GATE-TO-GATE LIFE-CYCLE INVENTORY OF LAMINATED VENEER LUMBER PRODUCTION

James B. Wilson
Professor

and

Eric R. Dancer
Former Graduate Research Assistant
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331

ABSTRACT

A life-cycle inventory (LCI) study is conducted of laminated veneer lumber (LVL) manufacturing. This gate-to-gate study includes all environmental impacts from the logs to produce either veneer or parallel laminated veneer (PLV) as input to the LVL process, through production of the LVL. The study includes all materials, fuels, and electricity inputs to produce LVL and related co-products and emissions. The input and site emissions data were collected through surveys of manufacturing facilities in the Pacific Northwest and the Southeast regions of the U.S. SimaPro software, a program to conduct life-cycle inventory studies, is used to process the data and measure environmental impacts in terms of material use and emissions. The data are allocated on a mass basis to LVL based on their contribution to the mass sum of all product and co-products produced in manufacturing. All data are provided on a production unit basis of 1000 m^3 and 1000 ft^3 (MCF). In addition to the LCI data, carbon flow data are also given. These data are publicly available through reports, this publication, and the U.S. LCI Database Project. The data are useful for generating cradle-to-gate product LCIs when combined with the LCIs to produce logs as input to the plants and the transportation impacts to deliver materials. The data are useful as a benchmark for assessing process performance, for conducting life-cycle assessments of structural assemblies and the shell of residential and light commercial buildings.

Keywords: Life-cycle inventory, LCI, laminated veneer lumber, building materials, carbon balance, energy, emissions.

INTRODUCTION

Background

Laminated veneer lumber (LVL) is a composite wood material made from sheets of veneer generally 2.54 mm or 3.18 mm (1/10 in. or 1/8 in.) thick that are laminated together with their grain orientation in the same direction and then hot-pressed. LVL was first used in WWII to make airplane propellers and since the 1970s it has been used as a construction product (Neuvonen et al. 1998). LVL can vary in thickness and width but is most commonly produced in the dimensions of 4.45 cm (1 3/4-in.) thick and 121.9 cm (4 ft) wide, with lengths generally of 18.29 m (60 ft). After being ripped into narrower dimensions, it is used as an alternative to structural lumber for headers and beams and also as the flange component in wood composite I-joists. According to the APA—The Engineered Wood Association, in the year 2000 the U.S. produced 1.257 million cubic meters (44.4 million cubic feet) of LVL of which 61% was used in the manufacture of I-joists and another 31% was used as headers or beams (APA 2001). Annual production of LVL has shown a steady increase.

This study documents the life-cycle inventory (LCI) of LVL production in the Pacific Northwest (PNW) and Southeast (SE) regions of the U.S. The LCI data were used as input material in the CORRIM cradle-to-grave analysis of wood building materials (Bowyer el al. 2004; Lippke et al. 2004; Perez-Garcia et al. 2005). For a cradle-to-grave analysis, the LVL LCI data would need to be cumulated with the log resource impact data and the transportation of materials data. This report deals only with the manufacturing of LVL and includes the relevant inputs and outputs as well as their environmental impacts. The primary data collection was done with the surveys while supporting secondary data were also used. The secondary data were necessary to assess the impacts of fuel, electricity, and resin manufacture and use, as well as associated impacts of using these materials in the LVL process. Electricity and fuel data were gathered from Franklin Associates (FAL 2001), PRe' Consultants (2001) and the U.S. Department of Energy (USDOE 2001), while information related to the production of phenol-formaldehyde resin came from ATHENA (1993).

Scope of study

The scope of this report covers a gate-to-gate LCI analysis of LVL for the PNW and SE regions. Included in the PNW region are Oregon and Washington. The states that make up the SE region are Alabama, Georgia, Louisiana, Mississippi, Florida, Arkansas, and Texas. Included in the study are the product LCIs, and the transportation mileage for delivery of wood and resin-based raw materials. Since this is a gate-to-gate LCI analysis, this report is limited to the production of LVL and the transportation of wood and resin materials to the manufacturing site, the LCI of the input materials of veneer and parallel laminated veneer, and the production of phenol-formaldehyde resin, electricity, natural gas, LVL and its co-products. The surveyed plants varied in the starting input material, some input dry veneer while one plant input parallel laminated veneer (PLV), while others not part of this survey input green veneer. To provide a single model for all plants, they were treated as having dry veneer and PLV inputs, with the burdens for these materials taken from the same unit process as developed for softwood plywood (Wilson and Sakimoto 2004). Some of the plants also produced composite I-joists, a structural product comprised of LVL flanges and oriented strandboard (OSB) webs. The plants only provided data for those resources that were directly attributed to the LVL production process.

This study relied almost exclusively on production and emissions data provided by the wood products industry. The data were gathered through primary surveys that were sent out to LVL production facilities. The surveys were extensive and included questions about annual production, energy and fuel uses, as well as emissions, and co-product volumes. According to a representative from the APA—The Engineered Wood Association, in the Pacific Northwest the annual production of LVL for 2001 was 0.572 million cubic meters (20.2 million cubic feet), which represented approximately 45% of the LVL production for the U.S. This study collected data from plants in the region that would be considered large-scale operations. The survey data collected for the PNW region totaled 0.187 million cubic meters (6.6 million cubic feet) of LVL, representing roughly 33% of the production for the region. In the SE region the annual production of LVL in 2001 was less than in the PNW at an estimated 0.425 million cubic meters (15.0 million cubic feet). This represents the equivalent of roughly 34% of the total LVL produced in the U.S. in the year 2000. Data gathered from the industry survey accounted for 0.221 million cubic meters (7.8 million cubic feet) of production, which is slightly over 52% of the total volume produced in the region.

This study was externally reviewed to assure that the study methodology, data collection, and analyses are scientifically sound, and are in compliance with ISO 14040 and 14041 and CORRIM research protocol (CORRIM 2001; ISO 1997; ISO 1998). Complete details of this study for LVL production and the overall CORRIM project can be found in Wilson and Dancer (2004) and Bowyer et al. (2004), respectively.

Laminated veneer lumber process and description

Two life-cycle inventory models were created for LVL manufacturing, one for the PNW region and another for the SE region. These models were based on production data and used as a guideline for the LCI. A black-box approach was taken, which simply means that all process inputs and outputs are lumped together into one LVL process (Fig. 1). The black-box approach is used because of the relative simplicity of the LVL manufacturing process having such a small number of unit processes and because of the large allocation (about 93%) of burdens to the LVL. The input materials of parallel laminated veneer (PLV) and dry veneer are included as a part of the process even though these materials are generated at other manufacturing facilities. The manufacturing of PLV is the same as that for plywood except that the veneers are all oriented in the same direction. The PLV is neither as thick nor as long as LVL; therefore, it must be face and finger-jointed, glued and pressed to make large LVL billets. Some LVL uses PLV as an input to produce product; however, most use dry or green veneer to directly produce the product. Although none of the surveyed mills used green veneer, the LCI of these plants would be the same since the dry veneer and PLV models include the environmental impacts for the production of green veneer. The LCI models for producing dry veneer and PLV used appropriate plywood unit process LCI models developed by Wilson and Sakimoto (2004).

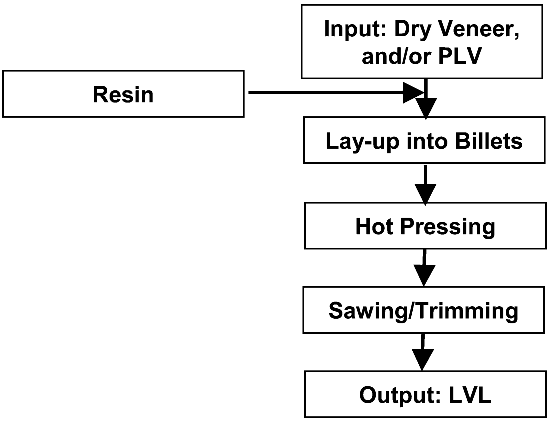

FIG. 1. Process steps for the production of laminated veneer lumber; if green veneer is input, then a drying step is added prior to resin application.

The following is a description of the process steps within the black box for producing LVL:

1. Lay-up of billets: Dried veneers at about 5% moisture content (oven-dry basis) are aligned in their grain direction, coated with phenol-formaldehyde resin, and composed into billets for pressing. Co-products include waste veneer. For PLV, a similar process is followed except that these panels are then finger-jointed and laminated to make billets.
2. Pressing: Heat and pressure of about 170°C and 1.72 MPa (about 340°F and about 250 lb/in^2) are applied to the LVL billets, which cures the resin, thereby bonding the veneers into LVL. There are no co-products or waste from this unit process.
3. Sawing/Trimming: After exiting the press, the billets are sawn to the proper width and length. Co-products include panel trim, sawdust, and tested LVL.

Different plants use different types of lay-up lines and press systems to manufacture LVL. Some plants use automated lay-up lines where resin is applied and the veneers are laid up automatically before entering the press. Other systems require hand feeding of veneer into the spreaders where resin is applied. The main system for pressing the billets is the hot press, which imparts heat and pressure to the unpressed LVL billets. Some presses are heated by hot-oil, which is heated by natural gas. Another heating system for presses is a microwave or radio-frequency system used in conjunction with oil-heated metal platens; this provides faster internal heating for these thick products.

Co-products are wood-based products that are generated during different phases of the LVL manufacturing process. They are called co-products because they are sold outside of the LVL boundary and their burdens are not attached to LVL. Rather, these co-products carry a weight-percentage of the total associated burdens.

Functional unit

The functional unit for laminated veneer lumber is one thousand cubic meters ($10^3 m^3$) and one thousand cubic feet (MCF). For conversion of units from U.S. industry measure, 1.0 MCF is equal to 0.02832 $10^3 m^3$. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with CORRIM and International Organization for Standardization (ISO) protocol (CORRIM 2001; ISO 1997; ISO 1998).

System boundaries

The cumulative system boundary for the LCI covers laminated veneer manufacturing and its associated processes such as the manufacture of dry veneer and PLV (Fig. 2). Although not directly described in the modeling, through the processes of dry veneer and PLV, green veneer is also included in the modeling. The system boundary (solid line box) includes the impacts due to the manufacture of dry veneer and PLV, the manufacture, delivery, and combustion of fuels, the generation and delivery of electricity, and the manufacture of resin. This study refers to the environment impacts in this system boundary as the cumulative impacts. Excluded are the impacts for the growing, harvesting, and transportation of logs and the transportation of resin and purchased veneer and wood and bark fuel. The cumulative system boundary considers both the off-site and on-site emissions.

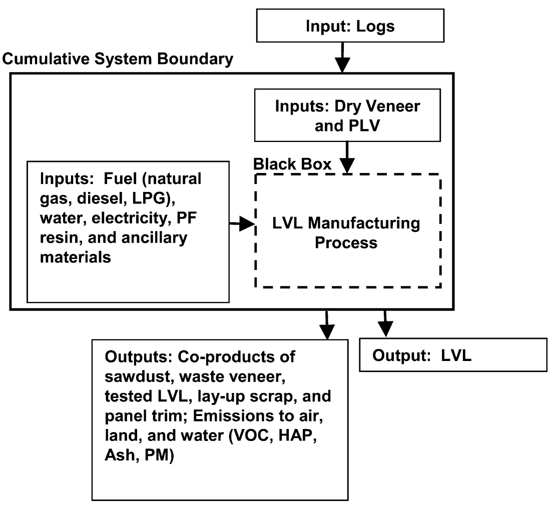

FIG. 2. The cumulative system boundary to define the life-cycle inventory of producing laminated veneer lumber (LVL); environmental burdens are included for production of veneer and parallel laminated veneer (PLV) but exclude those for the logs input to these products.

Assumptions

The data collection, analysis, and assumptions were based on the "Consortium for Research on Renewable Industrial Materials (CORRIM) protocol and research guidelines for life-cycle inventories" (CORRIM 2001). Other considerations include:

1. All data from the mill survey taken in 2000 were weighted-averaged for the four plants based on production of each plant in comparison to the total production for the year. Whenever missing data occurred for survey items, they would be checked with plant personnel to determine whether it was an unknown value or zero; if unknown, it was not included in the weighted-average calculations.
2. Survey data quality was found to be high based upon comparisons between plants and production regions, and on mass and heat balances.
3. Co-products were defined as those materials sold outside the system boundary.
4. Liquid petroleum gas (LPG) and diesel fuel were for material transport at the plants. LPG is used in equipment to transport materials inside the plant, and diesel fuel is used to transport materials outside the plant.
5. Density values for the wood species, relating to veneer and PLV, were obtained from the Wood Handbook–Wood as an Engineering Material (FPL 1999), and based on their estimated weighted percentage. The PLV input value was derived from the wood only weight of plywood as determined in Wilson and Sakimoto (2004).
6. Veneer and PLV inputs were given in MSF (1,000 ft^2 3/8-in. basis) volumes and converted to cubic meters and cubic feet.
7. At the time of the study, a suitable LCI data-

base was not available for phenol-resorcinol-formaldehyde resin; as such LCI data for phenol-formaldehyde were used as a substitute.
8. All conversions for forest products are taken from Forest Products Measurements and Conversion Factors, with special emphasis on the U.S. Pacific Northwest (Briggs 1994).

SimaPro version 5.0.009, a software package designed to analyze products through their entire life cycle, was used to complete the life-cycle inventories. The software is designed by PRe' Consultants and contains a database by Franklin Associates for U.S. materials (FAL 2001).

Material flows

Delivery of the input materials was by truck for all materials in the PNW and SE. The one-way delivery distances for dry veneer, PLV, and resin are listed in Table 1. These transportation data would be needed to determine any cradle-to-gate LCIs or for determining life-cycle assessments (LCAs) since they are not included in the product gate-to-gate LCI. Transportation data related to the production of plywood and dry veneer are from Wilson and Sakimoto (2004). The weight of the input wood to produce a functional unit of product for the PNW was determined to be the value for oven-dry density of Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) veneer at 481 kg/m^3 (30 lb/ft^3) and the density of PNW plywood (without resin) for PLV at 486 kg/m^3 (30.34 lb/ft^3) times the input volume of material from the surveys (Wilson and Sakimoto 2004). The input wood for the SE was comprised of slash pine (*P. elliottii* Engelm.) and loblolly pine (*P. taeda* L.) with an average density of 551 kg/m^3 (34.38 lb/ft^3) times the volume of veneer input. The density of the LVL for the PNW is 529 kg/m^3 (33.0 lb/ft^3) and for the SE is 606 kg/m^3 (37.8 lb/ft^3), when including both wood and resin in the density value.

TABLE 1. *Delivery distances (one-way) for inputs to plywood[1] and LVL manufacturing facilities.*

Material delivered to plant	Pacific Northwest delivery distance		Southeast delivery distance	
	km	mile	km	mile
Logs to plywood	97	60	156	97
Veneer to plywood	121	75	246	153
PF resin to plywood	196	122	158	98
Dry veneer to LVL	121	75	84	52
PLV to LVL	6	4	0	0
Resin to LVL	167	104	79	49

[1] Appropriate unit processes of the life-cycle models for producing plywood were used for producing dry veneer and parallel laminated veneer (PLV), the inputs to LVL manufacturing process.

A wood mass balance for each region was completed and is shown in Table 2. The wood was considered to be oven-dry, and all resin and resin component weights were subtracted from the total weight. A slight discrepancy appeared between input and output wood values for each region. In the PNW the amount of output material was larger than the input material by about 8.2%, while in the SE this difference was slightly smaller at about 5.5% more output wood. This difference can probably be attributed to not considering the amount of inventory at the end of a year, and the wide variety of measurement units used in the manufacturing facilities that can lead to conversion errors. To produce one thousand cubic meters (10^3m^3) of LVL in the PNW, the required inputs were 111,000 kg of dry veneer and 392,000 kg of PLV that were based on survey volumes and wood densities. The output yield from the survey data was 521,000 kg of oven-dry LVL without resin and 23,800 kg of oven-dry wood co-products. In the SE region of the U.S., the inputs required to produce 10^3m^3 of LVL include 615,000 kg of southern pine veneer based on wood volumes and densities. Output yield for the SE includes 593,000 kg of LVL and 56,300 kg of wood-based co-products. Also included in this table are the allocation factors that were based on mass of product and co-product; they were used to assign the environmental burdens in terms of fuel and materials use, as well as emissions in the LCI output. The allocation of environmental burdens for the production of LVL was 95.6% and 91.3% for the PNW and SE regions, respectively, with the remainder to the co-products.

Table 3 illustrates a complete listing of all inputs to produce 10^3m^3 (or 1.0 MCF) of LVL in the PNW and SE regions. This table includes the

TABLE 2. *Wood mass balance for production of a unit of laminated veneer lumber (LVL). All weights are reported on an oven-dry basis.*

	PNW		Allocation[1]	SE		Allocation
	kg/10^3m^3	lb/MCF	%	kg/10^3m^3	lb/MCF	%
Inputs						
Dry veneer	1.11E + 05	6.95E + 03		6.14E + 05	3.84E + 04	
PLV (wood only)[2]	3.92E + 05	2.45E + 04		0.00E + 00	0.00E + 00	
Total	5.03E + 05	3.14E + 04		6.14E + 05	3.84E + 04	
Outputs						
LVL (wood only)[2]	5.21E + 05	3.25E + 04	95.6	5.93E + 05	3.70E + 04	91.3
Veneer waste	7.54E + 03	4.71E + 02	1.4	1.09E + 04	6.83E + 02	1.7
Lay-up scrap	6.02E + 03	3.76E + 02	1.1	2.25E + 04	1.40E + 03	3.5
Tested LVL	1.36E + 03	8.46E + 01	0.2	1.74E + 03	1.09E + 02	0.3
Panel trim	6.73E + 02	4.20E + 01	0.1	1.66E + 04	1.04E + 03	2.6
Sawdust	8.23E + 03	5.14E + 02	1.5	4.52E + 03	2.82E + 02	0.7
Total	5.44E + 05	3.40E + 04	100	6.49E + 05	4.05E + 04	100

[1] The allocation factor for assigning environmental burdens in the life-cycle inventory is done on a mass contribution basis of product and co-product.
[2] The weight of wood in PLV and LVL was determined by subtracting the weight of resin from the weight of each product.

TABLE 3. *Gate-to-gate life-cycle inventory (LCI) inputs to produce a unit of laminated veneer lumber (LVL)[1]. These are unallocated values, allocation occurs within the SimaPro model.*

INPUTS	PNW Inputs		SE Inputs	
Materials[2]	kg/10^3m^3	lb/MCF	kg/10^3m^3	lb/MCF
Dry veneer	1.11E + 05	6.95E + 03	6.06E + 05	3.84E + 04
Parallel laminated veneer (PLV)	3.91E + 05	2.44E + 04	0.00E + 00	0.00E + 00
Phenol-formaldehyde resin (PF)	8.07E + 03	5.04E + 02	1.05E + 04	6.56E + 02
PF substitute for PRF resin	5.77E + 02	3.60E + 01	0.00E + 00	0.00E + 00
Extenders and fillers[3]	6.42E + 03	4.01E + 02	9.42E + 03	5.88E + 02
Catalyst[3]	1.22E + 02	7.60E + 00	5.38E + 02	3.36E + 01
Electrical Use	MJ/10^3m^3	kWh/MCF	MJ/10^3m^3	kWh/MCF
Electricity	2.11E + 05	1.66E + 03	2.45E + 05	1.92E + 03
Fuel Use	m^3/10^3m^3	ft^3/MCF	m^3/10^3m^3	ft^3/MCF
Natural Gas	3.77E + 03	3.77E + 03	1.07E + 04	1.07E + 04
	L/10^3m^3	gal/MCF	L/10^3m^3	gal/MCF
Liquid Petroleum Gas (LPG)	3.47E + 02	2.60E + 00	4.67E + 02	3.50E + 00
Diesel	1.68E + 02	1.26E + 00	3.60E + 02	2.70E + 00
Water Usage	kg/10^3m^3	lb/MCF	kg/10^3m^3	lb/MCF
Municipal water source	3.47E + 04	2.33E + 03	9.73E + 04	6.08E + 03
Well water	0.00E + 00	0.00E + 00	3.13E + 03	1.95E + 02
Recycled water	0.00E + 00	0.00E + 00	2.11E + 05	1.32E + 04

[1] Survey data for LVL plant site collected for 2000.
[2] All materials are given on an oven-dry or solids weight basis.
[3] These materials were not included in the LCI analysis based on the 2% exclusion rule.

wood inputs as well as the reported electricity, fuel, resin, and water inputs for the production of each unit of LVL; these are unallocated values. The site emissions for producing LVL that were input to the LCI model are given in Table 4. The site emissions' data were obtained by several methods: CO_2 was calculated using SimaPro LCI software using the Franklin database to determine the emission as a result of combusting an equivalent amount of fuel, a survey was taken of LVL manufacturers, and emissions data were taken from an NCASI report (1999) on manufacturing emissions; the data source of each emission is listed in the table.

TABLE 4. *LVL processing emissions data for plant site.*

Emissions to air	PNW LVL kg/10^3m^3	PNW LVL lb/MCF	SE LVL kg/10^3m^3	SE LVL lb/MCF	Data source
CO_2 (fossil)	6717	419	18308	1143	calc in SimaPro based on fuel use in Franklin database
CO	5.430	0.339	44.385	2.771	plant survey
NO_x	6.467	0.404	91.642	5.721	plant survey
SO_2	0.168	0.010	0.328	0.020	plant survey
VOC	0.354	0.022	2.913	0.182	plant survey
Acetone	3.912	0.244	14.417	0.900	NCASI[1]
Acetaldehyde	0.533	0.033	0.000	0.000	NCASI
Propionaldehyde	0.238	0.015	0.000	0.000	NCASI
Formaldehyde	0.210	0.013	1.498	0.094	NCASI & SE survey
Methanol	9.246	0.577	45.616	2.848	NCASI & SE survey
Particulates	11.835	0.739	2.420	0.151	plant survey
Particulates PM10	4.781	0.298	2.420	0.151	plant survey

[1] Data source: NCASI 1999

It should be noted that the site emissions are significantly less for the PNW than the SE region; this is due to the use of PLV as input for the PNW where emissions for pressing the PLV occur at the plywood manufacturing facility. However, when conducting a LCI for the cumulative system boundary that includes those for the PLV, all emissions are included and comparable between regions.

The data in Tables 3 and 4, and the LCI data for dry veneer and PLV were the input data used in the SimaPro software to determine the life-cycle inventory of manufacturing a unit of LVL based on the cumulative boundary conditions given in Fig. 2. The life-cycle inventory output of this analysis gives the product and co-product produced, as well as the raw materials, electricity, and water usage (Table 5). The raw materials include the input logs (with no impacts) that were used to produce the veneer and PLV, the primary fuels used to produce and deliver the fuels, electricity, and resins, and the water use for the manufacture of PLV, dry veneer, and LVL. The raw materials are allocated to the LVL based on each production region's allocation factor based on mass; it was 95.6% and 91.3% for the PNW and SE, respectively. This LCI output is for a gate-to-gate analysis, considering all impacts except those for the growing and harvesting of logs and the transportation of materials to the plant. Fuel to produce electricity is listed in the Raw Materials section of Table 5, whereas electricity that was not produced from fuel such as from hydro and unknown sources "other" is listed in the Electricity section. For a cradle-to-gate analysis from the forest to the output of the LVL plant, these data would need to be combined with the LCI data of harvested logs, and the transportation of logs, veneer, resin, and PLV to the plant; for cradle-to-gate LCIs (Puettmann and Wilson 2005).

MANUFACTURING ENERGY

Energy production for the manufacturing of LVL comes from electricity, natural gas, diesel, and liquid petroleum gas (LPG). Electricity is used to operate the lay-up and hot-pressing equipment, as well as pneumatic and mechanical conveying equipment, fans, and other equipment in the plant. Natural gas is used for the purpose of generating heat for the presses in the LVL plants. The diesel is used for equipment, which transports materials outside of the plant, and the LPG is used in forklift trucks, which are operated inside the plant. Other types of fuels are used to generate energy in the plywood plants that produce dry veneer and PLV. These energy sources are not analyzed in this report, but the burdens that are created are carried over into the data through their respective SimaPro models. For an analysis of wood fuel and other energy

TABLE 5. *Life-cycle inventory (LCI)[1] outputs to produce LVL. All weights are on an oven-dry or solids basis.*

	PNW LVL		SE LVL	
	$kg/10^3m^3$	lb/MCF	$kg/10^3m^3$	lb/MCF
Product				
Laminated Veneer Lumber	5.29E + 05	3.03E + 04	6.06E + 05	3.78E + 04
Co-products				
Sawdust	8.23E + 03	5.14E + 02	4.35E + 03	2.72E + 02
Veneer loss	7.54E + 03	4.71E + 02	1.11E + 04	6.94E + 02
Lay-up scrap	6.02E + 03	3.76E + 02	2.28E + 04	1.42E + 03
Tested LVL	1.35E + 03	8.45E + 01	1.92E + 03	1.20E + 02
Panel trim	6.73E + 02	4.20E + 01	1.60E + 04	9.99E + 02
Raw Materials				
PNW bark on logs	4.80E + 04	3.00E + 03	5.44E + 04	3.40E + 03
PNW logs	4.77E + 05	2.98E + 04	5.44E + 05	3.40E + 04
Coal	7.06E + 03	4.41E + 02	3.50E + 04	2.19E + 03
Crude oil	6.71E + 03	4.19E + 02	1.11E + 04	6.93E + 02
Limestone	9.38E + 02	5.86E + 01	3.40E + 03	2.12E + 02
Natural gas	2.22E + 04	1.38E + 03	3.88E + 04	2.42E + 03
Uranium	3.67E + 02	2.29E + 03	1.79E + 01	1.12E + 02
Wood/wood waste fuel[2]	9.23E + 03	5.76E + 02	2.40E + 04	1.50E + 03
Wood fuel (biomass)[3]	1.33E + 05	8.33E + 03	1.62E + 05	1.01E + 04
Electricity	$MJ/10^3m^3$	Btu/MCF	$MJ/10^3m^3$	Btu/MCF
Electricity from other sources	6.52E + 03	1.75E + 05	1.90E + 04	5.11E + 05
Electricity from hydro power	4.40E + 05	1.18E + 07	9.90E + 03	2.26E + 05
Water Usage	$kg/10^3m^3$	lb/MCF	$kg/10^3m^3$	lb/MCF
Municipal Water Source	2.19E + 05	1.37E + 04	9.73E + 04	6.08E + 03
Recycled Water	7.37E + 02	4.60E + 01	3.13E + 03	1.95E + 02
Well Water Source	6.57E + 04	4.10E + 03	2.11E + 05	1.32E + 04

[1] Includes burdens for manufacturing dry veneer and PLV as inputs to LVL process.
[2] Tracked separately; wood/waste fuel purchased by plywood plants for fuel.
[3] Tracked separately; wood and bark fuel generated and combusted for heat during plywood manufacturing.

sources for dry veneer and PLV (plywood) production for PNW and SE regions, see Wilson and Sakimoto (2004).

In order to make an accurate and complete LCI for LVL production, it is necessary to know what fuel sources contribute to electricity production in each region. The breakdown for each region is given in Table 6. The different energy sources used to generate electricity will have very different emissions, which factor into the LCI model. The source of the data was the U.S. Department of Energy (USDOE 2001). In 2000, the dominant form of fuel source in the PNW region was hydroelectric, which made up 74.3% of the total, followed by natural gas at 12.3%. There is no burden for hydro-generated electricity in the Franklin database used to determine impacts. In the SE, there are dramatic differences in the way that electricity is generated. For example in the SE, the leading fuel source in 2000 was coal at 45.6% followed by nuclear at 21.6%. A complete breakdown of fuel source by state to produce electricity in each region is given in Wilson and Sakimoto (2004). As with other resources, the electricity burdens are assigned to the LVL product in the SimaPro model on a mass-based allocation. The electricity val-

TABLE 6. *Breakdown of generation of electricity by fuel sources as defined by USDOE (2001).*

	Percentage share, 2000	
Fuel source	PNW	SE
Coal	8.1	45.6
Petroleum	0.3	4.5
Natural gas	12.3	23.0
Nuclear	4.0	21.6
Hydro	74.3	1.8
Others	1.1	3.5
Total	100	100

ues given as inputs to the LCI models are for total electricity use, allocation occurs within the model analysis.

The amount of energy used in the production of LVL was studied in terms of the energy content of the fuels and electricity consumed at the facility, and the cumulative energy content of fuels used to produce and deliver the fuels, electricity, and resin. For both cases the higher heating value (HHV) of the fuels was used to determine their energy content. When comparing energy use for LVL to other materials and processes, HHV values should be used for these materials too; however, if the comparative materials used the lower heating value (LHV), then the energy use for manufacturing LVL should be redone using LHV. Table 7 gives the on-site energy consumed to produce a functional unit of LVL; this is the total, unallocated amount of fuel and electricity consumed in the process. The energy values are based on the on-site fuel and electricity uses given in Table 3. The calculations consider only the energy content of combustion and do not consider the efficiency of producing and delivering the fuels. Likewise, the electricity was a direct conversion to energy, not considering the fuel inefficiency of combustion to produce the electricity and did not consider the line loss during delivery. The energy consumption was much smaller for the PNW than the SE since the PNW used a significant amount of PLV, which reduces the amount of energy needed in the hot-pressing operation for the LVL process.

To determine the allocated, cumulative energy use, the amount of fuel and undefined electricity consumed for the production of LVL from the input logs through production of LVL, the LCI output given in Table 5 was used. These values included the burdens for producing dry veneer and PLV, as well as those for producing LVL. Table 8 gives the energies based on HHVs of the fuels and the energy for electricity. This energy includes all fuels and feedstock for the cumulative system boundary. The electricity from hydro and other sources (undefined) that did not use primary fuels were determined at 3.6 MJ/kWh. The SE region consumed more energy for two basic reasons; one was the nature of the wood being processed in that more water needs to be dried from the wood, and another was the greater use of fossil fuels for producing electricity. The PNW uses a large amount of hydro-generated electricity that is taken at 100% efficiency when determining energy value, whereas fossil fuel efficiency to produce electricity is only at about 30% requiring more fuel to obtain equivalent energy.

LIFE-CYCLE INVENTORY

The life-cycle inventory output for producing LVL is given in Table 5 for product, co-product, raw materials, electricity, and water usage, and in Table 9 for emissions to air, water, and land. For a detailed listing of all outputs, see Wilson and Dancer (2004). The analysis does not include the impacts for production and delivery of logs to produce the dry veneer and PLV, or the transportation of materials to the plywood and

TABLE 7. *Fuel and electricity energy[1] use at the LVL plant site; both unallocated and allocated to LVL on a mass basis.*

	Unallocated energy use at LVL plant				Allocated energy use at LVL plant			
	PNW on-site energy		SE on-site energy		PNW on-site energy		SE on-site energy	
	$MJ/10^3m^3$	Btu/MCF	$MJ/10^3m^3$	Btu/MCF	$MJ/10^3m^3$	Btu/MCF	$MJ/10^3m^3$	Btu/MCF
Fuel use								
Natural gas	1.45E + 05	3.89E + 06	4.12E + 05	1.11E + 07	1.38E + 05	3.72E + 06	3.77E + 05	1.01E + 07
LPG	9.25E + 03	2.48E + 05	1.25E + 04	3.34E + 05	8.84E + 03	2.37E + 05	1.14E + 04	3.06E + 05
Diesel	6.53E + 03	1.75E + 05	1.40E + 04	3.75E + 05	6.24E + 03	1.67E + 05	1.28E + 04	3.43E + 05
Electrical use								
Electricity	2.11E + 05	5.66E + 06	2.44E + 05	6.55E + 06	2.02E + 05	5.41E + 06	2.23E + 05	5.99E + 06
Total	3.72E + 05	9.97E + 06	6.83E + 05	1.83E + 07	3.55E + 05	9.54E + 06	6.24E + 05	1.67E + 07

[1] Energy values were determined for the fuels using their higher heating values (HHV) in units of MJ/kg as follows: diesel 44.0, liquid petroleum gas (LPG) 54.0, and natural gas 54.4. Electricity was calculated as 3.6 MJ/kWh.

TABLE 8. *Allocated, cumulative energy[1] use to produce LVL.*

	Energy Use			
	PNW LVL		SE LVL	
	$MJ/10^3m^3$	BTU/MCF	$MJ/10^3m^3$	BTU/MCF
Renewable fuel use				
Wood fuel (biomass)[2]	1.49E + 06	4.01E + 07	1.95E + 06	5.24E + 07
Non-renewable fuel use				
Coal	1.85E + 05	4.97E + 06	9.19E + 05	2.47E + 07
Crude oil	3.05E + 05	8.20E + 06	5.05E + 05	1.36E + 07
Natural gas	1.21E + 06	3.24E + 07	2.10E + 06	5.64E + 07
Uranium	1.40E + 04	3.75E + 05	6.78E + 04	1.82E + 06
Electricity use				
Electricity from hydro power	4.40E + 05	1.18E + 07	9.87E + 03	2.65E + 05
Electricity from other sources	6.53E + 03	1.75E + 05	1.90E + 04	5.10E + 05
Total	3.65E + 06	9.80E + 07	5.57E + 06	1.50E + 08

[1] Energy values were determined for the fuels using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, crude oil 45.5, diesel 44.0, liquid petroleum gas (LPG) 54.0, natural gas 54.4, and wood oven-dry 20.9. Uranium energy determined at 381,000 MJ/kg and electricity at 3.6 MJ/kWh.

[2] Wood fuel includes both categories of wood fuel and wood/bark waste fuel; oven-dry weight.

TABLE 9. *Life-cycle inventory results for production of LVL; gives the allocated, cumulative emissions.*

	PNW LVL		SE LVL	
	$kg/10^3m^3$	lb/MCF	$kg/10^3m^3$	lb/MCF
Emissions to air				
Acetaldehyde	6.25E + 00	3.90E − 01	4.43E − 01	2.77E − 02
Acrolein	5.25E − 04	3.27E − 05	4.53E − 03	2.83E − 04
CO	1.09E + 03	6.81E + 01	1.60E + 03	1.00E + 02
CO_2 (biomass)	1.31E + 05	8.18E + 03	1.71E + 05	1.06E + 04
CO_2 (fossil)	5.95E + 04	3.71E + 03	1.55E + 05	9.68E + 03
CO_2 (non-fossil)	9.64E + 03	6.02E + 02	2.51E + 04	1.57E + 03
Formaldehyde	2.02E + 01	1.26E + 00	1.58E + 01	9.88E − 01
Methane	1.77E + 02	1.10E + 01	4.16E + 02	2.59E + 01
Methanol	6.59E + 01	4.12E + 00	4.98E + 01	3.11E + 00
NO_x	5.29E + 02	3.30E + 01	1.01E + 03	6.31E + 01
Particulates	1.95E + 02	1.22E + 01	6.09E + 01	3.80E + 00
Particulates (PM10)	1.21E + 02	7.56E + 00	3.14E + 01	1.96E + 00
Particulates (unspecified)	1.87E + 01	1.17E + 00	9.00E + 01	5.62E + 00
Phenol	1.65E + 01	1.03E + 00	2.06E + 01	1.29E + 00
SO_x	8.69E + 02	5.43E + 01	1.89E + 03	1.18E + 02
VOC	3.19E + 02	1.99E + 01	3.95E + 01	2.47E + 00
Emissions to water				
BOD	1.15E + 00	7.18E − 02	1.99E + 00	1.24E − 01
Cl-	5.35E + 01	3.34E + 00	9.39E + 01	5.86E + 00
COD	1.05E + 01	6.57E − 01	1.79E + 01	1.12E + 00
Dissolved solids	1.17E + 03	7.32E + 01	2.04E + 03	1.28E + 02
Oil	2.08E + 01	1.30E + 00	3.66E + 01	2.28E + 00
Suspended solids	1.86E + 01	1.16E + 00	6.70E + 01	4.18E + 00
Emissions to land				
Solid waste	1.12E + 04	7.00E + 02	2.80E + 04	1.75E + 03

LVL plants. The manufacturing of dry veneer and PLV is included in the cumulative system boundary of this study. For some of the plants, the system boundary represented the plant boundary, but in other cases this was not the case. The results were generated using SimaPro LCI software with the Franklin database (FAL 2001) for fuel use and electricity production burdens for their production. Emissions related to the production of resin were obtained from ATHENA (1993). All other data are based on survey data obtained from manufacturing facilities in each region. The CO_2 emissions are given in three categories based on their fuel source; combustion of biomass, fossil fuel, and non-fossil fuel that is most likely biomass. The non-fossil fuel data come from the Franklin database. The biomass (wood and bark hogged fuel) comes from the production models for dry veneer and PLV. Biomass and fossil fuel generated CO_2 are tracked separately since biomass CO_2 is considered to have a neutral impact on global warming as a result of greenhouse gases, whereas the fossil fuel CO_2 contributes significantly to global warming (EPA 2003). For the production of LVL in the PNW, CO_2 generated as a result of biomass and non-fossil fuel combustion is 70% of the CO_2 cumulative emissions. For LVL produced in the SE region, CO_2 biomass and non-fossil are 56% of the cumulative CO_2 emissions. No biomass was combusted at the LVL site; it was used as fuel at the plywood plants to produce dry veneer and PLV.

CARBON BALANCE

The biogenic carbon flow through the LVL production process is given in Table 10. Wood is commonly considered a storage place for carbon. In order to perform the carbon balance, it was necessary to quantify the amount of carbon in the wood inputs and the carbon in the wood-related outputs. The outputs in this case include waste and emissions as well as the finished product and co-products. The percentage of carbon in wood was taken from studies done by Birdsey (1992) and Skog and Nicholson (1998). The amount of carbon in wood is specific to each species of wood, but is about 50% by weight for most cases. In the PNW the only veneer species considered was Douglas-fir. However, there was the PLV input that had to be addressed as well. For the sake of simplicity and consistency, the PLV input was treated as being Douglas-fir material with the same carbon percentage as the veneer. The density data for dry veneer and plywood as PLV were taken from Wilson and Sakimoto (2004). The density of veneer was taken as 481 kg/m^3 and 551 kg/m^3 for the PNW and SE, respectively. For the PLV the density was taken as 486 kg/m^3 without resin. The inputs were allocated based on their percentage of the total amount of input into the system. For a complete breakdown of the densities and weight contribution of product for the carbon flow calculation, see Wilson and Dancer (2004). The percentage of carbon for the various air emissions was determined using the atomic mass of each element from their chemical formula.

Table 10 gives the biogenic carbon flow that is wood-based from the input to the output. The values are based on the mass balance of wood into and out of the plant and on the reported emissions for the plant. Most of the carbon occurs in the product (95.6% and 91.3% for PNW and SE, respectively) compared to that stored in the co-product (4.4% and 8.7% for PNW and SE, respectively), and an insignificant quantity of carbon (close to 0%) occurs in the air emissions. For 1000 m^3 of LVL, 263,000 kg and 287,000 kg of biogenic carbon are stored for product produced in the PNW and SE regions,

TABLE 10. *Biogenic carbon balance, tracking flow of wood carbon through the LVL manufacturing process.*

Substance	PNW		SE	
	kg/10^{3}m^3	lb/MCF	kg/10^{3}m^3	lb/MCF
Input				
Wood-based material	2.53E + 05	1.58E + 04	2.98E + 05	1.86E + 04
Output				
LVL product (wood only)	2.63E + 05	1.64E + 04	2.87E + 05	1.79E + 04
Co-products	1.20E + 04	7.49E + 02	2.72E + 04	1.70E + 03
Emissions to air	1.29E + 01	8.05E + 01	3.22E + 01	2.01E + 00
Total	2.75E + 05	1.71E + 04	3.14E + 05	1.96E + 04

respectively. It is significant to track this stored carbon since it represents CO_2 removed from that atmosphere and not available for contributing to the greenhouse gas effect and global warming. For every 1.0 kg of carbon in wood products, it represents 3.67 kg of CO_2 removed from the atmosphere; therefore, for 1000 m^3 of LVL there is 965,000 kg and 1,053,000 kg of CO_2 removed for the PNW and SE regions, respectively.

CONCLUSIONS

A study was conducted of the life-cycle inventory of the manufacture of laminated veneer lumber. To collect production data of all inputs and outputs from the plants, surveys were conducted in 2001 of two mills in each of the two major production regions of the U.S.: the Pacific Northwest and Southeast. The production of these plants represented 33% and 52% of total production for PNW and SE regions, respectively. The data were found to be of high quality based on comparisons of data between plants and regions, and upon mass and energy balances. Input data consisted of dry veneer, parallel laminated veneer (PLV), fuels, electricity, and phenol-formaldehyde resin, while outputs consisted of LVL product, a variety of wood co-products sold to other manufacturers, and emissions to air, water, and land. Impacts were also considered for the production of dry veneer and PLV, examining impacts from the input of resin, fuels, and electricity through their production.

LVL production is very consistent in both regions with the notable exception of one plant in the PNW. All but one of the plants used dried veneer as an input material; the one exception used parallel laminated veneer (PLV) panels as an input. None of the surveyed plants dried veneer on site, which is not always the case in LVL manufacturing. However, the results are the same as if green veneer were an input since environmental burdens for producing green veneer (data are cumulative) are included within the production impacts of the dry veneer and the PLV. The process of drying veneer is the same between plywood and LVL operations except that the fuel source may differ between operations.

The production of LVL contributes relatively small amounts of emissions when compared to the production of input products such as resin, dry veneer, PLV, fuel, and electricity. LCI results for each region that include only emissions generated at the LVL manufacturing facility demonstrate the small amount of emissions actually attributable to the LVL process.

The cumulative boundary system looked at the environmental impacts of manufacturing LVL from the logs used to make either the dry veneer or PLV, through their input into the production of the LVL. The LCI data are presented on the functional production unit of 1000 m^3 and 1.0 MCF, the U.S. industry product unit. The impacts included the production and delivery of electricity and fuel, and the production of resin. Transportation distances of materials to the plants are given. To obtain a complete cradle-to-gate LCI analysis for LVL, the LCI data for logs, and the transportation of logs, PLV, veneer, wood fuel and resin based on recorded distances, would have to be added to the gate-to-gate LCI data provided in this study.

Energy use for manufacturing LVL at the plant site is dominated by the combustion of natural gas and electricity use. However, when considering the fuel use for producing the dry veneer and PLV, the dominant fuel is wood fuel (biomass fuel) comprised of wood and bark waste generated during their manufacture. Wood fuel for the PNW and SE regions, respectively, represented 41% and 35% of the allocated, cumulative fuel use, which included fuel to produce and transport electricity, fuels, and resin, and the feedstock to produce resin, as well as fuels combusted on site and the electricity. Wood fuel contributes 70% and 56% of the CO_2 produced due to the combustion of fuels for the cumulative boundary condition for PNW and SE regions, respectively. This is beneficial in that the wood-derived CO_2 is considered to have a neutral impact on global warming and greenhouse gases in that it can be up taken by the forest ecosystem, storing carbon in the wood and releasing oxygen to the atmosphere, whereas combustion of fossil fuels generates CO_2 that contribute to both global warming and greenhouse gases (EPA 2003). Energy to produce the electricity varied significantly between the two production regions, with the PNW heavily dependent upon hydro generation, while the SE was dependant upon coal, oil, and nuclear fuels. Resins used to bond the veneers together to produce LVL were also dependent upon fossil fuels for both energy and feedstock.

Carbon studies were conducted to track carbon from the input materials through production of LVL, co-products, and emissions. Only carbon related to wood was tracked since this sequestered carbon could be seen as avoiding the formation of CO_2 that could be released to the atmosphere. Wood-based materials are about 50% carbon, whether it is in a product such as LVL or a co-product such as sawdust and trim that eventually are converted into other wood products for the consumer. Of the output wood material from the process, LVL contains 95.6% and 91.3% of the total biogenic carbon, with 263,000 kg and 287,000 kg for the PNW and SE, respectively. This represents 965,000 kg and 1,053,000 kg of CO_2 removed from the atmosphere per 1000 m^3 of LVL, respectively.

The LCI data for LVL are made available for public access through this publication and the U.S. LCI Database (NREL 2005), which is a database for all major materials and manufacturing processes in the U.S.

ACKNOWLEDGMENT

This research project would not have been possible without the financial and technical assistance provided by the USDA Forest Service, Forest Products Laboratory (JV1111169-156), DOE's support for developing the research plan (DE-FC07-961 D 13437), CORRIM's University membership, and the contributions of many companies. Our special thanks are extended to those companies and their employees that participated in the surveys to obtain production data. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the contributing entities.

REFERENCES

APA—The Engineered Wood Association (APA). 2001. E-mail from Craig Adair, Director, Market Research. North America production by geography 2000. (16 Nov 01). 1 p.

ATHENA™ Sustainable Materials Institute (ATHENA). 1993. Raw materials balances, energy profiles, and environmental unit factor estimates: Structural wood products. Forintek Canada Corp, Ottawa, Canada. March. 42 pp.

Birdsey, R. A. 1992. Carbon storage and accumulation in United States forest ecosystems. Forest Service, General Technical Report WO-59. United States Department of Agriculture. Washington, DC. 51 pp.

Bowyer, J., D. Briggs, B. Lippke, J. Perez-Garcia, and J. Wilson. 2004. Life cycle environmental performance of renewable building materials in the context of residential construction. CORRIM Phase I Final Report. University of Washington, Seattle, WA. http://www.corrim.org/reports/. 600+ pp.

Briggs, D. 1994. Forest products measurements and conversion factors: With special emphasis on the U.S. Pacific Northwest. Institute of Forest Resources. College of Forest Resources, University of Washington. Seattle, WA. Contribution No. 75. 161 pp.

Consortium for Research on Renewable Industrial Materials (CORRIM). 2001. Research Guidelines for Life Cycle Inventories. CORRIM, Inc. University of Washington, Seattle, WA. Apr. 47 pp.

Forest Products Laboratory (FPL). 1999. Wood handbook: Wood as an engineering material. Agric. Handbook. 72 Washington, DC: USDA Forest Service, Forest Products Laboratory. Madison, WI. 463 pp.

Franklin Associates LTD (FAL). 2001. The Franklin Associates Life Cycle Inventory Database. SimaPro5 Life-Cycle Assessment Software Package, version 36. http://www.pre.nl/download/manuals/DatabaseManualFranklinUS98.pdf. (11 May 01).

International Organization for Standardization (ISO). 1997. Environmental management—life cycle assessment—principles and framework. ISO 14040. First Edition 1997-06–15. Geneva, Switzerland. 16 pp.

———. 1998. Environmental management—life cycle assessment—goal and scope definition and inventory analysis. ISO 14041. First Edition 1998-10-01. Geneva, Switzerland. 26 pp.

Lippke, B., J. Wilson, J. Perez-Garcia. J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Prod. J. 54(6):8–19.

National Council of the Paper Industry for Air and

Stream Improvement, Inc. (NCASI). 1999. Volatile organic compound emissions from wood products manufacturing facilities, Part II – Engineered wood products. Technical Bulletin No. 769. Research Triangle Park, N.C. 46 pp.

National Renewable Energy Laboratory (NREL). 2005. Life-cycle inventory database project. http://www.nrel.gov/lci/. (31 May 05).

Neuvonen, E., M. Salminen, J. Heiskanen, M. Hochstrate, and M. Weber. 1998. Laminated veneer lmber: Overview of the forest product, manufacturing, and marketing situation. Kymenlaakson Ammattikorkeakoulu. Department of Forest Products Marketing, Wood Based Panels Technology. http//www.hochstrate.de/micha/reports/replvl.html. (25 Oct. 02).

Perez-Garcia, J., B. Lippke, D. Briggs, J. Wilson, J. Bowyer, and J. Meil. 2005. The Environmental Performance of Renewable Building Materials in the Context of Residential Construction. Wood Fiber Sci. This Special Issue.

PRe' Consultants. 2001. SimaPro5 Life-Cycle Assessment Software Package, Version 5.0.009. Plotter 12, 3821 BB Amersfoort, The Netherlands. http//www.pre.nl. (01 Oct 03).

Puettmann, M. E., and J. B. Wilson. 2005. Life-cycle analysis of wood products: Cradle-to-Gate LCI of residential building materials. Wood Fiber Sci. This Special Issue.

Skog, K. E., and G. A. Nicholson. 1998. Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. Forest Prod. J. 48(7/8): 75–83.

United States Environmental Protection Agency (EPA). 2003. Wood waste combustion in boilers 20 pp, *in* AP 42, Fifth Edition, Volume I Chapter 1: External combustion sources. http://www.epa.gov/ttn/chief/ap42/ch01/index.html.

United States Department of Energy (USDOE). 2001. State electricity profiles 2000. http:www.eia.doe.gov/cneaf/electricity/st_profiles/. (01 Oct 03).

Wilson, J. B., and E. R. Dancer. 2004. Laminated veneer lumber manufacturing. *In* CORRIM Phase I Final Report Module H. Life cycle environmental performance of renewable building materials in the context of residential construction. University of Washington, Seattle, WA. http://www.corrim.org/reports/. 92 pp.

———, and E. T. Sakimoto. 2004. Softwood plywood manufacturing. *In* CORRIM Phase I Final Report Module D. Life-cycle environmental performance of renewable building materials in the context of residential construction. University of Washington, Seattle, WA. http://www.corrim.org/reports/. 96 pp.