CRADLE-TO-GATE LIFE-CYCLE INVENTORY OF US WOOD PRODUCTS PRODUCTION: CORRIM PHASE I AND PHASE II PRODUCTS

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Abstract. This article documents cradle-to-gate life-cycle inventories for softwood lumber, hardwood lumber, and solid-strip hardwood flooring manufacturing from the Inland Northwest and the Northeast–North Central regions of the US. Environmental impacts were measured based on emissions to air and water, solid waste, energy consumption, and resource use. The manufacturing stage consumed the greatest amount of energy representing 90 – 92% of the total. Total energy consumption for softwood lumber manufacturing was about one-half of that required for hardwood lumber and hardwood flooring. The use of wood biomass as the primary energy source for manufacturing greatly reduced the environmental burdens by offsetting the demand for fossil fuels. Transportation impacts contributed approximately 3%, and forestry and harvesting operations accounted for 3 – 7%. Management and harvesting of softwoods in the Northeast–North Central regions required a greater amount of energy attributable to higher-intensity management scenarios.

Keywords: Life-cycle inventory, cradle-to-gate, LCI, wood products, CORRIM, energy, emissions, environmental impact, carbon, geographical regions.

INTRODUCTION

Forest land owners and product manufacturers are facing increased environmental regulations while struggling to stay competitive in the marketplace. Consequently, wood product companies need to rethink how they grow, manage, and produce products to efficiently meet expectations set forth by environmental regulations, government policies, and the public. These challenges provide an opportunity for change and create future "green" marketing opportunities.

Wood is a renewable building material that has proven to be "environmentally friendly" compared with alternative building materials such as steel and concrete (Lippke et al 2004). Steel, concrete, plastic, and aluminum are alternatives to wood building materials in certain applications, but their use can result in higher costs, higher fossil-based energy requirements in the extraction and manufacturing processes, and increased environmental impacts over product life cycles (CORRIM 2005).

Life-cycle assessment (LCA) began in the 1960s (Hunt et al 1992; Curran 1996) and has evolved into an internationally accepted method for analyzing complex environmental impacts and outputs of a product. Furthermore, LCA can accurately identify where, when, and how environmental impacts occur throughout a product's life.

Several guidelines on how to conduct LCA have been published. The most widely accepted methods are set forth in the International Organization for Standardization (ISO) 14000 series of standards (ISO 2006). Defined by ISO, LCA is a multiphase process consisting of four interrelated steps: 1) goal definition and scoping; 2) life-cycle inventory (LCI); 3) life-cycle impact assessment (LCIA); and 4) interpretation (Fig 1). Outcomes of these steps are based on the goals and purposes of a particular LCA study. In the goal definition and scoping step, the products to be considered and the system boundaries (eg scope of the study) are defined. The LCI step consists of an objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid wastes, and other environmental releases occurring within the system boundaries. The LCIA process characterizes and assesses effects of environmental releases identified in LCI. These are grouped into impact categories such as global warming potential, habitat modification, acidification, or noise pollution.

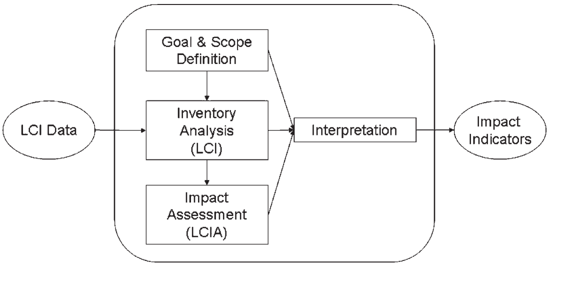

Figure 1. Steps in developing a life-cycle assessment. Picture extracted from http://www.nrel.gov/lci/assessments.html.

One of the most useful outcomes of LCA is the ability to assess both direct and indirect effects of material consumption. Direct effects are easily linked to a product such as using recycled materials reduces the need for virgin resources. Indirect effects are not always easily associated with consumption. For example, recycling operations can use large amounts of fossil fuel for collection of recyclables, resulting in releases of CO_2 into the atmosphere.

Life-Cycle Assessment of Renewable Materials

Beginning in 2000, several US wood products manufacturers, research institutions, associations, and government agencies initiated an extensive LCA effort through the Consortium for Research on Renewable Industrial Materials (CORRIM). CORRIM was organized to develop LCA databases to document the energy implications and environmental impacts of producing and using renewable building materials. Before the CORRIM work, only a few LCIs on wood products had been published (Arima 1993; ATHENA 1993; Buchanan 1993; Richter and Sell 1993; Hershberger 1996; Lippke et al 2004; Perez-Garcia et al 2005). Most of these were partial LCIs with a primary focus on energy consumption during harvesting and product manufacturing. Forest regeneration and management practices were not considered. Some of these early studies, although scientific and quantitative in their scope, were conducted before the development of the LCA framework (Arima 1993; ATHENA 1993; Buchanan 1993; Richter and Sell 1993; Hershberger 1996). Therefore, comparison of results from earlier studies has been difficult because of differences in system boundaries, goals and scope, and data quality.

Since 2000, 25 wood-product unit-process databases have been developed by CORRIM (Johnson et al 2004; Kline 2004; Milota 2004; Milota et al 2004; Puettmann and Wilson 2004; Wilson and Dancer 2004a, 2004b; Wilson and Sakimoto 2004) and are publicly available through the USLCI database (NREL 2003; Table 1). The database of wood product processes is focused on the manufacturing and forest management and harvesting stages. LCAs of several products within the CORRIM database have been conducted at the unit-process level, meaning that information can be used to evaluate products that are similar. For example, the database for plywood production includes the processes of conditioning, debarking, peeling, drying, layup, pressing, and trimming. The data can also be used to evaluate the laminated veneer lumber manufacturing process through the drying stage.

This study examines the environmental impact associated with softwood lumber produced in the Inland Northwest (INW) and softwood and hardwood lumber and hardwood flooring produced in the Northeast–North Central (NE-NC) regions in the US (Fig 2). The LCI included three stages: 1) regeneration and harvesting; 2) product manufacturing; and 3) transportation. Environmental impacts were based on fuel consumption, resource use, and associated emissions from each stage. The LCI results reported are a continuation of CORRIM Phase I product cradle-to-gate LCI (CORRIM 2004, 2005; Puettmann and Wilson 2005).

PROCEDURES

Goal and Scope of Study

This study was a cradle-to-gate LCI of the production of solid wood products representing the INW and NE-NC regions. The cradle-to-gate LCI models encompassed data from individual gate-to-gate LCI for each product and respective region. For detailed descriptions of the individual gate-to-gate product LCI, see Bergman and Bowe (2008a, 2008b), Hubbard and Bowe (2008), Johnson et al (2008), Oneil et al (2009), and Wagner et al (2009).

Primary data were collected for each wood manufacturing process. Secondary data for fuels used, emissions from the production of energy, and all transportation were obtained from other databases (FAL 2004; EIA 2007; PRé Consultants 2008). The wood manufacturing data represented regional production processes and

Table 1. *CORRIM Phase I and Phase II life-cycle inventory (LCI) processes.*[a]

	CORRIM LCI processes collected from industry surveys				
	CORRIM Phase I		CORRIM Phase II		
	Pacific Northwest	Southeast	Inland Northwest	Northeast/North central	CORRIM report
Forestry operations	1. Seedling growth 2. Management 3. Equipment 4. Final harvest	1. Seedling growth 2. Management 3. Equipment 4. Final harvest	1. Seedling growth 2. Management 3. Equipment 4. Final harvest	1. Management 2. Equipment 3. Final harvest	Johnson et al (2004, 2008), Oneil et al (2010)
Wood product					
Lumber, softwood	1. Sawing 2. Drying 3. Boiler 4. Planing	1. Sawing 2. Drying 3. Boiler 4. Planing	1. Log yard 2. Sawing 3. Drying 4. Boiler 5. Planing	1. Log yard 2. Sawing 3. Drying 4. Boiler 5. Planing	Wagner et al (2009), Bergmann and Bowe (2008b)
Lumber, hardwood				1. Log yard 2. Sawing 3. Drying 4. Boiler 5. Planing	Bergmann and Bowe (2008a)
Flooring, hardwood				1. Solid strip hardwood flooring	Hubbard and Bowe (2008)
Plywood, softwood	1. Debarking 2. Conditioning 3. Peeling/clipping 4. Drying 5. Layup/pressing 6. trimming/sawing 7. Boiler	1. Debarking 2. Conditioning 3. Peeling/clipping 4. Drying 5. Layup/pressing 6. Trimming/sawing 7. Boiler			Wilson and Sakimoto (2004)
Laminated veneer lumber (LVL), softwood	1. LVL	1. LVL			Wilson and Dancer (2004b)
Glued laminated beams (glulam), softwood	1. Glulam production 2. Boiler	1. Glulam production 2. Boiler			Puettmann and Wilson (2004)
I-Joist, softwood	1. I-joist production	1. I-joist production			Wilson and Dancer (2004a)
Oriented strandboard (OSB), softwood		1. Log handling/ flaking 2. Drying/screening 3. Blending/pressing 4. Sanding/sawing 5. Boiler 6. Emissions control			Kline (2004)

(continued)

Table 1. *Continued.*

	CORRIM LCI processes collected from industry surveys				
	CORRIM Phase I		CORRIM Phase II		
	Pacific Northwest	Southeast	Inland Northwest	Northeast/North central	CORRIM report
			CORRIM Phase II US average process		CORRIM report
Particle board			1. Particleboard		Wilson (2010a)
Medium-density fiberboard			1. Medium-density fiberboard		Wilson (2010b)
Urea–formaldehyde resin			1. Urea–formaldehyde resin		Wilson (2010c)
Melamine–urea–formaldehyde resin			1. Melamine–formaldehyde resin		Wilson (2010c)
Phenol formaldehyde resin			1. Phenol–formaldehyde resin		Wilson (2010c)
Phenol–resorcinol– formaldehyde resin			1. Phenol–resorcinol–formaldehyde resin		Wilson (2010c)

[a] The process data are available through the US LCI database (NREL 2004).

included all inputs and outputs associated with the growing and harvesting of trees and product manufacturing. Four product gate-to-gate LCIs were completed for softwood lumber, hardwood lumber, and solid-strip hardwood flooring and two LCIs, from cradle-to-forest road, were completed for forest resources from the INW and NE-NC regions (Bergman and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Johnson et al 2008; Wagner et al 2009; Oneil et al 2009). External reviews of the gate-to-gate LCIs were conducted to ensure compliance with CORRIM guidelines and ISO 14044 standards (CORRIM 2001; ISO 2006).

Functional unit. The functional unit for harvested logs and wood products production was 1 m^3 of finished product in compliance with CORRIM guidelines. For conversion of SI units from US industry units, see the individual LCI reports (Bergman and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Johnson et al 2008; Oneil et al 2009; Wagner et al 2009). All input and output data collected from manufacturers were allocated to functional units based on mass allocation. In the cradle-to-gate analysis presented in this article, comparisons between products were based on equal volume units representing different masses per unit volume.

System boundary. The system boundary encompassed forestry and product manufacturing processes beginning at seed germination and ending at the finished product and included cradle-to-gate LCI of electrical and fuel production (Fig 3). Transportation distances for raw materials to production facilities were reported for each individual product. Three resource production regions were included (Fig 2): INW (Idaho, Montana, eastern Oregon, and eastern Washington), NE-NC (Minnesota, Iowa, Missouri, Wisconsin, Illinois, New Jersey, Ohio, Indiana, Michigan, West Virginia, Pennsylvania, Maryland, Delaware, New York, Maine, Vermont, New Hampshire, Rhode Island, Massachusetts, and Connecticut), and an extended eastside US for hardwood

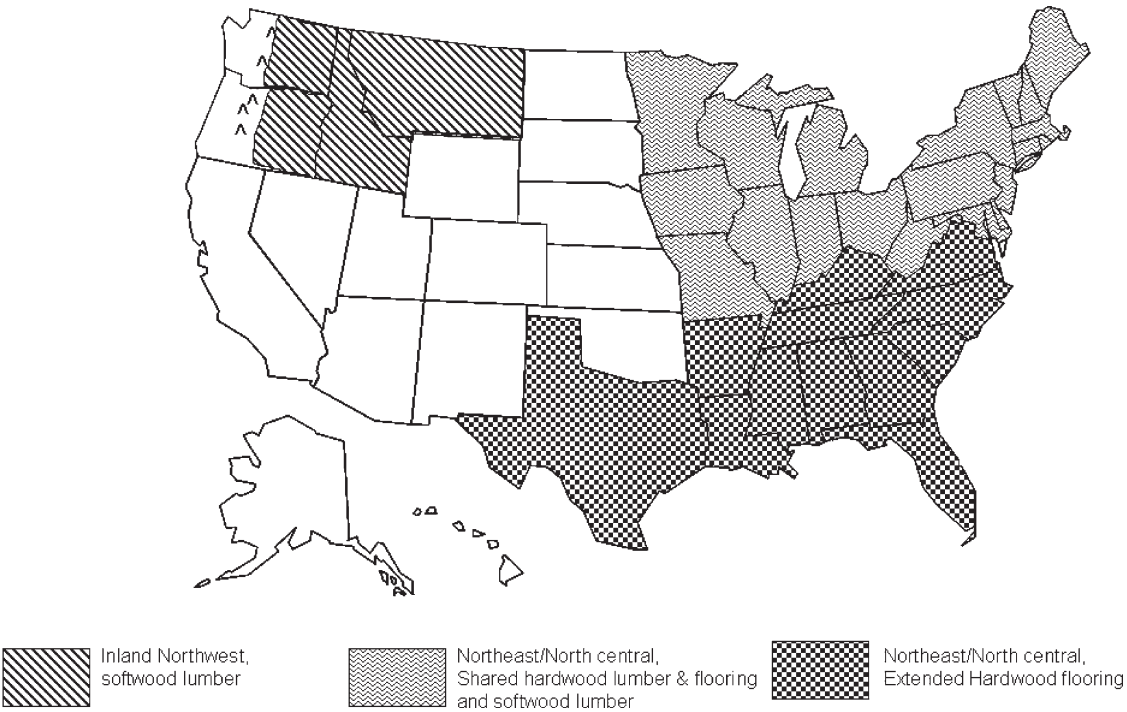

Figure 2. Resource and product manufacturing regions for CORRIM Phase II products; softwood lumber, hardwood lumber, and hardwood flooring.

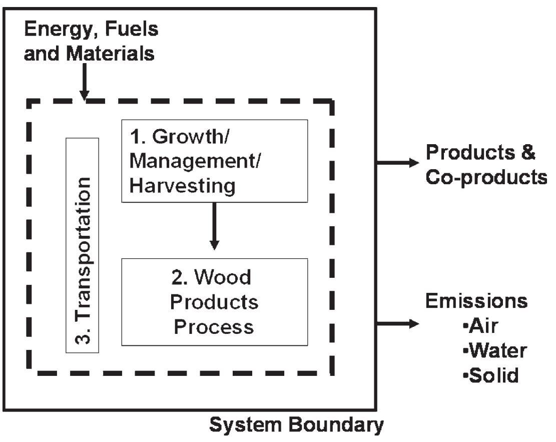

Figure 3. Cradle-to-gate system boundary.

flooring (Virginia, Kentucky, Arkansas, Louisiana, Mississippi, Alabama, Florida, Georgia, North Carolina, South Carolina, Tennessee, and Texas). The cradle-to-gate LCI system boundary encompassed each product manufacturing process, including inputs (logs, electricity, fuels) and transport to each production facility. Outputs included final products, manufacturing emissions, and solid wastes; resources needed for the production of coproducts were not considered. The cumulative system boundary included all upstream flows of energy, fuel, and raw material production (Fig 3).

Transportation

Energy consumed during transportation between harvesting and manufacturing was based on actual distances to production facilities reported by contributing wood products producers. Excluded from transportation were distances between the location of manufacturing and use. Transportation details can be found in individual product reports (Bergman and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Wagner et al 2009). Log transportation weights were based on green MC on an oven-dry basis. Log and bark MCs were from mill surveys and differed by region and species (Bergman and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Wagner et al 2009). Softwood logs from NE-NC were assumed to be transported at MC of 97%, whereas softwood logs from INW were assumed to be transported at 60% MC. This is consistent with the Milota (2004) LCI on PNW lumber production, which reported an average 60% MC for western wood species. Hardwood logs were reported to have 87% MC.

All transportation was by single-engine diesel trucks. Transportation impacts were based on a one-way loaded distance with an empty back-haul. A cradle-to-gate LCI process for a diesel trailer truck was available from the Franklin database through SimaPro 7 (FAL 2004) that included resource use and associated emissions. All transportation distances were as reported in mill surveys and were actual distances (weight-averaged) from log landing to mill gate.

Cradle-to-Gate Model Development

The cradle-to-gate models presented are an integration of four single gate-to-gate LCIs representing the two production regions. Three stages were considered in the LCI analyses: harvesting, manufacturing, and transportation (Fig 3). Inputs to the manufacturing stage included logs, bark, energy, and transportation fuels (Table 2). Input data considered in the analyses represented the consumption of raw materials and fuels for the production of the final product only. Output data represented final product and manufacturing emissions and solid waste.

Forest resources. Forest resource data covered two geographical regions in the US: INW and the combined NE-NC region. INW resource-management scenarios included state or private and national forest ownership for softwood logs. The cradle-to-gate LCI used an average management and harvest volume scenario that represented 9, 30, and 61% from national forest (50:50, gentle:steep slopes), state or private dry sites (90:10, gentle:steep slopes), and state or private moist sites (70:30, gentle:steep slopes), respectively. Hardwood and softwood logs were considered in the NE-NC harvesting LCI. Log volume removals originated from three different management scenarios. Hardwood volume removals were 14, 27, and 59% from high, medium, and low management intensities, respectively. Softwood volume removals were 19, 34, and 47% from high, medium, and low management intensities, respectively. Detailed descriptions for forest management and harvesting scenarios for log volume removals can be found in CORRIM report Module A: Forest Resources (Johnson et al 2008; Oneil et al 2010). Forest management practices included in the harvesting stage were regeneration (natural and greenhouse), seedling growth, thinning (precommercial and commercial), final harvest, and their associated equipment use.

Softwood lumber. Softwood lumber production data represented two geographical regions, INW and NE-NC. Softwood lumber data were collected through surveys that represented 12% (NE-NC) and 16% (INW) of the total production for each region (Table 3). Detailed production and LCI results for softwood lumber can be

Table 2. *Input data for the cradle-to-gate analysis.*[a]

	Harvesting		Transportation			Manufacturing		
	Logs	Bark	Logs	Bark	Lumber	Planed dry lumber	Rough dry lumber	Solid strip flooring
Final product	(m^3)	(kg)	(t·km)[b]			(m^3)	(kg)	(m^3)
INW softwood lumber	1.11	33	94	9	—	1 (= 436 kg)	—	—
NE-NC softwood lumber	1.08	53	83	11	—	1 (= 392 kg)	—	—
NE-NC hardwood lumber	1.24	74	149	17	—	1 (= 572 kg)	—	—
NE-NC hardwood solid strip flooring	1.44	86	174	20	204	—	667	1

[a] Data are allocated to final product, no coproducts included.
[b] Mass and delivery distance.
INW, Inland Northwest; NE-NC, Northeast–North Central.

Table 3. *Annual production totals reported in surveys from the Inland Northwest and the Northeast–North Central.*

Wood product	Unit	Production from survey manufacturers		% of regions production[a]
Northeast–North Central				
Softwood lumber	m^3	531,000	(256 MBF)	12
Hardwood lumber	m^3	784,000	(301 MBF)	6
Hardwood flooring	m^2	12,425,000	(134,000 ft^2)	28[b]
Inland Northwest				
Softwood lumber	m^3	755,852	(466 MBF)	16

[a] Bergmann and Bowe 2008a 2008b; Hubbard and Bowe 2008; Wagner et al 2009.
[b] Percentage of total US solid-strip flooring production.

found in CORRIM Reports B and D (Bergman and Bowe 2008b; Wagner et al 2009). Softwood lumber production processes (ie the manufacturing stage) included log-yard operations, primary log breakdown (sawing), drying, and planing. The mass of the 1-m^3 reference unit for softwood lumber was assumed to be 436 and 392 kg for the INW and NE-NC production regions, respectively.

Hardwood lumber. The data collected for hardwood lumber represented 6% of the total NE-NC hardwood lumber production (Table 3). Detailed production and LCI results for hardwood lumber can be found in CORRIM Report Module C (Bergman and Bowe 2008a). Hardwood lumber production processes included in the manufacturing stage were log-yard operations, primary log breakdown (sawing), drying, and planing. The mass of the reference unit for hardwood lumber was assumed to be 572 kg.

Hardwood flooring. The production of hardwood solid-strip flooring represented an extended NE-NC production region (Fig 2). Production data collected in surveys represented 28% of total US hardwood solid-strip flooring production (Hubbard and Bowe 2008; Table 3). Regional production data were not available. Hardwood-flooring production processes considered hardwood lumber production and hardwood solid-strip flooring production in a single-unit process. The analysis of the process for manufacturing hardwood flooring used data from hardwood lumber manufacturing (log-yard, sawing, and drying) to produce rough dry lumber (Bergman and Bowe 2008a). The mass of the reference unit for hardwood flooring was assumed to be 657 kg.

Environmental performance was measured on the basis of resource use, energy consumption, and emissions to air, water, and land. Comparisons were made among harvesting, product manufacturing, and transportation. Phase I cradle-to-gate data were also included for comparison where appropriate.

RESULTS AND DISCUSSION

Energy Consumption

Regional. The NE-NC region used more wood biomass fuel than did the western regions. Wood biomass consumption represented 58, 60, and 58% of total energy for the NE-NC softwood lumber, hardwood lumber, and hardwood flooring, respectively (Tables 4 and 5). In the CORRIM Phase I cradle-to-gate LCI in the Southeast (SE) region, woody biomass for energy generation represented 71% of the total energy requirements. Coal consumption was approximately 58% of total energy consumed for electrical generation in the NE-NC. In contrast, hydroelectric power was the main fuel source for electrical generation in the Western regions (Fig 2; Puettmann and Wilson 2005). Natural gas was the primary fuel source in the INW softwood lumber processes, representing 44% of the total energy demand, followed by wood biomass at 36%.

Harvesting. Energy consumption in the harvesting stage was determined by greenhouse operations and equipment used in regeneration, thinning, final harvest, and transportation of logs (with bark) to a forest road. Energy requirements were for electricity, gasoline, diesel fuel, oils and lubricants, and fertilizer production. The harvesting stage represented 3 – 7% of the total

Table 4. *Cradle-to-gate percentages of cumulative energy consumption by fuel source for products manufactured in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North Central (NE-NC) regions.*[a]

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
Coal	2	10	3	13	14	11
Crude oil	10	10	11	23	12	11
Natural gas	39	8	44	5	13	14
Uranium	0	1	0	1	1	1
Biomass	43	71	36	58	60	63
Hydropower	5	0	5	0	0	0
Other	0	0	0	0	0	0
Total (%)	100	100	100	100	100	100

[a] Electrical production and transportation of raw materials to the wood manufacturing facilities are included.

Table 5. *Cradle-to-gate cumulative energy*[a] *requirements by fuel source (MJ/m^3) allocated to 1 m^3 of product produced in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North Central (NE-NC) regions.*[b]

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring[c]
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
Coal	92	356	87	400	845	748
Crude oil	361	337	365	693	705	768
Natural gas	1447	279	1410	154	811	934
Uranium	7	35	10	27	54	48
Biomass	1595	2475	1152	1756	3601	4195
Hydropower	200	4	159	5	11	9
Other	3	8	6	3	7	7
Total	3705	3492	3189	3038	6034	6710

[a] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal (26.2), diesel (44.0), liquid propane gas (54.0), natural gas (54.4), crude oil (45.5), oven-dry biomass (20.9), and gasoline (48.4). Energy from uranium was determined at 381,000 MJ/kg.

[b] Electrical production and transportation of raw materials to the wood manufacturing facilities are included.

[c] Includes the cradle-to-gate production of 667 kg rough dried hardwood lumber to produce 1 m^3 of hardwood flooring.

cradle-to-gate energy consumption with the greatest use for NE-NC softwood log management and removal (211 MJ/m^3; Table 6).

Manufacturing. The primary energy demand for all products and regions was in the manufacturing stage (Table 6). The highest energy consumption was for the production of hardwood lumber and hardwood flooring. In the cradle-to-mill gate models, manufacturing energy represented 64 and 92% of total energy consumption for hardwood lumber and hardwood flooring, respectively (Table 6). Hardwood lumber and flooring production required almost twice the energy consumption as softwood lumber production. In general, manufacturing energy consumption as a percentage of total energy consumption was similar (90 – 92%) independent of region. Drying green lumber to specified MCs (see individual reports) was the primary source of energy consumed in the manufacturing stage. Wood biomass, either self-generated or purchased, was the main fuel source for drying. In some instances, heat energy was supplemented with natural gas and diesel fuel to a lesser extent. Natural gas consumption for softwood lumber drying was found to be higher in the Pacific Northwest and INW than in other regions, accounting for 46 – 47% of total energy consumed (Milota et al 2005; Wagner et al 2009).

Transportation. Product weight, transport distance, and mode of transportation were the main factors affecting fuel consumption and, therefore, environmental impacts associated with transportation. Transportation energy requirements from cradle-to-mill gate represented approximately 3% of the total energy

Table 6. *Cradle-to-gate, cumulative energy[a] (MJ/m^3) allocated to 1 m^3 of product manufactured in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North Central (NE-NC) regions.[b]*

	CORRIM Phase I[c]		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
	(MJ/m^3)					
Harvesting	143	203	164	211	195	204
Product manufacturing	3415	3175	2911	2721	5654	6135[d]
Transportation	147	114	114	105	185	253
Total	3705	3492	3189	3037	6034	6710

[a] Energy values were determined for the fuel using their higher heating values (HHVs) in units of MJ/kg as follows: coal 26.2, natural gas 54.4, crude oil 45.5, and oven-dry wood 20.9. Energy from uranium was determined at 381,000 MJ/kg.

[b] Electrical production and transportation of raw materials to the wood manufacturing facilities are included.

[c] Puettmann and Wilson (2005).

[d] Includes hardwood lumber and flooring processes.

(Table 6). Transportation distance associated with the manufacture of hardwood flooring was significantly greater than for hardwood or softwood lumber manufacturing. The average transportation distance of hardwood lumber to hardwood flooring manufacturers was 283 km (158 km farther than for logs to hardwood lumber producers). Also, the energy demand for transportation for the hardwood flooring model included the transportation of logs to hardwood lumber production and of hardwood lumber to the hardwood flooring manufacturers.

Electricity. Technology and fuel used for electrical production also played an important role in determining the environmental impacts of a product. This was evident from comparisons of wood-product manufacturing from different geographical regions (Puettmann and Wilson 2005; Table 5). Similar to the SE products in the CORRIM Phase I reports, the manufacturing of wood products in the NE-NC regions consumed a higher percentage of coal and crude oil than in other regions (Table 5). Coal was the primary fuel (58%) for electrical production in the NE-NC grid (EIA 2007; Bergmann and Bowe 2008a, 2008b). For the INW regions, the primary source of electrical production was hydroelectric (72%) followed by coal and natural gas at 9% each.

Environmental Emissions

Carbon balance. A mass balance on carbon indicated that most was stored in the wood products (Table 7). Overall cradle-to-gate emissions containing carbon were found to be 32, 49, and 95 kg/m^3 of product for INW softwood lumber, NE-NC softwood lumber, and NE-NC hardwood lumber, respectively. A significant amount was emitted to the atmosphere as biomass CO_2. These carbon-related emissions originated from the combustion of wood biomass, and the CO_2 was then sequestered by living trees. Carbon balances for each product are detailed in the individual LCI reports (Bergmann and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Wagner et al 2009).

Airborne emissions. CO_2 emissions were the greatest emission released over all stages (Table 8). Hardwood lumber and hardwood flooring manufacturing emitted greater amounts of CO_2 (biomass- and fossil-based) than did softwood lumber manufacturing. The CO_2 emissions were a direct result of higher energy demand for the production of hardwood lumber. Hardwood lumber manufacturing per unit product produced 345 kg of CO_2 and hardwood flooring released 431 kg of CO_2.

In general, manufacturing in the NE-NC resulted in the consumption of greater quantities of fossil fuels as a percentage of total energy consumption than in other regions, consequently leading to greater CO_2 emissions. Fossil fuel consumption was primarily linked to electrical production.

Waterborne and solid emissions. Total emissions to water from production were generally higher in the INW or the Pacific Northwest regions (Milota et al 2005; Table 9). Conversely, total solid waste from production was higher in the NE-NC regions (Table 10). These differences are likely a result of industry practices and regional industry reports to environmental agencies. Solid emissions included solid waste generated during the extraction and production of fuels. Ash was reported only for hardwood flooring manufacturing.

Many LCA studies have become public over the past 10 yr with a number in countries other than the US. Differences in system boundaries and functional units make it difficult to compare much of the published product LCI data. Additional differences unique to wood products such as densities, MCs, and energy content contribute to difficulties.

The cradle-to-gate LCIs presented here were part of CORRIM Phase II LCI studies of wood products. Comparisons have been made with similar products from CORRIM Phase I wood-product LCI studies. Because of the differences mentioned, comparisons with other LCIs are difficult. Therefore, all comparisons were made among the different CORRIM products only where the system boundaries and functional units were clearly known and comparable.

Environmental emissions are released during every stage of production and use. Even the "greenest" products result in emissions to the environment. They may have different impacts than their not-so-green alternatives, but more likely, environmental releases will be less. Fuel types used in production processes and transportation have the greatest influence on the type and quantity of environmental impact.

Table 7. *Carbon content in lumber products and air emissions for Inland Northwest (INW) and Northeast–North Central (NE-NC).*[a]

	Softwood lumber		Hardwood lumber
	INW	NE-NC	NE-NC
	(kg/m^3)		
CO_2 uptake (stem only)	895	813	1328
CO_2 biogenic emission	116	176	345
Carbon input, logs	229	199	381
Carbon output (in final product, at mill)	220	200	315
Total carbon containing emissions	32	49	95

[a] Coproducts are not considered.

CONCLUSIONS

Environmental impacts for wood products production from cradle-to-gate were measured by total energy consumption and associated emis-

Table 8. *Cradle-to-gate cumulative emissions to air allocated to 1 m^3 of structural wood products produced in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North Central (NE-NC) production regions; includes all life-cycle processes from forest regeneration through wood products production.*[a]

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
	(kg/m^3)					
CO	1.43	1.83	1.15	1.24	2.79	3.49
CO_2 (biomass)	160.00	248.00	116.00	176.00	345.00	431.00
CO_2 (fossil)	92.00	62.00	90.00	85.00	150.00	164.00
HAPS	0.01	0.01	0.03	0.001	0.02	0.02
Methane	0.19	0.10	0.19	0.09	0.25	0.25
Nitrogen oxides	0.67	0.64	0.67	0.72	1.24	1.44
NMVOC			0.33	0.15	0.29	0.38
Particulates	0.06	0.09	0.14	0.10	0.18	0.20
Sulfur oxides	1.03	0.43	1.00	0.41	1.08	1.14
Volatile organic compounds	0.08	0.49	0.17	0.65	1.17	1.37
Total	255.47	313.59	209.02	264.35	502.19	603.16

[a] Emissions resulting from transportation between life-cycle stages and with raw materials, fuels, and electrical production are included.
NMVOC, nonmethane volatile organic compounds.

Table 9. *Cradle-to-gate cumulative emissions to water allocated to 1 m^3 of wood product produced in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North central (NE-NC) production regions; includes all life-cycle processes from forest regeneration through wood products production.*[a]

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
	(kg/m^3)					
BOD[b]	0.0015	0.0004	0.0014	0.0003	0.0010	0.0012
Cl–	0.0643	0.0131	0.0004	0.0013	0.0024	0.0032
COD[c]	0.0203	0.0042	0.0197	0.0029	0.0119	0.0140
Dissolved solids	1.4205	0.2914	0.2914	0.0363	0.0650	0.0878
Oil	0.0251	0.0053	0.0053	0.0031	0.0144	0.0170
Suspended solids	0.0306	0.0254	0.0254	0.0263	0.0638	0.0602
Total	1.5622	0.3397	1.4322	0.0703	0.1585	0.1835

[a] Emissions resulting from transportation between life-cycle stages and with raw materials, fuels, and electricity are included.
[b] Biochemical oxygen demand.
[c] Chemical oxygen demand.

Table 10. *Cradle-to-gate cumulative emissions to land allocated to 1 m^3 of structural wood products produced in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest (INW), and Northeast–North Central (NE-NC) production region; includes all life-cycle processes from forest regeneration through wood products production.*[a]

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	INW	NE-NC	NE-NC	NE-NC
	(kg/m^3)					
Solid waste	5.32	8.44	9.01	14.76	30.73	33.24
Waste in inert landfill	0.67	—	0.12	0.22	6.39	7.44
Waste to recycling	0.08	0.33	—	0.02	0.19	0.22
Fly ash	—	—	—	—	—	0.62
Total	6.07	8.77	9.13	15.00	37.31	40.91

[a] Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electrical production are included.

sions. Emissions to air and water and solid wastes originated from the production, transportation, and use of fuels and electricity. Such emissions were determined from mill surveys, knowledge of equipment used in forest management, and well-established data for transportation of resources. For the wood products LCI presented here, the manufacturing stage consumed the greatest amount of energy. The use of wood biomass as the primary energy source for manufacturing greatly reduced the environmental impact by offsetting the demand for fossil fuels. Most of the biomass consumed at the mill sites was produced on-site, thereby offsetting the environmental impacts of transporting fuels.

Transportation impacts from cradle-to-gate contributed approximately 3% to the overall energy consumption of product manufacturing. Timber management and removals accounted for 3 – 7% of total energy consumption. The highest energy consumption linked to forest management and harvesting of softwoods was found for softwood timber removals in the NE-NC region. This higher consumption (7% of total energy) was attributed to higher intensity management.

Manufacturing energy ranged 90 – 92% of the total cradle-to-gate energy consumption independent of region. Hardwood lumber and flooring manufacturing required relatively high amounts of energy because of the heat generation needed for drying. Factors such as higher initial wood MCs, denser wood, and longer, slower kiln-drying schedules all contributed to higher manufacturing energy consumption. Total energy consumption for softwood lumber manufacturing (INW and NE-NC) was about one-half of that required for hardwood lumber and flooring.

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