Environmental Impacts of Redwood Lumber: A Cradle-to-Gate Assessment

Kamalakanta Sahoo[1]– Richard D. Bergman[2]*

[1] Post-doctoral Research Fellow, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, ** Corresponding author*
kamalakanta.sahoo@usda.gov
[2] Supervisory Research Wood Scientist, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA
richard.d.bergman@usda.gov

Abstract

Global demand for construction materials has grown greatly in the last century, contributing to unsustainable growth and detrimental impacts on the ecosystem. To aid in sustainable growth and reduce our environmental footprint, renewable construction materials, such as lumber, have been incorporated into green building activities. To quantify the environmental footprints of construction products, a method called life-cycle assessment is used. This study determined the environmental attributes associated with manufacturing redwood lumber in northern California using the unit process approach (1 m^3 or 380 oven-dry kg of lumber as the declared unit). The cradle-to-gate cumulative fossil energy demand of redwood lumber was found to be 1,120 MJ/m^3 of redwood lumber produced. Greenhouse gas emissions were estimated at about 69.8 $kgCO_2e/m^3$ of lumber produced excluding carbon storage in the lumber. Upstream operations (including silviculture, harvesting, and transport) and mainstream (mill) operations (including sawing, drying, and planing) contributed 52% and 48% of total greenhouse gas emissions, respectively. Carbon stored in redwood lumber is about twelve times more than its cradle-to-gate carbon footprint, a substantial environmental benefit. Many redwood lumber products such as decking are used green, and a large portion of green lumber is only air-dried, which has a much lower carbon footprint than kiln-dried lumber. In addition, even if the lumber requires kiln-drying, the heat comes from burning on-site mill residues, considered a carbon-neutral energy source. For wood production life-cycle stages, force- (kiln-) drying lumber tends to use a lot of thermal energy (albeit mostly from mill residues) compared with the whole life cycle. However, the carbon footprint for the redwood lumber drying unit process is low, only 14%, because the product tends to be used green. Furthermore, using mill residues to produce on-site combined heat and power (co-generation) was shown to be the most efficient way to reduce the environmental footprints of lumber production. Overall, the results showed that redwood lumber used in the construction sector can act as a carbon sink and can mitigate impacts to our ecosystem.

Key words: Lifecycle assessment, redwood, lumber, forest products, co-generation, carbon, green building materials, EPD, carbon foorprint

Introduction

Globally, the use of raw materials, especially for construction, has increased exponentially since the nineteenth century (Matos 2017). Buildings and construction account for more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions (Abergel et al. 2017). The demand for construction materials is predicted to grow because of global population growth and increased standard of living (Bringezu et al. 2017). However, climate change and resource depletion pose a serious threat to human civilization. Resources from forests provide renewable construction materials, pulp and paper, energy, bioproducts, and more. Forests sequestering carbon and wood products storing carbon have the greatest potential to mitigate climate change (Canadell and Raupach 2008, Malmsheimer et al. 2011). Combining wood carbon storage and avoiding greenhouse gas (GHG) emissions by using forest-based instead of fossil fuel-based construction materials, especially in building construction, is one of the most efficient options to mitigate climate change (Bergman et al. 2014a, Oliver et al. 2014, Sathre and O'Connor 2010). Because of environmental awareness and regulations, documenting the environmental performance of building products using life-cycle assessment (LCA) is becoming widespread and is the new normal. Quantifying environmental performance for structural wood products is one way to generate green building certifications (Bergman et al. 2014b), scientific documentation [e.g., environmental product declarations (EPDs)], and provide information to stakeholders including consumers, regulating agencies, and policymakers. EPDs, based on the underlying LCA data, not only provide verified data on the environmental performance of products and services but can also identify the environmental hot spots for continuous improvements in a consumer-friendly format (ISO 2006a, ISO 2007).

Redwood lumber is used to build decking, fencing, etc. in the western United States, and its demand has increased since the great recession because of the growing housing market. Bergman et al. (2014b) estimated the environmental impact of redwood decking (38 by 138 mm) compared with other alternative materials. However, with changes in the manufacturing process, sawmill size, and sawlog procurement distances, other input resources especially electricity and drying requirements to produce redwood lumber of various dimensions have gone through substantial changes. Therefore, the objective of this study was to measure the environmental performance of redwood lumber (*Sequoia sempervirens*) and compare the results with previous results. This will serve two important purposes: (i) the study results will be used to develop a redwood lumber EPD, and (ii) the changes (positive and negative) in the environmental performance of redwood lumber will be tracked. This study lists material flows, energy consumption, and emissions for the redwood lumber manufacturing process on a per-unit basis. Primary data were collected by surveying redwood sawmills primarily with a questionnaire. Peer-reviewed literature provided secondary data. Material balances constructed with a spreadsheet algorithm used data from primary and secondary sources. From material and energy inputs and reported emissions, SimaPro 8 software (PRé Consultants, Amersfoort, the Netherlands) modeled the estimates for raw material consumption, environmental outputs, and associated impacts (Pré-Consultants 2017).

Materials & Methods

Scope

This study followed the ISO 14040 and 14044 international standards to perform LCA of redwood lumber (ISO 2006b, ISO 2006c) and estimated the cradle-to-gate life-cycle impacts of redwood lumber produced in northern California, USA. The scope of this study covered the unit operations starting from forest management (silvicultural) and harvesting of redwood to the production of redwood lumber, i.e., redwood log transportation, sawing, drying, and planing. The focus of this study was the sawmill operations. However, the data related to redwood forest management and harvesting were taken from a previous study (Han et al. 2015). Major redwood lumber producing sawmills in northern California were surveyed and visited in 2018 to collect detailed information on redwood log logistics and lumber manufacturing. The surveyed mills provided detailed annual production data on their facilities including log volumes and transport distance, on-site fuel and materials consumption, electrical usage, and lumber production for 2017. This study included all dimensions and categories (redwood lumbers are classified into rough-green, rough-dry, and planed-dry) of redwood lumber produced from three sawmills. The studied sawmills produced redwood lumber along with another softwood species, i.e., Douglas-fir (*Pseudotsuga menziesii*). Redwood and Douglas-fir were tracked separately to remove any effect from processing Douglas-fir. Given that lumber production generates mill residues, an allocation approach was necessary to assign the environmental impacts associated with the final product of redwood lumber and its associated coproducts. For this analysis, all environmental impacts were assigned to the redwood lumber and none to its coproducts because redwood lumber and its coproducts have a large price differential (>10:1). This is consistent with previous redwood decking LCA studies (Bergman et al. 2013, Bergman et al. 2014b).

Declared Unit

It is important to provide a reference to which inputs (materials and energy) and outputs (products/coproducts and emissions) can be related. LCAs use a functional or declared unit as the reference depending on the scope. A declared unit of 1 m^3 of redwood lumber was used in this analysis because the whole life cycle (i.e., cradle-to-grave) was not covered. The life-cycle inventory (LCI) flows and life-cycle impact assessment (LCIA) results were reported on this per-declared-unit basis.

System Boundary and Unit Processes

This study considered the cradle-to-gate system boundary of redwood lumber, which included resource extraction (cradle) and product manufacturing. The boundary ended at the mill gate with products ready to ship. Figure 1 shows the system boundary of the cradle-to-gate LCA study of redwood lumber. Demarcating the boundary helps to track the material and energy flows crossing the boundary precisely. To track flows tied to redwood lumber production, two system boundaries were considered: (i) the gate-to-gate boundary (the dotted line in Fig. 1) shows the on-site system boundary of the mill and the four unit processes involved (log yard, sawing, drying, and planing); and (ii) the cradle-to-gate boundary shown by the solid line included gate-to-gate and upstream operations (this boundary considered both on- and off-site emissions for all material and energy consumed and began with forest management and ended with products at the sawmill gate ready for dispatch to consumers).

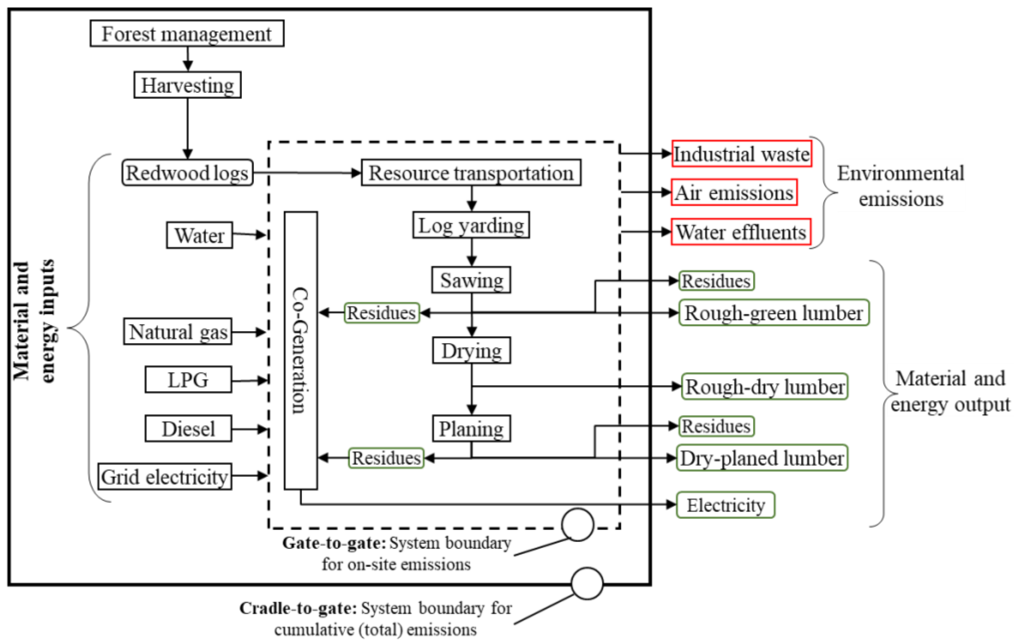

Figure12. System boundaries for redwood lumber manufacturing.

The resources used for the cradle-to-gate production of fossil energy and electricity were included within the cumulative system boundary. Off-site emissions included grid electricity production, transportation of logs to the mill, and fuels produced off-site but consumed on-site. Ancillary material data such as motor oil, paint, and hydraulic fluid were collected and were part of the analysis. The main unit processes in the manufacturing of redwood lumber were resource transport, log yard, sawing, drying, and planing with cogeneration of electricity and heat considered as auxiliary processes. As mentioned previously, all emissions (i.e., environmental outputs) and energy consumed were assigned to the redwood lumber and none to the coproducts (i.e., mill residues). Green wood residues included bark, chips, sawdust, and hog fuel. Some mills ground all wood residues into hog fuel. Redwood logs were transported in logging trucks from forest landings to the log yard. The procurement of redwood logs is seasonal, i.e., during the summer months. Logs in the log yard were wetted as needed to maintain log quality and prevent checking or splitting depending on the season and the mill. Log stackers or front-end loaders transported logs from the yard to the sawmill (the debarking unit). Sawing the debarked logs produces rough-green redwood lumber of different dimensions based on product demand. The sawing process (less the bark) produces rough-green lumber (58.9%), wood chips (16.0%), sawdust (5.3%), hog fuel (12.2%), and shavings (7.6%). Rough-green lumber can be sold directly to customers or dried to be sold as rough-dry lumber. The drying of lumber can be performed by either air-drying or kiln-drying based on the climate and time to fulfill customer demand. Overall, drying rough-green lumber occurs mostly by air-drying with minimal kiln-drying to reach the desired moisture content (MC). A certain volume of the rough-green and rough-dry lumber is planed and sold as surfaced-green lumber or surfaced-dry lumber (or planed-dry lumber), respectively. Both drying and surfacing can be full or partial based on customer demand.

Inventory Approach

Primary (mill) data were collected from three major redwood lumber manufacturing sawmills (for the year 2017) through a survey questionnaire to generate the gate-to-gate LCI for the LCA study. The data related to upstream forest operations for redwood logs came from Han et al. (2015). Secondary data, such as diesel, gasoline, natural gas, propane, grid electricity, chemicals, and transport, were taken from DATASMART LCI database (LTS 2017) in SimaPro and peer-reviewed literature.

Mass balances of the material flow (ins and outs) for each unit operation were performed to verify data consistencies and quality. Two levels of mass balances (individual facilities level and industry level) were performed, and the data were found to be consistent for the surveyed mills. A difference of less than 10% is considered good for wood product production. The primary data obtained from the surveys were analyzed using the weighted-average approach.

Life-Cycle Impact Assessment

SimaPro 8.5 software was used to generate the LCI flows, and the LCIA was performed using the TRACI 2.1 method (Bare 2011). Six impact categories were examined, including global warming (GW [kg CO_2 eq]), acidification (kg SO_2 eq), eutrophication (kg N eq), ozone depletion (kg chlorofluorocarbons-11 eq), photochemical smog (kg O_3 eq), and fossil fuel depletion (MJ). The six impact categories evaluated in this study were in line with the requirement of the structural and architectural wood products product category rule (PCR) currently under external review (UL-Environment 2019).

Results and Discussion

SimaPro 8.5 modeled weight-averaged 2017 survey data to estimate raw material use, emission profile, and environmental impacts on a 1.0 m^3 redwood lumber basis.

Mass Balance

Table 1 summarizes the mass balance of the redwood lumber production. Using a weight-averaged approach, 1.8 m^3 [656 oven-dried (OD) kg] of incoming redwood logs produced 1.0 m^3 (380 OD kg) of planed-dry redwood lumber. The sawing process yielded 386 kg of rough-green lumber with no loss of wood substance occurring during the drying process. Planing the rough lumber into a surfaced product decreased the 386 OD kg of rough-dry lumber to 380 OD kg of redwood lumber, for a 2% reduction in mass. This low value indicates a partial planing practice common among redwood lumber products. Some wood waste was converted on-site to thermal energy in a boiler; boilers burned all 6 OD kg of dry shavings produced per declared unit on-site for thermal process energy. Overall, an average redwood log was decreased to 51.2% (380/741) of its original dry mass (with bark) during its conversion to planed-dry redwood lumber. The conversion rate of lumber from redwood logs was higher compared with hardwood species [43.7-46.5% (Bergman and Bowe 2008, 2012)] and similar compared with other softwood species in the pacific northwest [53% (Milota et al. 2005)] as estimated in previous studies, which can be attributed to differences in the size of the logs and end product use. Overall, 355 OD kg of residues were generated and 78.3% (284 OD kg) of wood residues were used in the cogeneration unit to produce renewable electricity and thermal energy. The rest was sold for multiple uses such as land cover, soil amendments, etc.

Table 2: Mass balance for 1 m^3 planed-dry redwood lumber

	Sawing process		Dryer process		Planer process		Co-generation process
Material (OD kg)	In	Out	In	Out	In	Out	In
Green logs (wood only)	656	-	-	-	-	-	-
Green logs (bark only)	85	-	-	-	-	-	-
Green chips	-	105	-	-	-	-	82
Green sawdust	-	34	-	-	-	-	27
Green bark	-	85	-	-	-	-	67
Green shaving	-	50	-	-	-	-	39
Green hog fuel	-	80	-	-	-	-	63
Rough green lumber	-	386	386	-	-	-	-
Rough dry lumber	-	-		386	386	-	-
Planed dry lumber	-	-	-	-	-	380	-
Dry shavings	-	-	-	-	-	6	6
Sum	741	741	386	386	386	386	284

Material Inputs and Outputs

Table 2 provides the inputs of the material for the gate-to-gate product manufacturing stage. The main material inputs were natural inputs, i.e., redwood logs and water. Most water usages were for the drying, power generation, and log yard unit operations at the sawmills.

Table 2: Gate-to-gate material flow analysis of 1 m^3 of redwood lumber

Description	Unit	Value	Description	Unit	Value
Products			*Chemicals*		
Lumber	m^3	1	Oxygen scavenger (sulfite)	L	6.98E-03
Green chips (sold)	OD kg	22.918	Corrosion scale inhibiter	L	1.72E-02
Green sawdust (sold)	OD kg	7.501	pH adjuster	L	1.35E-01
Green bark (sold)	OD kg	18.561	Transport		
Green shaving (sold)	OD kg	10.874	Resource transport	tkm	125.625
Green hog fuel (sold)	OD kg	17.454	Chemicals transport	tkm	84.62
Renewable electricity	kWh	103.629	*Ancillary material*		
Resources inputs			Hydraulic fluid	kg	0.115
Water, well, in-ground	L	12.771	Motor oil	kg	0.101
Water, municipal	L	51.861	Grease	kg	0.001
Round redwood log	kg	741.385	Plastic strapping	kg	0.051
Fuels and energy			Paint	kg	0.001
Diesel	L	1.420	Replacement sticker	kg	1.072
Gasoline	L	0.067			
Natural gas	Nm^3	1.923			
Electricity	kWh	34.593			
Heat (biomass)	MJ	566.661			

Redwood lumber in service stores carbon. The carbon content for wood products is assumed to be 50% by mass of OD wood (Bergman et al. 2014a). Therefore, the carbon stored in 1 m^3 (380 OD kg) of redwood lumber is equivalent to 697 kg CO_2.

Cumulative Energy Consumption

Table 3 shows the cumulative unallocated energy consumption for 1 m^3 of redwood lumber. Cumulative energy consumption for cradle-to-gate manufacturing redwood lumber was 1,573 MJ/m^3 with wood fuel comprising about 44.5%. Crude oil (38.1%), natural gas (10.0%), and coal (3.5%) were the next three highest fossil energy resources consumed. Compared with a previous study (Bergman et al. 2014b), this study estimated a drastic reduction in energy from coal and natural gas but a multifold increase in energy from crude oil. Crude oil is the feedstock used to produce diesel, which is consumed in forest machines and logging trucks. Contrarily, the use of wood fuel increased ~3 times. However, wood fuel was used to generate electricity on-site. In this analysis, we did not take the credit of the extra electricity that was generated on-site but sold off-site. In retrospect, the wood products industry generates energy in-house by burning wood fuel generated on-site (Puettmann et al. 2010a). Overall, energy consumption increased compared with the previous redwood decking study (Bergman et al. 2014b). Still, redwood lumber production requires substantially lower energy compared with most other lumber products. The cumulative allocated energy consumption for 1 m^3 of planed-dry hardwood and softwood lumbers in the United States varied between 2,500 and 6,000 MJ/m^3 (Milota et al. 2005, Bergman and Bowe 2008, 2010, 2012, Puettmann et al. 2010b, Milota and Puettmann 2017,). The low cumulative energy consumption for redwood lumber occurs because of the minimal use of kiln-drying, which is the most energy-intensive part of producing dry lumber products (Bergman 2010).

Table 3: Cumulative energy (higher heating values (HHV)) consumed during the production of redwood lumber, cumulative, unallocated, and cradle-to-gate LCI values[a]

Fuel[b,c]	(kg/m^3)	(MJ/m^3)	(%)
Wood fuel/wood waste	33.5	700.0	44.5
Coal[d]	2.1	55.2	3.5
Natural gas[d]	2.9	157.0	10.0
Crude oil[d]	13.2	599.0	38.1
Hydro	0	13.0	0.8
Uranium[d]	0.00011	40.6	2.6
Energy, unspecified	0	8.7	0.5
Total	—	1,573	100

[a] Includes fuel used for electricity production and for log transportation (unallocated).
[b] Values are unallocated, cumulative, and based on HHV.
[c] Energy values were found using their HHV in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[d] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Environmental Emission Profile

Table 4 lists the unallocated environmental outputs for manufacturing one m^3 of redwood lumber for the cumulative and on-site system boundaries. The cumulative values included all emissions and were higher than the on-site emissions, as expected. For the cumulative system boundary, biogenic CO_2 and fossil CO_2 were 56.8 and 54.2 kg/m^3, respectively. For the cumulative case, fossil CO_2 was about three times the fossil CO_2 emitted for the on-site case, whereas biogenic CO_2 emissions were the same. For on-site, the only sources of fossil CO_2 came from rolling stock such as front-end loaders moving logs, forklifts moving lumber around the mill, and natural gas used for kiln-drying.

Table 4: Environmental outputs for manufacturing 1 m^3 of redwood lumber

Substance	Cumulative (kg/m^3)	On-site (kg/m^3)
Water effluents		
BOD5 (biological oxygen demand)	7.66E-02	6.86E+01
Chloride	2.06E+00	2.06E+00
COD (chemical oxygen demand)	5.29E-02	3.62E-02
DOC (dissolved organic carbon)	4.81E-02	4.56E-02
Oils, unspecified	3.00E-03	2.08E-03
Suspended solids, unspecified	7.91E-01	6.86E-01
Industrial waste[a]		
Waste in inert landfill	2.67E-01	2.67E-01
Waste to recycling	2.22E-01	2.22E-01
Solid waste[b]	1.11E-01	9.20E-02
Air emissions		
Acetaldehyde	1.56E-04	6.16E-05
Acrolein	5.41E-05	4.26E-05
Benzene	3.17E-04	2.02E-04
CO	1.04E+00	7.69E-01
CO_2 (biomass (biogenic))	6.03E+01	6.03E+01
CO_2 (fossil)	5.20E+01	1.69E+01
CH_4	6.57E-02	6.16E-02
Formaldehyde	6.24E-04	4.77E-04
Mercury	2.50E-07	2.21E-07
NO_x	6.39E-01	1.52E-01
Nonmethane VOC	2.77E-01	2.56E-01
Particulate (PM10)	4.01E+00	4.01E+00
Particulate (unspecified)	4.06E-03	7.68E-04
Phenol	2.07E-05	2.07E-05
SO_x	3.35E-02	1.58E-02
VOC	4.82E-02	3.28E-02

[a] Includes solid materials not incorporated into the product or coproducts but that left the system boundary.
[b] Solid waste was boiler ash from burning wood. Wood ash is typically used as a soil amendment or landfilled.

Life-Cycle Impact Assessment

Figure 2 shows the six midpoint environmental impact categories for redwood lumber without considering the credits from co-generating renewable electricity from burning mill residues. Forestry operation has a substantial contribution toward all categories of environmental impacts except ozone depletion. Forestry operation, sawing, and planing unit operations are the three major contributors to ozone depletion. Because of the use of diesel in harvesting equipment and logging trucks, most global warming and fossil fuel depletion impacts were from forestry operation and transportation of logs from landing to the mills. This study's environmental profiles of redwood lumber production (gate-to-gate) such as GW, ozone depletion, and smog were reduced by two to three times compared with the previous study

(Bergman et al. 2014b) mainly because of energy and power mix improvements such as more energy coming from co-generation and notable reduction in electricity usage in sawmill operations.

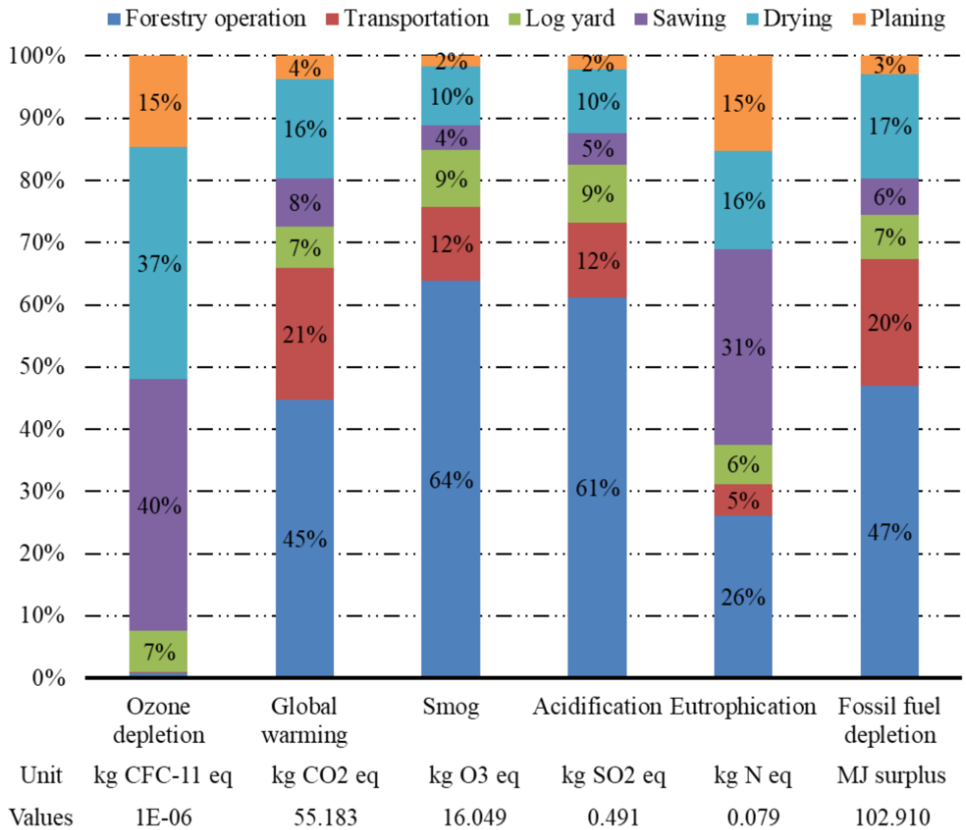

Figure 2. Contribution of environmental impacts for the cradle-to-gate life-cycle stages of redwood lumber production.

Summary and Conclusions

Construction materials made from wood have numerous environmental attributes. Redwood lumber, because of how it is processed, showed in this analysis an even greater benefit than other wood products. On resource efficiency, redwood lumber makes up about 51.2% of the incoming redwood logs while the rest is mill residues, primarily from sawing, that are used for other purposes and are not wasted. On GHG mitigation potential, our analysis showed redwood lumber stored about 12 times the total GHG emissions released during cradle-to-gate product manufacturing. CO_2 uptake from the atmosphere into the raw materials (i.e., trees) used to make wood products and the storage of the resultant carbon in long-lived building products are a substantial environmental attribute because this carbon is kept from the atmosphere. Other wood building products have this environmental advantage of storing carbon while in service to offset the effects from production while also avoiding the production of fossil fuel-intensive products (Puettmann and Wilson 2005, Puettmann 2010b; Bergman et al. 2016).

The unit process approach shows how product production facilities can improve their environmental profiles because of the many inherent details required compared with a system process approach. For most wood products, the drying process tends to have the greatest environmental impacts on the cradle-to-gate manufacturing process compared with other unit processes. However, compared with almost all other lumber species, redwood lumber drying process consumes less energy because it tends to be produced and sold green or air-dried. Contrary to most other wood products, forestry operation for redwood lumber production was found to be the most dominant life-cycle stage, contributing to most of the environmental impact categories. In retrospective, the impacts from the forest operation stage were still consistent with other wood products (Han et al. 2015, Oneil and Puettmann 2017), but because redwood lumber has minimal kiln-drying, the forest operation stage contributed a higher percentage of the overall impacts, as was reported.

This study showed substantial reductions in environmental profiles compared with the previous study in 2013 (Bergman et al. 2014b) because of the usage of heat and electricity from co-generation and reduction in electricity usage in the sawmill.

Acknowledgments

We gratefully acknowledge those companies and their employees that participated in the surveys to obtain production data and those who provided financial assistance to the USDA Forest Service, Forest Products Laboratory, for this research project (19-CO-11111137-010). The authors acknowledge the following peer reviewers: Charlie Jourdain, Manager, Business Development, Mendocino Forest Products and Humboldt Redwood; Sevda Alanya-Rosenbaum, Postdoctoral research fellow, USDA Forest Service, Forest Products Laboratory; Steven Hubbard, Lead Consultant, Hubbard Forest Solutions, LLC.

References

Abergel T, Dean B, Dulac J (2017) Towards a zero-emission, efficient, and resilient buildings and construction sector: Global Status Report 2017. Paris, France: UN Environment, International Energy Agency.

Bare J (2011) TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies Environmental Policy 13: 687-696.

Bergman RD, Bowe SA (2008) Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Sci 40: 448-458.

Bergman RD (2010) Drying and control of moisture content and dimensional changes. In: Wood handbook—wood as an engineering material. General Technical Report FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. pp. 13-1–13-20.

Bergman RD, Bowe SA (2010) Environmental impact of manufacturing softwood lumber determined by life-cycle inventory. Wood Fiber Sci 42(CORRIM SpecialIssue):67-68.

Bergman RD, Bowe SA (2012) Life-cycle inventory of manufacturing hardwood lumber in southeastern US. Wood and Fiber Sci 44: 71-84.

Bergman R, Han H-S, Oneil E, Eastin I (2013) Life-cycle assessment of redwood decking in the United States with a comparison to three other decking materials. Seattle, WA: Consortium for Research on Renewable Industrial Materials. https://www.fpl.fs.fed.us/documnts/pdf2013/fpl_2013_bergman001.pdf

Bergman R, Puettmann M, Taylor A, Skog KE (2014a) The carbon impacts of wood products. Forest Products Journal 64: 220-231.

Bergman RD, Oneil E, Eastin IL, Han HS (2014b) Life cycle impacts of manufacturing redwood decking in Northern California. Wood and Fiber Sci 46: 322-339.

Bergman RD, Kaestner D, Taylor AM (2016) Life cycle impacts of North American wood panel manufacturing. Wood and Fiber Sci 48: 40-53.

Bringezu S et al. (2017) Assessing global resource use: A systems approach to resource efficiency and pollution reduction. A report of the International Resource Panel. Nairobi, Kenya: United Nations Environment Programme.

Canadell JG, Raupach MR (2008) Managing forests for climate change mitigation. Science 320: 1456-1457.

Han HS, Oneil E, Bergman RD, Eastin IL, Johnson LR (2015) Cradle-to-gate life cycle impacts of redwood forest resource harvesting in northern California. Journal of Cleaner Production 99: 217-229.

ISO (2006a) Environmental labels and declarations-type iii environmental declarations-principles and procedures. International Organization for Standardization.

ISO (2006b) Environmental management: Life cycle assessment; principles and framework. International Organization for Standardization.

ISO (2006c) Environmental management: Life cycle assessments: Requirements and guidelines. International Standardization Organization.

ISO (2007) Sustainability in building construction: Environmental declaration of building products. ISO 21930. International Organization for Standardization.

LTS (2017) DATASMART LCI package (US-EI SimaPro® Library). https://ltsexperts.com/services/software/datasmart-life-cycle-inventory/.

Malmsheimer RW et al. (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. Journal of Forestry 109: S7-S50.

Matos GR (2017) Use of raw materials in the United States from 1900 through 2014. U.S. Geological Survey Fact Sheet 2017-3062. 6 p., https://doi.org/10.3133/fs20173062. Reston, VA: National Minerals Information Center.

Milota M, Puettmann ME (2017) Life-cycle assessment for the cradle-to-gate production of softwood lumber in the pacific northwest and southeast regions. Forest Products Journal 67(Special Issue): 331-342.

Milota MR, West CD, Hartley ID (2005) Gate-to-gate life-cycle inventory of softwood lumber production. Wood and Fiber Sci 37(Special Issue): 47-57.

Oliver CD, Nassar NT, Lippke BR, McCarter JB (2014) Carbon, fossil fuel, and biodiversity mitigation with wood and forests. Journal of Sustainable Forestry 33: 248-275.

Oneil E, Puettmann ME (2017) A life-cycle assessment of forest resources of the Pacific Northwest, USA. Forest Products Journal 67: 316-330.

Pré-Consultants (2017) SimaPro8 life-cycle assessment software package, version 8.5.2. Plotter 12. 3821 BB Amersfoort, the Netherlands.

Puettmann ME, Wilson JB (2005) Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood and Fiber Sci 37(Special Issue):18–29.

Puettmann ME, Bergman R, Hubbard S, Johnson L, Lippke B, Oneil E, Wagner FG (2010a) Cradle-to-gate life-cycle inventory of US wood products production: CORRIM Phase I and Phase II products. Wood and Fiber Sci 42(Special Issue): 15-28.

Puettmann ME, Wagner FG, Johnson L (2010b) Life cycle inventory of softwood lumber from the inland northwest US. Wood and Fiber Sci 42(Special Issue): 52-66.

Sathre R, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science & Policy 13: 104-114.

UL-Environment (2019) Guidance for building-related products and services: Part b: Structural and architectural wood products epd requirements. Washington, DC: UL Environment.

In: Proceedings of the 62nd International Convention of Society of Wood Science and Technology; pp. 266-277; 2019