Fuels required for harvesting operations and to deliver logs to the manufacturing sites were not included in this LCI analysis but are reported in another module of the Phase II study. Energy values were determined using the HHVs given in Table 3.

Table 4 shows the LCI results for the cumulative energy requirements for the production of 1 m^3 of softwood lumber. Because this LCI is a continuation of previous softwood lumber LCI from different regions in the US, Table 5 shows the regional energy requirement differences among softwood lumber producers. Several reasons could explain the large differences among regions. First, in the Southeast region, southern pines are denser than some of the softwoods of the Pacific and Inland Northwest regions, therefore requiring additional energy for sawing and drying. In addition, southern pine logs have higher MCs than some Northwest species so more energy is required for drying lumber. Also, electrical generation can explain the differences among fuel sources. In the Pacific and Inland Northwest regions, the primary fuel source for electrical generation is hydroelectric; in the Southeast, coal is the main primary fuel. Southeast wood producers obtain nearly 100% of their heat energy fuel from wood (Milota et al 2005), whereas in the Pacific and Inland Northwest regions, the manufacturers use nearly an equal mix of wood fuel and natural gas. The differences that are more difficult to

Table 3. *Heat values used to convert raw materials for fuel production into energy values.*

Fuel type	Higher heating value (MJ/kg)
Coal[a]	26.2
Crude oil[a]	45.5
Diesel[a]	44.0
Gasoline[a]	48.4
Natural gas[a]	54.4
Wood fuel/biomass[a,b]	20.9
Uranium[c]	381,000

[a] As per CORRIM guidelines.
[b] Oven-dry bases.
[c] Todreas NE, Kazimi MS (1993) Nuclear system I—Thermal hydraulics fundamentals. Taylor & Francis, Philadelphia, PA. Page 2, Table 1-1.

Table 4. *Cumulative energy use for the production of 1 m^3 of planed, dry softwood lumber produced in the Inland Northwest region of the US.*[a]

Fuel[b]	kg/m^3	MJ/m^3
Natural gas	25.7	1389
Wood fuel/wood waste	55.0	1152
Hydroelectric power	0	159
Crude oil	4.7	112
Coal	3.3	84
Uranium	0.00003	10
Other energy	0	6
Total		2911

[a] Includes fuel used for electrical production. Values are higher heating values (allocated).
[b] Based on higher heating values.

Table 5. *Cumulative energy use for the production of 1 m^3 of planed, dry softwood lumber produced in the Inland Northwest region compared with that of softwood lumber produced in the Pacific Northwest and Southeast.*[a]

	CORRIM Phase I		CORRIM Phase II
	Pacific Northwest	Southeast	Inland Northwest
Fuel[b]	MJ/m^3		
Natural gas	1344	232	1389
Wood fuel/wood waste	1592	3023	1152
Hydroelectric power	200	4	159
Crude oil	91	97	112
Coal	95	411	84
Uranium	39	170	10
Other energy	3	8	6
Total	3364	3945	2911

[a] Includes fuel used for electrical production. Values are higher heating values (allocated).
[b] based on higher heating values.

explain are those between Pacific Northwest and Inland Northwest manufacturers. These differences could be attributed to data quality. For the Pacific Northwest softwood lumber LCI, Milota (2004) conducted a second survey with manufacturers specifically targeting boiler data. This provided the Pacific Northwest LCI with more data specific to the boiler process.

On-site energy is defined as that combusted on-site for lumber production and allocated to 1 m^3 of softwood lumber. This is energy in the form of electricity, natural gas, diesel, gasoline, and wood fuel. Energy required to produce these fuels and deliver them to the lumber production site are outside this system boundary. These fuel consumption values are reported only in total amounts used (Table 2) and their environmental releases are reflected in the on-site emission LCI results (Wagner et al 2009).

Electrical Use Summary

The source of fuel used to generate the electricity used in the manufacturing process is important in determining the type and amount of impact in the LCA. The proportional breakdown of electricity for the Inland Northwest region by fuel source is given in Table 6. The source of these data are the US Department of Energy (DOE 2007). In 2005, the dominant form of electrical generation in the region was hydroelectric, representing 71.5% of the total, followed by coal (9.4%) and natural gas (9.0%). The Franklin database (Franklin Associate 2004) was used in the LCI for the extraction, transportation, and combustion fuels for electrical generation.

Table 6. *Electric power industry generation of electricity by primary energy sources and state for the Inland Northwest region as defined by the US Department of Energy.*

Percentage share 2005	Average percent share
Fuel source	
Coal	9.4
Petroleum	0.1
Natural gas	9.0
Other gases	0.3
Nuclear	7.3
Hydroelectric	71.5
Other renewables	2.4
Other	0.1
Pumped storage	0.01
Total	100

Energy Information Administration/State Electric Power Annual 2005 Volume I, Department of Energy (Department of Energy 2007). http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html.

Considering the entire lumber production process allocated to 1 m^3 of planed dry softwood lumber, the planing of kiln dry lumber required 45% of the total electrical requirement with sawmilling and drying requiring 27% and 24%, respectively (Table 7). Cumulative process energy for electrical use allocated to 1 m^3 (436 kg) of planed dry softwood lumber was 60 kWh/m^3 (nonallocated = 76.23 kWh/m^3). This compares to Milota (2004) and Milota et al (2004) values of 51 and 93 kWh/m^3 for softwood lumber produced in the Pacific Northwest and the Southeast, respectively. Electrical demand is needed for air circulation during lumber drying. Electrical use can vary with air velocity, quantity of lumber dried, planed or rough lumber, and sticker thickness (Simpson 1991). Electrical consumption for drying Southeast softwood lumber species can be much higher because of greater air velocity and lower average MCs. Electrical consumption for drying southeast lumber was reported by Milota et al (2005) at 19.12 kWh/m^3 and for softwood lumber in the Pacific Northwest at 14.5 kWh/m^3. Electrical use for drying inland Northwest softwood lumber was 18.26 kWh/m^3 (Table 7).

Thermal Energy

Inland Northwest softwood lumber is typically dried to an average MC of 15%. In this study, approximately 50% of the bark generated during debarking as well as other wood waste sources

Table 7. *Electrical distribution by subunit process for lumber production in the Inland Northwest region (not allocated).*

Subunit process	kWh	MJ	Allocation
Log yard	3.12	11.22	4.09%
Sawmill	20.77	74.76	27.24%
Drying	18.26	65.72	23.95%
Planing	34.09	122.74	44.72%
Total	76.23	274.44	100%

All values are given per 1.0 m^3 of lumber (436 kg of planed dry lumber).

from downstream processes were used as wood fuel in the boiler for steam generation. The total wood fuel burned was 110 kg/m^3 at 50% wet-basis MC or 55 kg/m^3 of oven-dry weight wood fuel. Wood fuel (55 kg) and natural gas (25 m^3) were the fuel sources consumed in the boiler process at 54 and 46%, respectively. Milota et al (2005) reported that 52% of the energy to dry softwood lumber from the Pacific Northwest was generated from wood waste produced on-site with the remaining energy requirements from natural gas (48%) and a small amount (less than 0.1%) of diesel. In other regions of the US, it has been reported that 100% of the thermal energy requirements were produced by self-generated wood fuel (Milota et al 2005).

A breakdown of heat energy use for the boilers by fuel source is in Table 8. Total heat-energy requirement for Inland Northwest softwood lumber was 2124 MJ/m^3. Milota reported heat-energy requirements for softwood lumber at 2936 and 3023 MJ/m^3 for Pacific Northwest and Southeast production regions, respectively.

Table 8. *Inland Northwest lumber weighted data metric conversion of boiler inputs into heat energy for 1m^3 planed, dry lumber production (allocated).*

Fuel type	Value	Energy (MJ)	Fuel source breakdown (%)
Wood fuel (kg)[a,b]	55	1148	54
Natural gas (m^3)[c]	25	975	46
Total		2124	100

[a] Oven-dry weight.
[b] Weight of dry wood fuel multiplied by 20.92 MJ/kg with a 67% efficiency.
[c] Volume of natural gas multiplied by 54.4 MJ/kg of natural gas, 80% efficiency—source ATHENA (1993). Density of natural gas = 0.7048 kg/m^3.

Environmental Emissions

Sawmill operations together with the production and combustion of fuels generates a range of air emissions (Table 9). CO_2 is the largest emitter from each process stage. Fossil-based CO_2 was generated in the log yard (2.52 kg/m^3), sawmill (4.08 kg/m^3), and planing (6.58 kg/m^3). CO_2 emissions from the combustion of biomass was largest in the drying process releasing 116 kg/m^3. Overall, 98% by mass of all emissions was CO_2 with 62% classified as CO_2 biomass.

The wood drying process, including natural gas and wood boilers, is the main source of air emissions because of the combustion of wood and natural gas and the volatile wood emissions released during drying. Of the total air emissions released for manufacturing softwood lumber, 93% was generated in the wood drying process. Other emissions from drying reported by softwood lumber producers were volatile organic compounds, formaldehyde, acetaldehyde, and

Table 9. *Process emissions (kg/m^3) for the production of softwood lumber in the Inland Northwest region.*[a]

	Log yard	Sawmill	Drying	Planing	Total[b]
Substance[c]	Planed, dry softwood lumber (kg/m^3)				
Carbon dioxide, biogenic	0.0011	0.0021	115.5445	0.0029	115.5506
Carbon dioxide, fossil	2.5220	4.0834	58.5243	6.5769	71.7067
Carbon monoxide	0.0280	0.0414	0.8788	0.0368	0.9849
Sulfur oxides	0.0113	0.0208	0.8705	0.0541	0.9566
Nitrogen oxides	0.0713	0.0153	0.2861	0.0435	0.4160
NMVOC[d]	0.0140	0.0062	0.2286	0.0139	0.2628
Methane	0.0013	0.0050	0.1639	0.0128	0.1831
VOC (volatile organic compounds)	0.0000	0.0000	0.1669	0.0000	0.1669
Particulates, less than 10 μm	0.0050	0.0010	0.0149	0.0026	0.0234
Methanol	0.0000	0.0000	0.0224	0.0000	0.0224
Formaldehyde	0.0011	0.0001	0.0014	0.0003	0.0029
Phenol	0.0000	0.0000	0.0022	0.0000	0.0022
Acetaldehyde	0.0000	0.0000	0.0022	0.0000	0.0022
Total	3	4	177	7	190

[a] Emissions are allocated per 1 m^3 of planed dry softwood lumber.
[b] Totals may vary from other life-cycle inventory tables in this article because of rounding errors.
[c] Total includes emissions for production and delivery of electricity and fuel production and combustion.
[d] NMVOC = nonmethane volatile organic compounds, unspecified origin.

methanol. The log yard, sawing, and planing process contributed the remaining 7% with the planing process generating 50% of that portion. These emissions are primarily released by fossil-based fuels combusted in equipment used in on-site transportation.

Data for water emissions reported by the softwood lumber manufacturers were limited. Most of the waste-water emissions came from secondary databases for fuel and electrical production (Table 10). Milota et al (2005) also reported limited water emissions from lumber producers. Because the mills reported no discharge emissions, it was assumed that water used for spraying logs was collected and recycled or soaked into the ground. Any water waste generated in boilers or kilns was assumed to have evaporated.

Three of the four mills reported no solid waste to landfills; therefore, 100% of the logs entering the mill were used (Table 11). One manufacturer reported in the survey a small amount of wood waste (1%) and rock and mud (10%) as solid waste generated in the log yard. Cumulative solid waste reported in Table 11 originates from the production of fuels.

Table 10. *Cumulative emissions to water allocated to 1 m^3 or 436 kg planed dry softwood lumber produced in the Inland Northwest region.*[a]

Waterborne emissions	kg/m^3
Dissolved solids	1.3597
Chloride	0.0616
Sulfate	0.0511
Suspended solids, unspecified	0.0290
Oils, unspecified	0.0238
COD (chemical oxygen demand)	0.0190
Organic substances, unspecified	0.0039
BOD5 (biological oxygen demand)	0.0013
Iron	0.0005
Boron	0.0003
Manganese	0.0003
Sulfuric acid	0.0001
Cadmium, ion	0.0001
Chromium	0.0001
Metallic ions, unspecified	0.0001
Phosphate	0.0000
Ammonia	0.0000
Fluoride	0.0000
Zinc, ion	0.0000

[a] Results include the production of electricity, fuels, and ancillary materials. Transportation burdens of resources and raw materials to the lumber production facility have been omitted (allocated).

On-site emissions. It is also useful to examine those emissions attributed to only the production of lumber or on-site emissions. Table 12 provides output data for site-generated emissions from manufacturing softwood lumber. Included are those emissions generated by the direct manufacturing of softwood lumber through each unit process and the combustion emissions of the various fuels used (diesel, gasoline, natural gas, and wood fuel). This includes emissions generated from boilers and emissions released during drying of wood. Not included are those emissions released by the production and delivery of fuels and electricity.

Carbon balance. Practices that aim to reduce carbon emissions and sequester carbon are on the increase. Forest and long-term wood products sequester carbon and avoid the release of carbon into the atmosphere for decades. Carbon was tracked for softwood lumber production using the gate-to-gate LCI results. This analysis followed carbon from the inputs of material, electricity, and fuels through the production of softwood lumber. An average carbon ratio of 0.5037 was used for wood and bark (Birdsey 1994). Carbon ratios in substances other than wood were either taken from the Merck Index (1989) or were calculated using atomic masses of from chemical formulas.

A list of carbon inputs and outputs to the lumber manufacturing LCI can be found in Table 13.

Table 11. *Cumulative solid waste allocated to 1 m^3 or 436 kg planed dry softwood lumber produced in the Inland Northwest region.*[a]

Solid waste	Total kg/m^3
Waste, solid	8.91
Wood waste	5.84
	Total m^3/m^3
Waste, rock, and mud	0.12

[a] Results include the production of electricity, fuels, and ancillary materials. Transportation burdens of resources and raw materials to the lumber production facility have been omitted (allocated).

Table 12. *On-site emissions for the production of 1 m^3 of Inland Northwest softwood lumber.*[a]

	kg/m^3
Emissions to air	
Carbon dioxide, biogenic	115
Carbon dioxide, fossil	54
Carbon monoxide	0.8742
Nitrogen oxides	0.3174
VOC (volatile organic compounds)	0.1670
Particulates, unspecified	0.0866
Potassium	0.0430
Sulfur oxides	0.0420
Methanol	0.0224
Particulates, less than 10 µm	0.0209
NMVOC[b]	0.0150
Organic substances, unspecified	0.0092
Phenol	0.0022
Formaldehyde	0.0020
Acetaldehyde	0.0020
Methane	0.0015
Sodium	0.0010
Formaldehyde	0.0006
Manganese	0.0005
Chlorine	0.0004
Hydroelectric carbons, unspecified	0.0002
Barium	0.0002
Iron	0.0002
Zinc	0.0002
Benzene	0.0002
Acetaldehyde	0.0002
Naphthalene	0.0001
Lead	0.0001
Emissions to land	
Log yard, wood waste to landfill	5.8347
Waste, solid	4.9534
Emissions to water	
Suspended solids, unspecified	0.0204
Solved solids	0.0192
COD (chemical oxygen demand)	0.0098
BOD5 (biological oxygen demand)	0.0001

[a] Data are from on-site production softwood lumber and the combustion of all fuels used on-site. Excludes impacts associated with fuel and electrical production and delivery (allocated).

[b] NMVOC = nonmethane volatile organic compounds, unspecified origin.

Carbon contents (kg/m^3) are based on carbon-containing emissions in LCI results, the quantity of wood entering the mill as logs with bark, and all wood product and coproduct outputs. The sum of carbon output from the production of 1 m^3 of softwood lumber was 458 kg/m^3 of planed dry softwood lumber. Of this, 45% was in the final product with 36% in coproducts and 6% from wood fuel. The other 13% was air emissions with CO_2 (biomass) contributing 94% that was a result of the combustion of wood in the boiler to dry lumber. Note that the carbon balance has a difference of –8.5%.

Table 13. *Carbon content balance including carbon containing emissions and materials for the production of 1 m^3 softwood lumber from the Inland Northwest region.*

Substance	Carbon content (kg/m^3)
Input	
Wood materials	422
Output	
Planed dry softwood lumber	220
Coproducts	202
Air emissions	33
Solid emissions	3
Total	458

DISCUSSION

Resource use requirements were comparable to product yields in other studies (Milota et al 2005). The goal of any industry is to reduce waste and make more from less. The use of wood waste for energy generation reduces the need to obtain fuel from other resources. The use of fuel generated on-site also reduces the environmental impact associated with transportation and production of another fuel. In the Inland Northwest softwood lumber production region, over 50% of the energy needed originated on-site. If this resource is not used, non-biomass fuel sources would be required at a consequence of a larger overall environmental impact associated with lumber production.

Production emissions associated with softwood lumber remain relatively low because of the use of required emission control devices. CO_2 remains the largest emitter from each process stage. Fossil-based CO_2 was generated in the log yard, sawmill operation, and planing, whereas CO_2 emissions from the combustion of biomass were largest in the drying process. Overall, 98% by mass of all emissions was CO_2 with 62% classified as CO_2 (biomass).

Total energy consumption per 1 m^3 of planed dry softwood lumber was found to be lower than previously published data for softwood lumber production from the Pacific Northwest and the Southeast regions of the US (Milota et al 2005). However, these differences could be from higher energy requirements for sawing and drying southern pines and because of their higher densities and green MCs. For the Pacific Northwest region, a second survey was submitted to softwood lumber manufacturers specifically requesting boiler data and this could have resulted in more precise results. The region considered in this study (Inland Northwest) introduces an operational issue in the winter when logs might be frozen. These issues are not a consideration in the other two regions. The sawmill will use special teeth for the saws to saw frozen logs, but there may be additional energy consumption in the drying process if the lumber is still frozen at that stage. The Inland survey data did not distinguish between summer and winter operations because the survey covered a full year of operations. If specific data had been collected only on the boilers in summer and in winter, differences between energy consumptions related to season might have been determined.

Energy consumption and fuel source are two of the most important elements in an LCI and LCIA. In the wood products industry, with the availability of self-produced wood fuel, there are significant reductions in CO_2 (fossil) emitted. Although an LCIA was beyond the scope of this study. The use of a biomass fuel source together with producing a long-term product that can sequester carbon are key variables in the overall carbon footprint of a product. Comparisons in Global Warming Potentials as kg CO_2 equivalents between wood products and alternative materials (steel and concrete) have consistently shown a lower environmental impact for wood products (Kunniger and Richter 1996; Perez-Garcia et al 2005; Knight et al 2005; Koch 1992; Kunniger and Richter 1995).

CONCLUSIONS

This study completed a gate-to-gate LCI for the production of softwood lumber produced in the Inland Northwest region of the US. Survey data were collected as representative of softwood lumber producers. The combined annual production of these manufacturers was 755,852 m^3, representing 16% of the regional production. The LCI used inputs of raw material use, heat energy, fuels, and electrical consumption and outputs from wood production emissions. Thermal energy requirements from drying lumber had a significant contribution to the total energy consumption for wood production. In this study, approximately 72% of the total energy was used for drying green lumber to 15% MC. Thermal energy was generated both from wood fuel and natural gas, representing 54 and 46% of the total, respectively. Total heat energy requirement for Inland softwood lumber was 2124 MJ/m^3. Equipment used in the planing process of kiln dry lumber consumed the largest amount of electricity (45%) compared with the other processes. The major emission to air was CO_2 that represented 98% by mass of all emissions and 62% were from combustion of biomass.

Caution is required when using wood product LCA studies for comparison with alternative materials. It is important to understand the goal, scope, and system boundaries of each study and functional unit (reference unit) used. Several impact assessment studies are available to the public. Although most are European-based, North American impact assessment methodologies are slowly becoming available.

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