Cradle to Gate Life Cycle Assessment of Softwood Plywood Production from the Pacific Northwest

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1 Background

CORRIM, the Consortium for Research on Renewable Industrial Materials, has derived life cycle inventory (LCI) data for major wood products and wood production regions in the United States. The life cycle inventory data cover all stages of processing from forest regeneration through to final product at the mill gate. Research has covered nine major forest products including both structural and nonstructural uses and four major regions: in this report we focus on softwood plywood produced in the US Pacific Northwest (PNW) region. The PNW regional data is a representative cross-section of forest growth and manufacturing processes for western Washington and Oregon. This document updates the current plywood LCI's from a gate to gate to a cradle to gate LCI. Updates include the addition of PNW forestry operations, and boiler, resin, and electrical grid data that have been developed since the original mill surveys were conducted in 1999 and 2000. The updated LCI data were used to conduct life cycle impact assessments (LCIA) using the North American impact method, TRACI 2.0 (Simapro version 4.0) (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare et al. 2011). These updates are necessary for the development of environmental product declarations (EPD) which will be based on this document. This document originates from the CORRIM LCI report by Wilson and Sakimota (2004 and 2005) and Johnson et al. (2005). Data updates in this report from the original Wilson and Sakimoto LCI report include: wood combustion boiler updates, electricity grid updates (Goemans 2013), and resin data to reflect average US resin production (Wilson 2009) and a cradle to grave LCIA. The functional unit is 1 m^3 (for conversion of units to the US Industry standard, 0.8849m^3 is equal to 1000 square feet, 3/8-inch basis)) of softwood plywood. Updates to the forestry operations report include electricity grid updates and an LCIA using the TRACI method. This report follows data and reporting requirements as outlined in the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (PCR 2011) that will provide the guidance for preparation of North American wood product EPD. This report does not include comparative assertions.

2 Introduction

The goal of this work is to determine energy and material inputs and outputs associated with the production of softwood plywood from the manufacturing base located in the Pacific Northwest region of

North America. These data are needed for the inclusion of the production process in life cycle analyses of wood. The data were obtained through a scientifically sound and consistent process established by the Consortium for Research on Renewable Industrial Materials (CORRIM), following ISO14040 standards (ISO 2006).

The scope of this study includes cradle to gate LCIs based on primary data for softwood plywood from logs using practices and technology common to the PNW region. The logs are obtained from the forest resource base located in western Washington and Oregon as representative of the region. Data for the LCA are based on manufacturing gate to gate LCI's from CORRIM reports (Wilson and Sakimoto 2004) and forest resources cradle to gate LCI's specific to the region (Johnson et al. 2005). The report does not consider the impact of how the wood was used which requires a comparison to the impact of substitute products.

3 Description of Product

Softwood plywood has had a long tradition as a structural building material for both commercial and residential construction. Plywood is used as structural sheathing for roofs, walls and flooring, and for sub-flooring applications in home construction, furniture, and cabinet panels. Plywood is also used as a component in other engineered wood products and systems in applications such as prefabricated I-joists, box beams, stressed-skin panels, and panelized roofs. Plywood is a panel product built up wholly or primarily of sheets of veneer called plies (Figure 1). Softwood plywood in the US is produced by peeling logs into veneer sheets, drying the veneer, applying resin (phenol-formaldehyde) to the veneer sheets, and stacking sheets together, typically with alternating grain orientation. The veneer stacks are put into a hot press where pressure and heat are used to provide contact and curing, and the cured panel is then removed and sawn to standard sizes, with 1.22 × 2.44 meters (4 × 8 feet) sheets being the most common. Plywood is made from various species: in the PNW, it is made primarily from Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), with other species such as spruce *(Picea spp.)* and western larch (*Larix spp.*) also used in lesser quantities. The total softwood plywood production in 2000 for the US was 15,464,000 m^3 (17,475,000 thousand square feet (MSF) 3/8-inch equivalence) (APA 2001). This production represents 59% of structural panel production in the U.S., with the remainder being oriented strandboard (OSB).

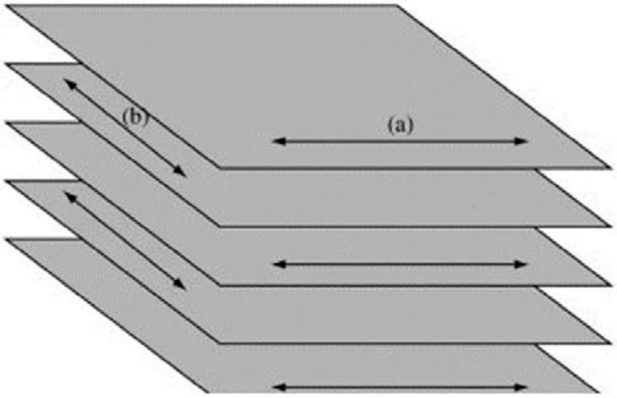

Figure 1 Position of layers in plywood

3.1 Functional and declared unit

In accordance with the PCR (2011), the declared unit for plywood is one cubic meter (1.0 m^3). A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated (PCR 2011). For conversion of units from the US industry measure, 1.0 MSF (1000 square feet) is equal to 0.8849 m^3. All input and output data were allocated to the declared unit of product based on the mass of products and co-products in accordance with International Organization for Standardization (ISO) protocols (ISO 2006). As the analysis does not take the declared unit to the stage of being an installed building product no service life is assigned.

3.2 System Boundaries

The system boundary begins with regeneration of forest in the PNW (Johnson et al. 2005) and ends with softwood plywood packaged to leave the mill gate. The forest resources system boundary includes: planting the seedlings, forest management which included site preparation, thinning, and fertilization on a subset of hectares, and final harvest. The transportation of logs from the woods to the mill is accounted for with the plywood manufacturing (Figure 2). Seedlings and the fertilizer and electricity it took to grow them were considered as inputs to the system boundary. The plywood manufacturing complex was divided into eight process units: transportation, debarking and bucking, log conditioning, log peeling, veneer drying, panel pressing, trimming, and energy generation (Figure 2). Separating the LCI into these unit processes is necessary to ensure accurate allocation of burdens among co-products as some of them leave the manufacturing facility at various stages of processing resulting in changes to allocation of burdens among as the end products moves through the unit processes. This is particularly critical prior to drying which is the unit process that has the most significant environmental load. Outputs to the system boundary include 1 m^3 of plywood ready to be shipped, air and water emissions, solid waste and small volumes of co-products (chips and sawdust). The co-products are no longer tracked once they leave the system boundary.

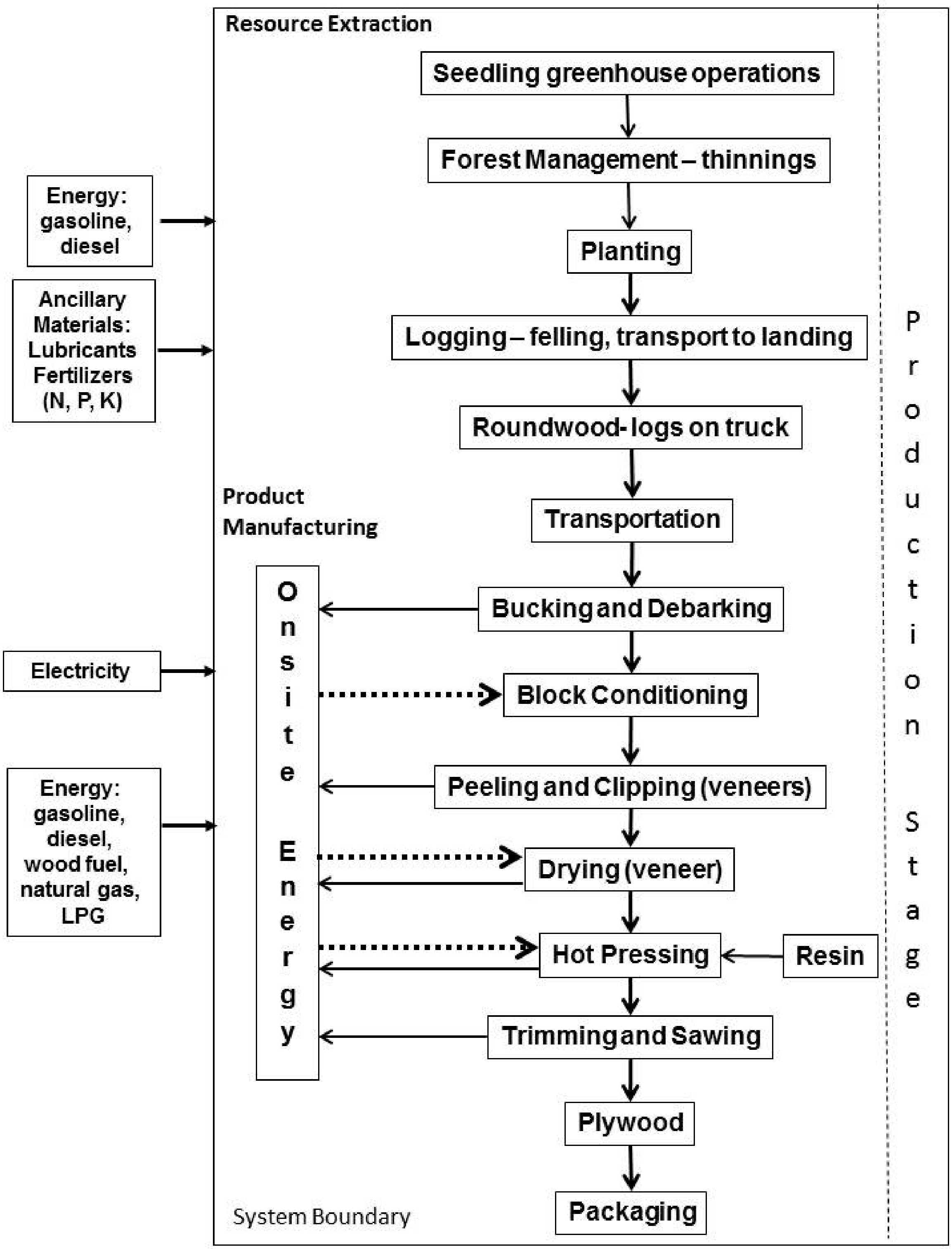

Figure 2 Processes included in the cradle to gate LCA for PNW softwood Plywood.

3.3 Description of data/Process Description

3.3.1 Forestry Operations

Forestry operations include growing seedlings, planting, thinning, fertilization (where applicable) and final harvest. The specific processes involved are reforestation: which includes seedling production, site preparation, planting, pre-commercial thinning, and fertilization, and harvesting: which includes felling, skidding, processing, and loading for both commercial thinning and final harvest operations. Weighted average allocation to different processes takes into account inherent differences in site productivity and energy usage by different kinds of logging equipment. Inputs to the forest resources management LCI include seed, electricity used during greenhouse operations, fertilizer used during seedling production and stand growth, and the fuel and lubricants needed to power and maintain equipment for thinning, and harvest operations. The primary output product for this analysis is a log destined for the plywood mill. The co-product, non-merchantable slash, is generally left at a landing. Slash disposal was not modeled as it was assumed to decay in-situ.

Logs used in the production of softwood plywood in the PNW include in their life cycle the upstream activities associated with establishment, growth, and harvest of trees (Figure 2). This group of activities is collectively referred to as forest resource management. The forest resource management life cycle stages includes the efforts required to establish a forest stand, to treat that stand through to maturity, and to harvest the merchantable logs from the stand. Stand establishment involves planting seedlings. Intermediate stand treatments enhance growth and productivity while the stand is growing and can involve thinning, fertilization, or both. Only 12% of stands in the PNW have fertilizer applications, while 58% have thinning operations.

In the PNW most harvested volume comes from forest operations on private lands where investment in timber is the precursor to harvest. For all non-federal land managers in the region, reforestation is a statutory requirement as harvests are administered under state forest practices acts. Harvested lands are reforested for the next crop cycle with the sequence of treatments from planting to harvest averaging 45 years. Forestry operations and their associated impacts are not stationary and will change based on both past and prospective technologies, evolving forest management procedures, and market demands. Given that the nature of productivity gains is not confirmed or well developed, this assessment was based on data representing the current state of the art in forest operations: it does not discount future operations or estimate potential productivity gains from future technologies. Outputs representing quantities of product, measures of consumed resources, and the emissions associated with those consumed resources were developed as a weighted average across the hectares managed for timber production. These quantities of product are used as inputs to the wood product manufacturing LCI and the consumed resources and emissions are tracked for inclusion in the cradle to gate LCI.

The forest resource management LCI was structured from three general combinations of management intensity and site productivity (Table 1). Management intensities ranged from little intervention on low site productivity lands to higher management intensities involving combinations of fertilization and thinning on high productivity lands. Associated with each combination of management intensity and site productivity is an estimated yield of biomass based on forest growth and yield generated using the Forest Vegetation Simulator (FVS) growth and yield model (Wykoff 1986). FVS is developed from empirical data on forest growth and provides a reasonable estimate of standing and harvested biomass along with other stand attributes through time from seedling establishment to final harvest of the forest stand at rotation age.

3.3.1.1 Regeneration (seedling production and planting process)

Environmental burdens associated with the production of seedlings including fertilizer used in greenhouses or fields, and the electrical energy required to operate forest nursery pumps and to keep seedlings cool for planting were included as inputs to the regeneration process (Table 1). Greenhouse operations data for the PNW were developed from personal communication with forest nursery managers (Wenny 2003) and published documentation of greenhouse operations for containerized seedlings (Schlosser et al. 2003). All seedlings in the PNW were planted by hand. The only energy inputs associated with planting were related to travel to and from the planting site.

Stand treatment operations were based on growth and yield modeling and management scenarios developed at the University of Washington (Lippke and Comnick 2002). Based on that input, fertilization occurred once seedlings were planted in the forest for the subset of hectares that were in higher management intensities. Fertilization was done in years 20, 30, and 40 on acres in the high-intensity management class and the environmental burdens associated with these efforts are included as part of the reforestation process. The fertilizer mixture included nitrogen, potassium, and phosphorus.

Table 1 Inputs to the regeneration phase and mid-rotation fertilization per hectare (ha) of forest.

		Low intensity	**Medium intensity**	**High intensity**	**Weighted Average**
		Reforesting 1 ha			
Diesel and Gasoline	L	12	12	12	12
Seedlings, at greenhouse	p[1]	988	1,482	1,482	1,275
Nitrogen in fertilizer					
In Seedlings	kg	0.04	0.06	0.06	0.05
On Site	kg	-	-	396.78	47.61
Phosphorous in fertilizer		-	-	-	-
In Seedlings	kg	0.07	0.11	0.11	0.09
On Site	kg	-	-	67.25	8.07
Potassium in fertilizer		-	-	-	-
In Seedlings	kg	0.17	0.26	0.26	0.22
On Site	kg	-	-	-	-

[1] p = individual seedling

3.3.1.2 Equipment

Timber harvesting activities include four components: felling (severing the standing tree from the stump), processing (bucking, limbing and/or topping) which involves removal of non-merchantable limbs and tops and cutting of the tree into merchantable and transportable log lengths, secondary transportation (called skidding on gentle slopes and yarding on steep slopes), which is a transportation step that moves trees or logs from the point of felling to a loading point near a haul road, loading (moving logs from the ground to haul vehicles). Although all functions are required to remove logs from the woods, the specific order and location of the operations will vary by harvesting system as cable yarding systems used in steep terrain have the processing step occur prior to the secondary transport step. A fifth step, primary transportation, includes hauling logs from the woods to a manufacturing location and it is included in the LCI for the primary manufacturing facility.

Although harvesting operations in the PNW can be found on both gentle and steep terrain, they are more likely to involve steep slope conditions that dictate the use of manual felling and cable yarding harvest systems, therefore that system is modeled for the PNW region. Cable yarding systems rely on manual felling and transporting the logs up the hill using a long cable attached to a large woods tractor with a tall boom (a cable yarder). Most final harvest operations in the PNW use clearcut harvests with retention of a minimum number of trees to meet statutory green tree retention requirements. Operations under these conditions are modeled using production rates for clearcut systems.

Variations in harvest equipment size affect machine productivity and therefore emissions per m^3 of logs produced. Harvest equipment operational efficiencies vary between thinning and final harvest (clearcut), which also affects machine productivity and therefore emissions per m^3 of logs produced. To account for these inherent variations, equipment usage was allocated between thinning operations and final harvest for those management regimes that use thinning (Table 2).

Table 2 Equipment allocation by treatment and management intensity

Management Intensity	Thinning	Final Harvest (usage per final volume harvested)
Low intensity site		
Chain saw	NA	100%
Cable yarder, large	NA	100%
Loader	NA	100%
Medium intensity		
Chain saw	19.6%	80.4%
Cable yard, medium	19.6%	
Cable yarder, large		80.4%
Loader	19.6%	80.4%
High intensity		
Chain saw	12.6%	87.5%
Cable yard, medium	12.6%	
Cable yarder, large		87.5%
Loader	12.6%	87.5%

3.3.1.3 Thinning and Final Harvest Process

A single estimate of the average volume harvested per unit area was developed by weighting three combinations of site productivity and management intensity (Table 3) based on the relative percentage of the land base they occupy. Site productivity as measured by site index, the height of dominant trees at 50 years, and ownership class was obtained from the U.S. Forest Service Resource Planning Assessment database (USDA 2000, Mills 2001). A combination of these data and expert opinion were used to categorize the number of private forest hectares into management intensity classes. The management intensity and site productivity classes used in the Forest Service analysis were associated with, and were represented by three general management intensity combinations. Specific assumptions associated with these three scenarios are outlined in Table 3. In the PNW, 42% of the lands were classified in the lowest productivity/ management intensity class, 46% in the middle class, and 12% in the highest management intensity class. The allocation of forested area to management intensity/site productivity class produces the log volume recovered from the forest resource as shown in Table 3. Allocating per ha values from Table 1 to the total yield of 501 m^3/ha is used to carry forward the environmental burdens of the reforestation effort on a per m^3 basis.

Table 3 Input assumptions for three levels of management intensity in the PNW.

Management intensity class prescription	**Low Intensity**	**Medium Intensity**	**High Intensity**	**Weighted Average**
	per hectare			
Rotation age (yr)	45	45	45	
Planting density (trees per hectare)	988	1,482	1,482	1,275
Fertilization	None	None	Years 20, 30, 40	
Pre-commercial thinning	None	Year 15	Year 15	
Final thinned density (Trees per hectare)	0	*740*	*680*	
Commercial thinning—m^3	0	81	81	47
at year		*30*	*25*	
Final harvest— m^3	433	409	701	454
at year	*45*	*45*	*45*	
Total yield/hectare - m^3	433	490	782	501
Percent sawlogs	100%	100%	100%	
Percent area in class	42%	46%	12%	

Fuel consumption and energy use for forest resource management processes were averaged by the percent area in each class to develop weighted average values for the PNW region by major process (Table 4).

Table 4 Fuel consumption for PNW forest resource management processes (regeneration, thinning, and harvest).

	Unit	**Fuel Consumption per m^3**
Seedling, Site Prep, Plant, Pre-commercial Thinning		
Diesel and gasoline	L	0.088
Lubricants	L	0.002
Electricity	kWh	0.107
Commercial Thinning and Final Harvest		
Diesel	L	2.850
Lubricants	L	0.051
Total Forest Extraction Process		
Gasoline and Diesel	L	2.938
Lubricants	L	0.053
Electricity	kWh	0.107

3.3.2 Product Manufacturing

3.3.2.1 Transportation Process

Transportation is the first process of product manufacturing (Figure 2). Logs typically arrive at the mill by truck. For the PNW the average haul distance is 97 km (Table 5) from forest landing to plywood production facility. Dry veneer and resin are also delivered to the plywood mill, involving transportation distances of 121 km and 196 km, respectively.

Table 5 Average delivery distance (one-way) for materials to plywood mill, PNW.

Material delivered to mill	Delivery Distance (km)	
	km	**miles**
Logs with bark	97	60
Purchased veneer	121	75
Purchased wood fuel	89	55
Phenol-formaldehyde resin	196	122

3.3.2.2 Energy use and generation

To produce plywood heat and steam are used for conditioning logs, drying veneer, and pressing panels. The boiler processes (energy generation) encompass fuel storage, the boiler, and the steam distribution system. Both wood-fired and natural gas boilers are used by PNW softwood plywood mills (Table 6). For the wood boiler, wood waste from various plywood operations is used for fuel. Inputs include green and dry wood waste and bark generated during debarking (section 3.3.2.3) and trimming (section 3.3.2.9). Outputs include wood fuel on an oven dry basis.

Table 6 Boiler energy requirements for conditioning, drying, and pressing processes used in plywood production for the PNW.

Fuel Inputs	Conditioning	Drying	Pressing
	MJ/m^3		
Wood fuel	223.82	1799.47	339.79
Natural gas	5.83	124.83	30.07
Total	229.64	1924.31	369.86
Percent %	9%	76%	15%

Wood fuel used represented 94% of the total energy requirement for producing plywood with the remainder from natural gas. Veneer drying used the dominant amount of energy for heating (76%), followed by hot pressing (15%) and conditioning (9%) (Table 6). The USLCI database was used for boiler processes inputting natural gas or wood fuel (NREL 2012). These boiler processes are based on the US Environmental Protection Agency (EPA) AP-42, Compilation of Air Pollutant Emission Factors (EPA 1998, 2006). The AP-42 emission factors assume no emission controls and therefore likely over-estimate the impact factors for wood emissions (Table 7).

Table 7 Wood Boiler Process

Product	Value	Unit/m^3
Wood biomass, combusted in industrial boiler	1.00	kg
Materials/fuels	**Value**	**Unit/m^3**
Bark, green	0.5100	kg
Trim waste	0.4874	kg
Wood waste, purchased	0.0026	kg
Emissions to air	**Value**	**Unit/m^3**
Acetaldehyde	7.47E-06	kg
Acrolein	3.60E-05	kg
Antimony	7.11E-08	kg
Arsenic	1.98E-07	kg
Benzene	3.78E-05	kg
Beryllium	9.90E-09	kg
Cadmium	3.69E-08	kg
Carbon dioxide, biogenic	1.76E+00	kg
Carbon monoxide	5.40E-03	kg
Chlorine	7.11E-06	kg
Chromium	1.89E-07	kg
Cobalt	5.85E-08	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1.50E-08	kg
Formaldehyde	3.96E-05	kg
Hydrogen chloride	1.71E-04	kg
Lead	4.32E-07	kg
Manganese	1.44E-05	kg
Mercury	3.15E-08	kg
Metals, unspecified	3.85E-04	kg
Methane	1.89E-04	kg
Methane, dichloro-, HCC-30	2.61E-06	kg
Naphthalene	8.73E-07	kg
Nickel	2.97E-07	kg
Nitrogen oxides	1.17E-04	kg
Nitrogen oxides	1.98E-03	kg
Particulates, > 2.5 um, and < 10um	4.50E-03	kg
Phenols, unspecified	4.59E-07	kg
Selenium	2.52E-08	kg
Sulfur oxides	2.25E-04	kg
TOC, Total Organic Carbon	3.68E-05	kg

Electricity was used in all processes. Electricity was consumed by the debarker, bucker, lathe, pneumatic and mechanical conveying equipment, fans, hydraulic pumps, saws, and a radio-frequency re-dryer (Tables 8-13). Diesel fuel use is attributed solely to log loaders in the "Debarking" sub-unit process

(Table 8). As such, all of the diesel use was assigned to this process. Forklift trucks used small amounts of LPG in one or more of the remaining five sub-unit processes (Tables 8 - 13). This fuel use was assigned evenly over the five sub-unit processes from "Conditioning" to "Trimming and Sawing". That meant 20% of the LPG use and emissions were assigned to each of these operations.

3.3.2.3 Debarking and Bucking

The debarking and bucking process includes mechanically removing the bark from the logs and cutting them to the proper length to make peeler "blocks[1]" (Table 8). Co-products generated include bark and some wood waste. Inputs include electricity to operate equipment and diesel fuel for the log haulers. All flow analyses of wood and bark in the process were determined on an oven-dry weight basis and a green specific gravity[2] of 0.437.

Table 8 Unit process inputs/outputs for debarking and bucking to produce 1 m^3 of debarked-bucked log for softwood plywood, PNW.

Products	**Value**	**Unit/m^3**	**Allocation (%)**
Peeler Blocks	1.00	m^3	89.63
Bark, green	50.56	kg	10.37
Materials/fuels	**Value**	**Unit/m^3**	
Electricity, at Grid	9.28	kWh	
Diesel	0.81	L	
Transport	71.58	tkm	
Logs	1.06	m^3	
Waste to Treatment	**Value**	**Unit/m^3**	
Solid waste, to landfill	11.26	kg	

3.3.2.4 Conditioning

Conditioning of the block involves heating the wood blocks with either hot water or direct steam to improve the quality of peeled veneer. This step makes them easier to peel, reduces veneer breakage, and results in smoother, higher quality veneer. The unit process inputs and outputs for this production step are provided in Table 9. There are no co-products and the inputs include steam and electricity. Conditioning consumed 9% of the total heat energy requirements for producing PNW plywood.

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[1] A block is a log to be used in veneer production that has been cut to a designated length, usually 8 feet.

[2] Green specific gravity uses oven dry mass and green volume of the wood resource.

Table 9 Unit process inputs/outputs for conditioning block to produce 1 m^3 of Conditioned block for softwood plywood, PNW.

Products	**Value**	**Unit/m^3**
Conditioned Blocks	1.00	m^3
Materials/fuels	**Value**	**Unit/m^3**
Electricity, at Grid	5.17	kWh
LPG	0.14	L
Wood waste, combusted in industrial boiler	10.71	kg
Natural gas, combusted in industrial boiler	0.15	m^3
Peeler Block	1.00	m^3
Waste to Treatment		
Solid waste, to landfill	11.26	kg

3.3.2.5 Log Peeling

The conditioned blocks are then conveyed to a veneer lathe. Each block is gripped on the ends at the block's geometric center and rotated at high speed. The rotating block is fed against a stationary knife parallel to its length. Veneer is peeled from the block in a continuous, uniformly thin sheet, at a speed of up to 4.1 m/s (13.3 linear ft/s). Veneer thickness can range from 1.6 to 4.8 mm (1/16 to 3/16 in) depending on the final use. The long sheets of veneer are transported by conveyor to a clipper where they are cut into usable widths and defects are removed. Co-products represent about 30 percent by mass of the outputs from the peeling process (Table 10). A small amount (<1%) of green, trimmed veneer is sold off site. The trimmed wet veneer is then transported to the dryers.

Table 10 Unit process inputs/outputs for peeling to produce 1 m^3 of green veneer for softwood plywood, PNW.

Products	**Value**	**Unit/m^3**	**Allocation (%)**
Veneer, green	1.00	m^3	70.01
Veneer, green, sold	5.59	kg	0.89
Clippings, green	148.45	kg	23.78
Peeler core[3], green	33.19	kg	5.32
Materials/fuels			
Electricity, at Grid	18.81	kWh	
LPG	0.20	L	
Diesel	0.44	L	
Conditioned Block	1.43	m^3	
Emissions to air			
Particulates, > 2.5 um, and < 10um	0.0046	kg	
Particulates, unspecified	0.0023	kg	

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[3] A peeler core is that portion of the block that remains after the veneer has been taken.

3.3.2.6 Veneer Drying

Veneers are dried in continuous direct-fired dryers. This is the most energy intensive unit process and uses various heat sources. Drying reduces the moisture content of green veneer from approximately 25-60% to 3-6% (oven-dry basis). Dryer temperatures range from 149 º- 185 ºC (300 to 365ºF). The wood veneer does not experience the higher temperatures until much of its moisture is evaporated near the output end of the dryer. Table 11 shows emissions generated from dryers. Co-products include veneer downfall and other wood waste. Inputs include steam and electricity.

Table 11 Unit process inputs/outputs for drying to produce 1 m^3 of dry softwood veneer, PNW.

Products	**Value**	**Unit/m^3**	**Allocation (%)**
Veneer, dry	1	m^3	95.21
Veneer, dry, sold	0.05	m^3	4.79
Materials/fuels	**Value**	**Unit/m^3**	
Electricity, at Grid	41.20	kWh	
Natural gas, combusted in industrial boiler	3.28	m^3	
LPG	0.21	L	
Wood waste, combusted in industrial boiler	86.10	kg	
Veneer, green	452.00	kg	
Emissions to air	**Value**	**Unit/m^3**	
Acetaldehyde	0.0040	kg	
Acrolein	0.2302	kg	
Formaldehyde	0.0108	kg	
Methanol	0.0126	kg	
Particulates, > 2.5 um, and < 10um	0.0984	kg	
Particulates, unspecified	0.1106	kg	
Phenol	0.0010	kg	
VOC, volatile organic compounds	0.2197	kg	

3.3.2.7 Phenol-formaldehyde Resin

The life cycle inventory for the production of phenol-formaldehyde (PF) resin covers its cycle from in-ground resources through the production and delivery of input chemicals and fuels, through to the manufacturing of a resin as shipped to the customer (Wilson 2009). It examines the use of all resources, fuels and electricity and all emissions to air, water and land; it also includes feedstock of natural gas and crude oil used to produce the chemicals. The PF resin survey data were from 13 plants in U.S. that represented 62% of total production for the year 2005 (Wilson 2009). Total annual production was 779,063,000 kg (1,717,500,000 lb) of neat phenol-formaldehyde (PF) resin at 47.4% non-volatile solids content. The inputs to produce 1.0 kg of neat (PF) resin consist of the two primary chemicals: 0.244 kg of phenol and 0.209 kg of methanol, and a lesser amount of sodium hydroxide (0.061 kg), and 0.349 kg of water. Electricity is used for running fans and pumps, and for operating emissions control equipment. Natural gas is used for boiler fuel and emission control equipment, and propane fuel is used in forklifts.

3.3.2.8 Lay-up and Pressing

After drying the veneers are taken to the lay-up area. In the lay-up and pressing process the veneers are coated with PF resin on both sides, and stacked in alternating directions to produce panels for hot-pressing (Table 12). Once assembled to the desired thickness, panels are conveyed from the lay-up area to the press. Panels are first subjected to cold pressing to flatten the veneers and transfer the resin to uncoated areas. The panels are then hot pressed to provide direct contact between veneers while the PF resin cures at temperatures ranging from 163-171°C (325-340°F). Emissions are generated during the curing process from both the PF resin and the wood. Pressing consumed 15% of the total heat requirements for producing softwood plywood in the PNW.

Table 12 Unit process inputs/outputs for pressing veneers to produce 1 m^3 of softwood plywood, PNW.

Products	**Value**	**Unit/m^3**
Plywood, pressed	1.00	m^3
Materials/fuels	**Value**	**Unit/m^3**
Electricity, at Grid	13.28	kWh
Natural gas, combusted in industrial boiler	0.79	m^3
Wood waste, combusted in industrial boiler	16.26	kg
LPG	0.22	L
Phenol-formaldehyde resin	8.13	kg
Veneer, dry	437.00	kg
Emissions to air	**Value**	**Unit/m^3**
2-Butanone, 3,3-dimethyl-	0.0003	kg
Acetaldehyde	0.0017	kg
Acetone	0.0026	kg
alpha-Pinene	0.0386	kg
Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-	0.0150	kg
D-limonene	0.0043	kg
Formaldehyde	0.0007	kg
Hydrocarbons (other than methane)	0.0790	kg
Methanol	0.0552	kg
Methyl ethyl ketone	0.0006	kg
Particulates, unspecified	0.0473	kg
Phenol	0.0006	kg
VOC, volatile organic compounds	0.0986	kg

3.3.2.9 Panel Trimming

After pressing, the panels that require further processing are sent to a finishing area for trimming and sanding depending on their final use (Table 13). During the trimming and sawing process the plywood panels coming out of the press are sawn to dimension, usually 1.22 × 2.44 meters (m) (4 × 8 feet). Co-products include plywood trim and sawdust. Emissions include particulates. Final product density, excluding resin was 470 kg/m^3.

Table 13 Unit process inputs/outputs for final trimming to produce 1 m^3 of softwood plywood, PNW

Products	**Value**	**Unit/m^3**	**Allocation (%)**
Plywood, final product	1	m^3	78.6
Panel trim, dry	53.67	kg	8.97
Sawdust, dry	5.016	kg	0.84
Wood fuel, dry	69.22	kg	11.59
Materials/fuels	**Value**	**Unit/m^3**	
Electricity, at Grid	23.65	kWh	
LPG	0.23	L	
Plywood, pressed	598.24	kg	
Wrapping material - Packaging	0.460	kg	
Strap Protectors - Packaging	0.200	kg	
Strapping - Packaging	0.083	kg	
Spacers - Packaging	4.672	kg	
Emissions to air	**Value**	**Unit/m^3**	
Particulates, unspecified	0.004	kg	
Particulates, > 2.5 um, and < 10um	0.004	kg	

3.3.2.10 Packaging

Materials used for packaging plywood for shipping are shown in Table 14.

Table 14 Materials used in packaging and shipping per m^3, PNW plywood

Material	**Value**	**Unit**
Wrapping Material – HDPE and LDPE laminated paper	0.4601	kg
PET Strapping	0.0834	kg
Cardboard strap protectors	0.2002	kg
Wooden spacers	4.6721	kg

Packing materials for PNW softwood plywood represent 1.15% of the cumulative mass of the model flow. The wooden spacers make up the bulk of this mass, representing 86 percent of the total packaging material. The wrapping material, strap protectors, and strapping made up, 8, 4, and 2 percent of the packaging by mass.

4 Cut-off rules

According to the PCR, if the mass/energy of a flow is less 1% of the cumulative mass/energy of the model flow it may be excluded, provided its environmental relevance is minor. This analysis included all energy and mass flows for primary data.

In the primary surveys, manufacturers were asked to report total hazard air pollutants (HAPS) specific to their wood products manufacturing process: formaldehyde, methanol, acrolein, acetaldehyde, phenol, and propionaldehyde. If applicable to the wood product, HAPS are reported in Table 16 and would be included in the impact assessment. Table 16 shows all air emissions to 10^{-4} to simplify and report on the dominant releases by mass. There were no cut-offs used in the impact assessment. A complete list of all air emissions is located in Section 13 (Appendix) of this report.

5 Data quality requirements

In 2000 the total annual softwood plywood production for the PNW region was 4,146,641 m^3 (4,686,000 MSF); the five mills surveyed collectively produced 26 percent of this production figure (APA 2001). They provided primary data on plywood and co-product production, raw material inputs, electricity and fuel use, and emissions.

An external critical review of the survey procedures, data, analysis, and report was done for conformance with CORRIM and ISO 14040 standards (Werner 2004). The review provided assurances that the study methodology, data collection, and analyses were scientifically sound, and in conformance with ISO 14040 and CORRIM research protocol (ISO 2006). Details of this study for plywood production and the overall CORRIM project can be found in Wilson and Sakimoto (2004) and Lippke et al. (2004), respectively.

6 Life cycle inventory analysis

6.1 Data collection

Primary data for the LCI was collected through surveys in accordance with CORRIM and ISO 14040 protocols. This study relied almost exclusively on production and emissions data provided by plywood producers from the PNW, with some secondary data on electrical grid inputs from the US LCI database Goemans 2010). Data for packaging was obtained from field sampling and personal communications with manufacturers.

The primary mill survey data are more than 10 years old and were updated using current electricity grid and boiler data to complete this LCA. Boilers are the most energy intensive process for the cradle to production gate and therefore generate the dominant share of the environmental footprint. Milling technology has not changed substantially in the past 10 years so the data likely continue to reflect processes as they are now with one caveat. With the collapse of the US housing market, a lot of smaller inefficient mills were closed during 2006-2010 therefore any future mill surveys are likely to show even better environmental performance than is represented here.

6.2 Calculation rules

Fuel consumption was calculated per seedling and then multiplied by the number of planted seedlings per unit area specified for each of the three management scenarios to determine fuel consumption rates per unit area. Total fuel consumption per unit area was divided by the final harvested volume per unit area to establish the contribution of fuel consumption for site preparation, seedlings, and planting per unit of harvested volume.

To determine the environmental burdens of equipment used for forest extraction part of the forest management life cycle stage (Figure 1) the applicable fuel and oil consumption rates were developed for each equipment component within the harvesting system (Table 2). These data were derived from existing studies for the types of harvesting equipment used in the region and included both published information and personal interviews with timber harvesting contractors (Biltonen 2002; Hochrein and Kellogg 1988; Jorgenson 2002; Keegan et al. 1995; Kellogg and Bettinger 1995; Kellogg et al. 1996; Lawson 2002; Ledoux 1984; Reynolds 2002; Stevens and Clarke 1974). Production and consumption factors of the harvesting system were calculated by adding the emissions for each piece of equipment used per m^3 of production.

The survey results for each unit process were converted to a production basis (e.g., logs used per m^3 of plywood produced) and production-weighted averages were calculated for each material. This approach resulted in a plywood production complex that represents a composite of the mills surveyed, but may not represent any mill in particular. The USLCI database was used to assess off-site impacts associated with the materials and energy used. SimaPro, version 7+ (Pré Consultants 2012) was used as the accounting program to track all of the materials, and their allocation among products and co-products.

Missing data is defined as data not reported in surveys by the softwood lumber facilities. Whenever missing data occurred for survey items, they were checked with plant personnel to determine whether it was an unknown value or zero. Missing data were carefully noted so they were not averaged as zeros.

6.3 Allocation rules

All allocation was based on the mass of the products and co-products. PNW Plywood does not have a value differential 10 times greater than the value of the main co-product that is sold outside the mill at today's prices.

6.4 LCI results

Life cycle inventory results for plywood are presented by two life stages, 1) forestry operations, 2) plywood production which encompasses resin production (Tables 15-18). The majority of the raw material energy consumption and emissions occur during wood production with only a small portion arising from forestry operations. Raw material energy requirements are presented in Table 15 for 1 m^3 of softwood plywood. Air emissions are reported in Table 16, water emissions are reported in Table 17, and solid waste emissions are reported in Table 18. Plywood production encompasses resin production.

Table 15 Cradle to gate raw material energy consumption per 1 m^3 of softwood plywood, PNW.

Fuel	Total	Forestry Operations	Wood Production
	kg/m^3		
Coal, in ground	20.4479	0.1859	20.2620
Gas, natural, in ground	16.7655	0.1672	16.5983
Oil, crude, in ground	10.3869	3.1648	7.2221
Uranium oxide, in ore	0.0004	0.0000	0.0004
Wood waste[1/]	133.3000	0.0000	133.3000

1/ included in total wood waste burned for energy is wet and dry co-products produced during debarking and trimming.

Table 16 Cradle to gate air emissions released per 1 m^3 of softwood plywood, PNW.

Air Emission[1/]	Total	Forestry Operations	Plywood Production
	kg/m^3		
Carbon dioxide, biogenic	234.5057	0.0081	234.4976
Carbon dioxide, fossil	104.1538	10.2858	93.8680
Nitrogen oxides	0.7687	0.1864	0.5823
Particulates, > 2.5 um, and < 10um	0.7335	0.0057	0.7278
Carbon monoxide	0.7194	0.0000	0.7194
Sulfur dioxide	0.6853	0.0067	0.6786
Particulates, < 2.5 um	0.5134	0.0000	0.5134
VOC, volatile organic compounds	0.3943	0.0050	0.3893
Methane	0.3409	0.0139	0.3270
Acrolein	0.2729	0.0000	0.2729
Carbon monoxide, fossil	0.2560	0.0935	0.1625
Particulates, unspecified	0.2205	0.0010	0.2195
Carbon dioxide	0.0918	0.0280	0.0638
Hydrocarbons (other than methane)	0.0899	0.0000	0.0899
Methanol	0.0775	0.0000	0.0775
Sulfur oxides	0.0659	0.0103	0.0556
Metals, unspecified	0.0511	0.0000	0.0511
alpha-Pinene	0.0440	0.0000	0.0440
Methane, fossil	0.0348	0.0011	0.0338
Hydrogen chloride	0.0333	0.0001	0.0332
NMVOC, non-methane volatile organic compounds, unspecified origin	0.0323	0.0062	0.0260
Formaldehyde	0.0188	0.0001	0.0188
Isoprene	0.0186	0.0002	0.0184
Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-	0.0170	0.0000	0.0170
Benzene	0.0093	0.0001	0.0092
Acetaldehyde	0.0076	0.0000	0.0076
Cumene	0.0060	0.0000	0.0060
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	0.0058	0.0001	0.0058
D-limonene	0.0049	0.0000	0.0049
TOC, Total Organic Carbon	0.0049	0.0000	0.0049
Acetone	0.0029	0.0000	0.0029
Propene	0.0024	0.0001	0.0023
Manganese	0.0019	0.0000	0.0019
Phenol	0.0018	0.0000	0.0018
Dinitrogen monoxide	0.0015	0.0002	0.0014
Hydrogen fluoride	0.0013	0.0000	0.0013
Chlorine	0.0009	0.0000	0.0009

Air Emission[1/]	**Total**	**Forestry Operations**	**Plywood Production**
	kg/m^3		
Particulates, < 10 um	0.0008	0.0000	0.0008
Methyl ethyl ketone	0.0007	0.0000	0.0007
Radionuclides (Including Radon)	0.0006	0.0000	0.0006
Aldehydes, unspecified	0.0004	0.0001	0.0003
Methane, dichloro-, HCC-30	0.0003	0.0000	0.0003
2-Butanone, 3,3-dimethyl-	0.0003	0.0000	0.0003
Ammonia	0.0003	0.0001	0.0002
Hydrocarbons, unspecified	0.0001	0.0000	0.0001
Naphthalene	0.0001	0.0000	0.0001

[1/] Due to large amount of air emissions, total emissions less than 10^{-4} are not shown. A complete list of all air emissions can be found in Section 13.

Waterborne emissions are all off-site (Table 17). No mill in the survey discharged any process water. The water sprayed on logs is collected and recycled or soaks into the ground. Water used at the boiler and kilns is evaporated. A complete list of all emissions to water is located in the Appendix (Section 13) of this report.

Table 17 Emissions to water released per 1 m^3 of softwood plywood, PNW.

Water emission[1/]	**Total**	**Forestry Operations**	**Plywood Production**
	kg/m^3		
Solved solids	5.0176	0.5348	4.4827
Chloride	4.0499	0.4336	3.6163
Sodium, ion	1.1421	0.1223	1.0199
Calcium, ion	0.3603	0.0386	0.3217
Suspended solids, unspecified	0.1535	0.0315	0.1220
COD, Chemical Oxygen Demand	0.1318	0.0042	0.1276
BOD5, Biological Oxygen Demand	0.1140	0.0022	0.1118
Lithium, ion	0.0808	0.0008	0.0800
Magnesium	0.0704	0.0075	0.0629
Barium	0.0667	0.0140	0.0527
TOC, Total Organic Carbon	0.0268	0.0000	0.0268
DOC, Dissolved Organic Carbon	0.0268	0.0000	0.0268
Bromide	0.0240	0.0026	0.0215
Sulfate	0.0178	0.0010	0.0168
Cumene	0.0145	0.0000	0.0145
Iron	0.0114	0.0020	0.0093
Benzene	0.0101	0.0000	0.0101
Strontium	0.0061	0.0007	0.0055
Propene	0.0054	0.0000	0.0054
Aluminum	0.0039	0.0010	0.0029
Oils, unspecified	0.0024	0.0003	0.0021
Ammonia	0.0016	0.0002	0.0014
Aluminum	0.0010	0.0000	0.0010
Fluoride	0.0009	0.0008	0.0001
Phosphate	0.0006	0.0006	0.0000
Boron	0.0004	0.0000	0.0003
Sulfur	0.0003	0.0000	0.0003
Manganese	0.0003	0.0000	0.0003
Silver	0.0002	0.0000	0.0002
Toluene	0.0002	0.0000	0.0002
Zinc	0.0001	0.0000	0.0001
Benzoic acid	0.0001	0.0000	0.0001
Detergent, oil	0.0001	0.0000	0.0001

[1/] Due to large amount of air emissions, total emissions less than 10^{-4} are not shown.

Solid emissions include ash generated at the boiler and the extraction of natural gas. Some waste that is collected from the log-yard and cannot be sent to the boiler because it is mixed with dirt is also included.

Table 18 Waste to treatment per 1 m^3 of dry softwood plywood, PNW.

Waste to treatment	Total	Forestry Operations	Plywood Production
	kg/m^3		
Solid waste	33.50	0.16	33.34

7 Life cycle impact assessment

The life cycle impact assessment (LCIA) phase establishes links between the life cycle inventory results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 19. Environmental impacts are determined using the TRACI method (Bare et al. 2011). These five impact categories are reported consistent with the requirement of the wood products PCR (PCR 2011).

Table 19 Selected impact indicators, characterization models, and impact categories.

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (H+) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of H^+ mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning that no single indicator is given more or less value than any of the others. Additionally, each impact indicator value is stated in units that are not comparable to others. For these reasons indicators should not be combined or added. Table 20 provides the environmental impact by category for softwood plywood produced in the PNW region. In addition, energy and material resource consumption values and the waste generated are also provided.

Environmental performance results for global warming potential (GWP), acidification, eutrophication, ozone depletion and smog, energy consumption from non-renewables, renewables, wind, hydro, solar, and nuclear fuels, renewable and nonrenewable resources, and solid waste are shown in Table 20. For GWP, 90 percent of the CO_2 equivalent emissions come from producing plywood, with remainder assigned to forestry operations.

Table 20 Environmental performance of 1 m^3 softwood plywood, PNW.

Impact category	**Unit**	**Total**	**Forestry Operations**	**Plywood Production**
Global warming potential (GWP)	kg CO_2 equiv	114.10	10.74	103.36
Acidification Potential	H+ moles equiv	70.56	8.34	62.21
Eutrophication Potential	kg N equiv	0.04920	0.01021	0.03899
Ozone depletion Potential	kg CFC-11 equiv	0.00000	0.00000	0.00000
Smog Potential	kg O3 equiv	23.39	4.65	18.74
Total Primary Energy Consumption	**Unit**	**Total**	**Forestry Operations**	**Plywood Production**
Non-renewable fossil	MJ	1921.07	157.97	1763.09
Non-renewable nuclear	MJ	158.65	1.66	156.99
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	115.70	0.26	115.44
Renewable, biomass	MJ	2790.74	0.00	2790.73
Material resources consumption (Non fuel resources)	**Unit**	**Total**	**Forestry Operations**	**Plywood Production**
Non-renewable materials	kg	0.62	0.01	0.61
Renewable materials	kg	465.39	0	465.39
Fresh water	L	482.19	10.29	471.91
Waste generated	**Unit**	**Total**	**Forestry Operations**	**Plywood Production**
Solid waste	kg	32.75	0.17	32.59

8 Treatment of biogenic carbon

Treatment of biogenic carbon is consistent with the Intergovernmental Panel for Climate Change (IPCC 2006) inventory reporting framework in that there is no assumption that biomass combustion is carbon neutral. Instead, it is accepted that net carbon emissions from biomass combustion are accounted for under the Land-Use Change and Forestry (LUCF) Sector and are therefore ignored in energy emissions reporting for the product LCA to prevent double counting. Standards such as ASTM D7612, which are used in North America to define legal, responsible and/or certified sources of wood materials, are in place to provide assurances regarding forest regeneration and sustainable harvest rates that serve as proxies to ensure stable carbon balances in the forest sector. They are outside the accounting framework for this LCA.

This approach to the treatment of biogenic carbon was taken for the Norwegian Solid Wood Product PCR (Aasestad 2008), and the North American PCR has adopted an identical approach to ensure comparability and consistency. The North American PCR approach is followed here for GWP reporting therefore the default TRACI impact assessment method was used. This default method does not count the CO_2 emissions released during the combustion of woody biomass during production. Other emissions associated from wood combustion, e.g., methane or nitrogen oxides, do contribute to and are included in the GWP impact category. For a complete list of emissions factors for the GWP method used, see Bare et al. (2011). Using this method, 114 kg CO_2e were released in the production of 1 m^3 of plywood. That same 1 m^3 of plywood stores 846 kg CO_2e (Table 21).

Table 21 Carbon balance per 1 m^3 softwood plywood, PNW.

	kg CO_2 equivalent
released forestry operations	10.74
released manufacturing	103.36
CO_2 eq. stored in product	846.01

9 Conclusions

The cradle to gate LCA for softwood plywood includes the LCI of forest resources that rely on secondary and tertiary data and the LCI of manufacturing and resin production that relies on primary survey data and secondary data on process inputs such as natural gas, diesel, and electricity. The survey results were representative of the forest operations in the region that would produce the relative amounts of Douglas fir and hemlock plywood that are reported as outputs for the region. The survey data are representative of the plywood processes and production volumes consistent with trade association production data.

To produce one cubic meter of plywood in the PNW, it took 917 kg of roundwood and 10.6 kg of purchased veneer. These raw material inputs produced 470 kg of plywood, 98 kg of self-produced wood fuel, and 359 kg of co-product (chips, sawdust, trimming, peeler cores). The self-produced wood fuel contained approximately 51 kg bark.

Emissions from the forest resources LCI and LCIA are small relative to manufacturing emissions. The plywood manufacturing process has some onsite emissions from drying veneers and pressing the panels with the resins. These emissions were reported by the mills in the surveys. Of the total CO_2 emissions, both biogenic and fossil, 69 percent were biogenic based emissions from the combustion of wood fuel.

Energy use for manufacturing plywood is dominated by the combustion of wood fuel (biomass), which is comprised of wood and bark waste generated during the manufacture of plywood. Wood fuel represented 94% of the mill site use of heat energy. Energy generated by renewable fuels, such as woody biomass, represents about 56 percent of the total energy from cradle to gate. Of the renewable biomass fuels, 99 percent was wood fuel from the plywood production (99.9%) and purchased wood waste (<1%). Total nonrenewable fossil fuel use was 38 percent of the total energy from cradle to gate. Resins used to bond the veneers also almost exclusively dependent upon fossil fuels for both energy and feedstock. Forestry operations consumed exclusively (98%) fossil fuels. Plywood production alone consumed 58 percent of the total energy from biomass (wood fuel) and 36 percent from non-renewable fossil fuels.

The TRACI impact method does not count the contribution of wood-derived CO_2 emissions from burning wood fuel in the boiler towards the global warming impact estimate. This is consistent with the current US EPA rules on wood emissions from stationary sources which counts the CO_2 taken up by the forest ecosystem when the tree grew as balancing any CO_2 emissions when it is burned. Under the TRACI method, combustion of fossil fuels generates CO_2 and other air emissions that contribute to the global warming impact as do methane and nitrous oxides that are emitted during biomass burning. Using this method, 114 kg CO_2e were released in the production of 1 m^3 of plywood. That same 1 m^3 of plywood stores 846 kg CO_2e.

10 Acknowledgments

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11 Critical Review

11.1 Internal Review

An internal review of the LCA product was provided using two knowledgeable and experienced LCA and wood products reviewers. They are:

- Wayne B. Trusty, President, Wayne B. Trusty and Associates Limited,
- Bruce Lippke, Professor Emeritus, University of Washington

The purpose of the LCA Report internal review is to check for errors and conformance with the PCR prior to submittal to for external review. The technical and editorial comments of the reviewers were carefully considered and in most instances incorporated into the final document. CORRIM addressed the internal review comments, as appropriate, and maintains a record of all comments and responses for future reference.

11.2 External Review

The external review process is intended to ensure consistency between the completed LCA and the principals and requirements of the International Standards on LCA (ISO 2006) and the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (PCR 2011). Following CORRIM's internal review evaluation, documents were submitted to UL Environment (ULE) for independent external review. The independent external review performed by ULE was conducted by:

- Thomas Gloria, Ph.D., Industrial Ecology Consultants

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13 Appendix

13.1 Air Emissions

Table A.1 Air emissions released per1 m^3 of softwood plywood, PNW.

Air Emissions	Unit	Total	Forestry Operations	Plywood Production
2,4-D	kg	1.37E-09		1.37E-09
2-Butanone, 3,3-dimethyl-	kg	3.04E-04	0.00E+00	3.04E-04
2-Chloroacetophenone	kg	3.36E-10	1.77E-12	3.34E-10
5-methyl Chrysene	kg	1.94E-10	1.79E-12	1.92E-10
Acenaphthene	kg	4.50E-09	4.15E-11	4.46E-09
Acenaphthylene	kg	2.21E-09	2.03E-11	2.19E-09
Acetaldehyde	kg	7.64E-03	4.28E-05	7.59E-03
Acetochlor	kg	1.90E-08		1.90E-08
Acetone	kg	2.92E-03	0.00E+00	2.92E-03
Acetophenone	kg	7.19E-10	3.79E-12	7.15E-10
Acrolein	kg	2.73E-01	5.19E-06	2.73E-01
Alachlor	kg	1.87E-09		1.87E-09
Aldehydes, unspecified	kg	4.32E-04	1.29E-04	3.03E-04
alpha-Pinene	kg	4.40E-02	0.00E+00	4.40E-02
Ammonia	kg	2.82E-04	8.60E-05	1.96E-04
Ammonium chloride	kg	2.21E-05	2.31E-07	2.19E-05
Anthracene	kg	1.85E-09	1.71E-11	1.84E-09
Antimony	kg	9.60E-06	1.46E-09	9.60E-06
Arsenic	kg	3.00E-05	4.64E-08	3.00E-05
Atrazine	kg	3.70E-08		3.70E-08
Barium	kg	2.14E-07		2.14E-07
Bentazone	kg	1.51E-10		1.51E-10
Benzene	kg	9.25E-03	5.22E-05	9.20E-03
Benzene, chloro-	kg	1.05E-09	5.56E-12	1.05E-09
Benzene, ethyl-	kg	7.19E-08	2.38E-11	7.19E-08
Benzo(a)anthracene	kg	7.06E-10	6.51E-12	6.99E-10
Benzo(a)pyrene	kg	3.35E-10	3.09E-12	3.32E-10
Benzo(b,j,k)fluoranthene	kg	9.71E-10	8.95E-12	9.62E-10
Benzo(ghi)perylene	kg	2.38E-10	2.20E-12	2.36E-10
Benzyl chloride	kg	3.36E-08	1.77E-10	3.34E-08
Beryllium	kg	1.51E-06	2.28E-09	1.51E-06
Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-	kg	1.70E-02	0.00E+00	1.70E-02
Biphenyl	kg	1.50E-08	1.38E-10	1.49E-08
Bromoform	kg	1.87E-09	9.86E-12	1.86E-09
Bromoxynil	kg	3.31E-10		3.31E-10
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	kg	5.85E-03	5.88E-05	5.79E-03

Air Emissions	Unit	Total	Forestry Operations	Plywood Production
Butadiene	kg	3.10E-06	2.18E-06	9.17E-07
Cadmium	kg	5.72E-06	1.13E-08	5.71E-06
Carbofuran	kg	2.83E-10		2.83E-10
Carbon dioxide	kg	9.18E-02	2.80E-02	6.38E-02
Carbon dioxide, biogenic	kg	2.35E+02	8.13E-03	2.34E+02
Carbon dioxide, fossil	kg	1.04E+02	1.03E+01	9.39E+01
Carbon disulfide	kg	6.23E-09	3.29E-11	6.20E-09
Carbon monoxide	kg	7.19E-01	3.83E-06	7.19E-01
Carbon monoxide, fossil	kg	2.56E-01	9.35E-02	1.62E-01
Chloride	kg	5.69E-10	6.23E-12	5.63E-10
Chlorinated fluorocarbons and hydrochlorinated fluorocarbons, unspecified	kg	1.12E-07		1.12E-07
Chlorine	kg	9.45E-04	0.00E+00	9.45E-04
Chloroform	kg	2.83E-09	1.49E-11	2.81E-09
Chlorpyrifos	kg	2.17E-09		2.17E-09
Chromium	kg	2.79E-05	3.32E-08	2.78E-05
Chromium VI	kg	6.97E-07	6.43E-09	6.91E-07
Chrysene	kg	8.82E-10	8.14E-12	8.74E-10
Cobalt	kg	8.96E-06	6.34E-08	8.89E-06
Copper	kg	2.06E-08	5.70E-10	2.00E-08
Cumene	kg	6.05E-03	1.34E-12	6.05E-03
Cyanazine	kg	3.26E-10		3.26E-10
Cyanide	kg	1.20E-07	6.32E-10	1.19E-07
Dicamba	kg	1.92E-09		1.92E-09
Dimethenamid	kg	4.54E-09		4.54E-09
Dimethyl ether	kg	4.37E-05		4.37E-05
Dinitrogen monoxide	kg	1.55E-03	1.74E-04	1.37E-03
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	1.98E-06	2.35E-17	1.98E-06
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	7.54E-12	2.05E-13	7.33E-12
Dipropylthiocarbamic acid S-ethyl ester	kg	3.11E-09		3.11E-09
D-limonene	kg	4.93E-03	0.00E+00	4.93E-03
Ethane, 1,1,1-trichloro-, HCFC-140	kg	1.93E-09	3.02E-10	1.63E-09
Ethane, 1,2-dibromo-	kg	5.75E-11	3.03E-13	5.72E-11
Ethane, 1,2-dichloro-	kg	1.92E-09	1.01E-11	1.91E-09
Ethane, chloro-	kg	2.01E-09	1.06E-11	2.00E-09
Ethene, tetrachloro-	kg	3.85E-07	4.20E-09	3.81E-07
Ethene, trichloro-	kg	6.15E-14		6.15E-14
Fluoranthene	kg	6.27E-09	5.78E-11	6.21E-09
Fluorene	kg	8.03E-09	7.40E-11	7.96E-09
Fluoride	kg	2.96E-06	3.34E-07	2.62E-06
Formaldehyde	kg	1.88E-02	6.64E-05	1.88E-02
Furan	kg	4.34E-11	3.72E-13	4.30E-11
Glyphosate	kg	4.08E-09		4.08E-09

Air Emissions	Unit	Total	Forestry Operations	Plywood Production
Heat, waste	MJ	6.34E+00		6.34E+00
Hexane	kg	3.21E-09	1.69E-11	3.20E-09
Hydrazine, methyl-	kg	8.15E-09	4.30E-11	8.11E-09
Hydrocarbons (other than methane)	kg	8.99E-02	0.00E+00	8.99E-02
Hydrocarbons, unspecified	kg	1.28E-04	1.33E-06	1.26E-04
Hydrogen	kg	3.27E-06		3.27E-06
Hydrogen chloride	kg	3.33E-02	1.04E-04	3.32E-02
Hydrogen fluoride	kg	1.32E-03	1.22E-05	1.31E-03
Hydrogen sulfide	kg	1.84E-11	2.01E-13	1.82E-11
Indeno(1,2,3-cd)pyrene	kg	5.38E-10	4.96E-12	5.33E-10
Iron	kg	2.14E-07		2.14E-07
Isophorone	kg	2.78E-08	1.47E-10	2.77E-08
Isoprene	kg	1.86E-02	2.04E-04	1.84E-02
Kerosene	kg	1.06E-05	1.11E-07	1.05E-05
Lead	kg	6.15E-05	5.14E-08	6.15E-05
Magnesium	kg	9.71E-05	8.95E-07	9.62E-05
Manganese	kg	1.92E-03	6.89E-08	1.92E-03
MCPA	kg	2.55E-11		2.55E-11
Mercaptans, unspecified	kg	1.04E-05	5.44E-08	1.03E-05
Mercury	kg	5.24E-06	9.14E-09	5.23E-06
Metals, unspecified	kg	5.11E-02	2.31E-14	5.11E-02
Methacrylic acid, methyl ester	kg	9.58E-10	5.06E-12	9.53E-10
Methane	kg	3.41E-01	1.39E-02	3.27E-01
Methane, bromo-, Halon 1001	kg	7.67E-09	4.04E-11	7.63E-09
Methane, dichloro-, HCC-30	kg	3.49E-04	7.07E-08	3.49E-04
Methane, dichlorodifluoro-, CFC-12	kg	1.20E-09	3.67E-10	8.37E-10
Methane, fossil	kg	3.48E-02	1.06E-03	3.38E-02
Methane, monochloro-, R-40	kg	2.54E-08	1.34E-10	2.53E-08
Methane, tetrachloro-, CFC-10	kg	9.07E-08	3.67E-11	9.07E-08
Methanol	kg	7.75E-02	0.00E+00	7.75E-02
Methyl ethyl ketone	kg	7.09E-04	9.86E-11	7.09E-04
Methyl methacrylate	kg	8.64E-13		8.64E-13
Metolachlor	kg	1.50E-08		1.50E-08
Metribuzin	kg	6.95E-11		6.95E-11
Naphthalene	kg	1.16E-04	1.32E-08	1.16E-04
Nickel	kg	4.66E-05	8.02E-07	4.58E-05
Nitrogen oxides	kg	7.69E-01	1.86E-01	5.82E-01
Nitrogen, total	kg	6.33E-06	6.33E-06	1.83E-09
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.23E-02	6.23E-03	2.60E-02
N-Nitrodimethylamine	kg	1.38E-14		1.38E-14
Organic acids	kg	8.12E-08	8.50E-10	8.04E-08
Organic substances, unspecified	kg	6.66E-05	5.05E-07	6.61E-05

Air Emissions	Unit	Total	Forestry Operations	Plywood Production
PAH, polycyclic aromatic hydrocarbons	kg	1.33E-05	9.38E-06	3.93E-06
Paraquat	kg	3.03E-10		3.03E-10
Parathion, methyl	kg	2.29E-10		2.29E-10
Particulates	kg	2.14E-05		2.14E-05
Particulates, < 10 um	kg	8.40E-04	0.00E+00	8.40E-04
Particulates, < 2.5 um	kg	5.13E-01	0.00E+00	5.13E-01
Particulates, > 2.5 um, and < 10um	kg	7.34E-01	5.71E-03	7.28E-01
Particulates, SPM	kg	8.07E-05		8.07E-05
Particulates, unspecified	kg	2.20E-01	1.02E-03	2.19E-01
Pendimethalin	kg	1.56E-09		1.56E-09
Permethrin	kg	1.40E-10		1.40E-10
Phenanthrene	kg	2.38E-08	2.20E-10	2.36E-08
Phenol	kg	1.83E-03	4.04E-12	1.83E-03
Phenols, unspecified	kg	6.13E-05	3.68E-08	6.13E-05
Phorate	kg	7.18E-11		7.18E-11
Phosphate	kg	1.45E-07	1.45E-07	
Phthalate, dioctyl-	kg	3.50E-09	1.85E-11	3.48E-09
Potassium	kg	3.79E-05		3.79E-05
Propanal	kg	1.82E-08	9.61E-11	1.81E-08
Propene	kg	2.43E-03	1.44E-04	2.29E-03
Propylene oxide	kg	6.11E-08		6.11E-08
Pyrene	kg	2.91E-09	2.68E-11	2.89E-09
Radioactive species, unspecified	Bq	4.97E+05	4.60E+03	4.92E+05
Radionuclides (Including Radon)	kg	5.92E-04	6.19E-06	5.86E-04
Selenium	kg	1.49E-05	1.13E-07	1.48E-05
Simazine	kg	9.84E-10		9.84E-10
Sodium	kg	8.74E-07		8.74E-07
Styrene	kg	1.20E-09	6.32E-12	1.19E-09
Sulfur	kg	4.61E-06		4.61E-06
Sulfur dioxide	kg	6.85E-01	6.71E-03	6.79E-01
Sulfur oxides	kg	6.59E-02	1.03E-02	5.56E-02
Sulfur, total reduced	kg	2.70E-06		2.70E-06
Sulfuric acid, dimethyl ester	kg	2.30E-09	1.21E-11	2.29E-09
Tar	kg	6.40E-10	7.00E-12	6.33E-10
t-Butyl methyl ether	kg	1.68E-09	8.85E-12	1.67E-09
Terbufos	kg	2.45E-09		2.45E-09
TOC, Total Organic Carbon	kg	4.89E-03	0.00E+00	4.89E-03
Toluene	kg	3.27E-05	2.28E-05	9.87E-06
Toluene, 2,4-dinitro-	kg	1.34E-11	7.08E-14	1.34E-11
Vinyl acetate	kg	3.64E-10	1.92E-12	3.62E-10
VOC, volatile organic compounds	kg	3.94E-01	5.00E-03	3.89E-01
Xylene	kg	2.27E-05	1.59E-05	6.81E-06

Air Emissions	Unit	Total	Forestry Operations	Plywood Production
Zinc	kg	3.44E-07	1.18E-07	2.27E-07

13.2 Water Emissions

Table 22 Emissions to water released per 1 m^3 of softwood plywood, PNW.

Water Emission	Unit	Total	Forestry Operations	Plywood Production
2,4-D	kg	5.86E-11		5.86E-11
2-Hexanone	kg	7.32E-07	7.84E-08	6.54E-07
2-Propanol	kg	2.54E-09		2.54E-09
4-Methyl-2-pentanone	kg	4.71E-07	5.05E-08	4.21E-07
Acetochlor	kg	8.13E-10		8.13E-10
Acetone	kg	1.12E-06	1.20E-07	1.00E-06
Acidity, unspecified	kg	5.67E-15		5.67E-15
Acids, unspecified	kg	3.62E-06	1.31E-10	3.62E-06
Alachlor	kg	8.00E-11		8.00E-11
Aluminium	kg	9.86E-04	0.00E+00	9.86E-04
Aluminum	kg	3.91E-03	1.02E-03	2.89E-03
Ammonia	kg	1.65E-03	2.24E-04	1.42E-03
Ammonia, as N	kg	6.00E-09	6.57E-11	5.93E-09
Ammonium, ion	kg	4.72E-06	4.94E-08	4.68E-06
Antimony	kg	2.91E-06	6.39E-07	2.27E-06
Arsenic, ion	kg	2.73E-05	3.55E-06	2.37E-05
Atrazine	kg	1.58E-09		1.58E-09
Barium	kg	6.67E-02	1.40E-02	5.27E-02
Bentazone	kg	6.46E-12		6.46E-12
Benzene	kg	1.01E-02	2.01E-05	1.01E-02
Benzene, 1-methyl-4-(1-methylethyl)-	kg	1.12E-08	1.20E-09	1.00E-08
Benzene, ethyl-	kg	1.06E-05	1.13E-06	9.45E-06
Benzene, pentamethyl-	kg	8.40E-09	9.00E-10	7.50E-09
Benzenes, alkylated, unspecified	kg	2.55E-06	5.60E-07	1.99E-06
Benzoic acid	kg	1.14E-04	1.22E-05	1.02E-04
Beryllium	kg	1.33E-06	1.82E-07	1.14E-06
Biphenyl	kg	1.65E-07	3.63E-08	1.29E-07
BOD5, Biological Oxygen Demand	kg	1.14E-01	2.19E-03	1.12E-01
Boron	kg	3.52E-04	3.77E-05	3.14E-04
Bromide	kg	2.40E-02	2.57E-03	2.15E-02
Bromoxynil	kg	8.55E-12		8.55E-12
Cadmium, ion	kg	4.09E-06	5.75E-07	3.52E-06
Calcium, ion	kg	3.60E-01	3.86E-02	3.22E-01
Carbofuran	kg	1.21E-11		1.21E-11
CFCs, unspecified	kg	2.54E-09		2.54E-09

Water Emission	Unit	Total	Forestry Operations	Plywood Production
Chloride	kg	4.05E+00	4.34E-01	3.62E+00
Chlorpyrifos	kg	9.32E-11		9.32E-11
Chromate	kg	3.38E-13		3.38E-13
Chromium	kg	8.87E-05	2.73E-05	6.13E-05
Chromium VI	kg	3.71E-07	1.13E-07	2.58E-07
Chromium, ion	kg	4.38E-05	2.13E-06	4.17E-05
Cobalt	kg	2.48E-06	2.66E-07	2.22E-06
COD, Chemical Oxygen Demand	kg	1.32E-01	4.16E-03	1.28E-01
Copper, ion	kg	2.58E-05	3.58E-06	2.22E-05
Cumene	kg	1.45E-02	0.00E+00	1.45E-02
Cyanazine	kg	1.40E-11		1.40E-11
Cyanide	kg	8.15E-09	8.67E-10	7.29E-09
Decane	kg	3.27E-06	3.50E-07	2.92E-06
Detergent, oil	kg	1.06E-04	1.01E-05	9.56E-05
Dibenzofuran	kg	2.13E-08	2.28E-09	1.90E-08
Dibenzothiophene	kg	1.78E-08	1.96E-09	1.58E-08
Dicamba	kg	8.23E-11		8.23E-11
Dimethenamid	kg	1.94E-10		1.94E-10
Dipropylthiocarbamic acid S-ethyl ester	kg	8.03E-11		8.03E-11
Disulfoton	kg	4.80E-12		4.80E-12
Diuron	kg	1.35E-12		1.35E-12
DOC, Dissolved Organic Carbon	kg	2.68E-02	4.02E-13	2.68E-02
Docosane	kg	1.20E-07	1.28E-08	1.07E-07
Dodecane	kg	6.20E-06	6.64E-07	5.54E-06
Eicosane	kg	1.71E-06	1.83E-07	1.52E-06
Fluorene, 1-methyl-	kg	1.28E-08	1.37E-09	1.14E-08
Fluorenes, alkylated, unspecified	kg	1.48E-07	3.25E-08	1.15E-07
Fluoride	kg	8.85E-04	8.09E-04	7.61E-05
Fluorine	kg	7.80E-08	1.60E-08	6.20E-08
Furan	kg	9.32E-11		9.32E-11
Glyphosate	kg	1.75E-10		1.75E-10
Hexadecane	kg	6.77E-06	7.25E-07	6.04E-06
Hexanoic acid	kg	2.36E-05	2.52E-06	2.10E-05
Hydrocarbons, unspecified	kg	9.32E-08	5.03E-13	9.32E-08
Iron	kg	1.14E-02	2.05E-03	9.33E-03
Lead	kg	4.63E-05	7.00E-06	3.93E-05
Lead-210/kg	kg	1.16E-14	1.25E-15	1.04E-14
Lithium, ion	kg	8.08E-02	8.24E-04	8.00E-02
Magnesium	kg	7.04E-02	7.54E-03	6.29E-02
Manganese	kg	2.67E-04	1.34E-05	2.54E-04
MCPA	kg	1.09E-12		1.09E-12
Mercury	kg	6.17E-08	1.54E-08	4.63E-08

Water Emission	Unit	Total	Forestry Operations	Plywood Production
Metallic ions, unspecified	kg	2.61E-09	6.14E-12	2.60E-09
Methane, monochloro-, R-40	kg	4.51E-09	4.83E-10	4.03E-09
Methyl ethyl ketone	kg	9.03E-09	9.67E-10	8.06E-09
Metolachlor	kg	6.42E-10		6.42E-10
Metribuzin	kg	2.98E-12		2.98E-12
Molybdenum	kg	2.58E-06	2.76E-07	2.30E-06
m-Xylene	kg	3.40E-06	3.64E-07	3.03E-06
Naphthalene	kg	2.04E-06	2.19E-07	1.82E-06
Naphthalene, 2-methyl-	kg	1.78E-06	1.90E-07	1.59E-06
Naphthalenes, alkylated, unspecified	kg	4.18E-08	9.18E-09	3.27E-08
n-Hexacosane	kg	7.48E-08	8.02E-09	6.68E-08
Nickel	kg	2.34E-05	3.36E-06	2.01E-05
Nickel, ion	kg	2.94E-13		2.94E-13
Nitrate	kg	3.02E-07	4.40E-14	3.02E-07
Nitrate compounds	kg	1.62E-10	1.77E-12	1.60E-10
Nitric acid	kg	3.63E-07	3.98E-09	3.59E-07
Nitrogen, total	kg	2.23E-05	1.23E-07	2.21E-05
o-Cresol	kg	3.23E-06	3.45E-07	2.88E-06
Octadecane	kg	1.67E-06	1.79E-07	1.49E-06
Oils, unspecified	kg	2.39E-03	2.76E-04	2.12E-03
Organic substances, unspecified	kg	1.86E-09		1.86E-09
Paraquat	kg	1.30E-11		1.30E-11
Parathion, methyl	kg	9.82E-12		9.82E-12
p-Cresol	kg	3.48E-06	3.73E-07	3.11E-06
Pendimethalin	kg	6.68E-11		6.68E-11
Permethrin	kg	6.00E-12		6.00E-12
Phenanthrene	kg	2.02E-08	3.31E-09	1.69E-08
Phenanthrenes, alkylated, unspecified	kg	1.73E-08	3.81E-09	1.35E-08
Phenol	kg	1.68E-05	5.01E-06	1.18E-05
Phenol, 2,4-dimethyl-	kg	3.14E-06	3.36E-07	2.80E-06
Phenols, unspecified	kg	3.62E-05	1.04E-06	3.51E-05
Phorate	kg	1.86E-12		1.86E-12
Phosphate	kg	6.31E-04	6.09E-04	2.27E-05
Phosphorus	kg	5.21E-06		5.21E-06
Phosphorus compounds, unspecified	kg	3.44E-08		3.44E-08
Phosphorus, total	kg	3.07E-06		3.07E-06
Process solvents, unspecified	kg	9.32E-09		9.32E-09
Propene	kg	5.35E-03	0.00E+00	5.35E-03
Radioactive species, Nuclides, unspecified	Bq	6.86E+02	7.18E+00	6.79E+02
Radium-226/kg	kg	4.05E-12	4.34E-13	3.62E-12
Radium-228/kg	kg	2.07E-14	2.22E-15	1.85E-14
Selenium	kg	2.22E-06	1.41E-07	2.08E-06

Water Emission	Unit	Total	Forestry Operations	Plywood Production
Silver	kg	2.35E-04	2.52E-05	2.10E-04
Simazine	kg	4.22E-11		4.22E-11
Sodium, ion	kg	1.14E+00	1.22E-01	1.02E+00
Solids, inorganic	kg	9.23E-10	1.01E-11	9.13E-10
Solved solids	kg	5.02E+00	5.35E-01	4.48E+00
Strontium	kg	6.11E-03	6.55E-04	5.46E-03
Styrene	kg	1.93E-10		1.93E-10
Sulfate	kg	1.78E-02	9.74E-04	1.68E-02
Sulfide	kg	3.32E-05	5.82E-07	3.26E-05
Sulfur	kg	2.97E-04	3.18E-05	2.65E-04
Sulfuric acid	kg	8.15E-11		8.15E-11
Suspended solids, unspecified	kg	1.54E-01	3.15E-02	1.22E-01
Tar	kg	9.15E-12	1.00E-13	9.05E-12
Terbufos	kg	6.34E-11		6.34E-11
Tetradecane	kg	2.72E-06	2.91E-07	2.43E-06
Thallium	kg	6.14E-07	1.35E-07	4.80E-07
Tin	kg	1.66E-05	2.61E-06	1.40E-05
Titanium, ion	kg	4.47E-05	9.81E-06	3.49E-05
TOC, Total Organic Carbon	kg	2.68E-02	0.00E+00	2.68E-02
Toluene	kg	1.78E-04	1.90E-05	1.59E-04
Vanadium	kg	3.04E-06	3.26E-07	2.72E-06
Waste water/m3	m3	7.68E-04		7.68E-04
Xylene	kg	9.33E-05	1.02E-05	8.31E-05
Yttrium	kg	7.56E-07	8.09E-08	6.75E-07
Zinc	kg	1.21E-04	2.37E-05	9.70E-05
Zinc, ion	kg	4.11E-07		4.11E-07