The International Journal of Life Cycle Assessment (2021) 26:1702–1720
https://doi.org/10.1007/s11367-021-01937-7

WOOD AND OTHER RENEWABLE RESOURCES

Life-cycle assessment of redwood lumber products in the US

Kamalakanta Sahoo[1,2] · Richard Bergman[1] · Troy Runge[2]

Received: 1 June 2020 / Accepted: 3 June 2021 / Published online: 20 July 2021

Abstract

Purpose Global demand for construction materials has grown exponentially in the last century, contributing to climate change 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. The purpose of this study was to quantify the environmental impacts associated with manufacturing redwood lumber in northern California using the life-cycle assessment (LCA) approach.

Methods This study surveyed and visited redwood manufacturing facilities in the US and collected data including lumber production, co-products, resource inputs, and direct emissions to air and water. The life-cycle inventory (LCI) was developed using the mass allocation of products and co-products. Cradle-to-grave (cradle-to-gate and gate-to-grave) LCA method was used to estimate the environmental impacts and energy usage in the production of redwood lumber (1 m^3 of lumber), used in a redwood-deck, and its end-of-life (i.e., the deck was demolished after 25 years of its life and redwood lumber disposed of in a landfill that captures methane).

Results and discussions About 48% of dry mass in the redwood logs were converted to lumber in the sawmill. Depending on the redwood lumber product analyzed, the cradle-to-gate cumulative fossil energy demand was estimated to be 1862 (522–4877) MJ/m^3 of redwood lumber produced. The cradle-to-gate and cradle-to-grave global warming (GW) impact were estimated at 36 (22–65) and 139 (127–167) kgCO_2eq/m^3 of lumber, respectively. Upstream operations (including silviculture, harvesting, and transport) and mainstream (mill) operations (including sawing, drying, and planing) contributed 53% and 47% of total cradle-to-gate GW impact, respectively. However, the disposal of the redwood lumber products was the most dominant contributor (45–65%) to the cradle-to-grave GW impact of redwood lumber. Carbon stored in the whole lifecycle of redwood lumber is about 4 (range of 3−5) times more than its cradle-to-grave carbon footprint (CFP), a substantial environmental benefit. Considering credits from co-generation (used mill residues to generate both heat and electricity) supplying renewable electricity to the local grid decreases the net GW impact from − 468 to − 579 kgCO_2eq/m^3 of lumber. Many redwood lumber products such as decking are used green (freshly-cut), and a large portion of green lumber is only air-dried, which has a much lower GW impact than kiln-dried (force-dried) lumber. Also, even if the lumber requires kiln-drying, the heat comes from burning on-site mill processing residues, considered a carbon–neutral energy source. For lumber production life-cycle stages, kiln-drying of lumber tends to use a lot of thermal energy (albeit mostly from mill residues) compared with the whole life cycle. However, the GW impact from the redwood lumber drying unit process is low, only 27%, 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.

Conclusion Overall, the results showed that redwood lumber production has a negative GW impact and acts as a carbon sink if used in the construction sector. Specifically, the final products store 3–5 times more greenhouse gas emissions over than what is released from cradle-to-grave. There are large differences in GW impact among five categories of redwood lumber products and the rough-green lumber types have the lowest GW impact (or highest GW reduction potential) among all.

Keywords Life-cycle assessment · Redwood · Lumber · Forest products · Co-generation · Carbon · Green building materials

Communicated by: Jörg Schweinl

✉ Kamalakanta Sahoo
kamalakanta.sahoo@usda.gov

Extended author information available on the last page of the article

1 Introduction

Globally, the use of raw materials has grown exponentially since the mid-nineteenth century, especially for construction (Matos 2017). The estimation (from 1969) of global populations' resource use had been exceeding what nature can regenerate—by about 75% in 2019 (Global Footprint Network 2020). 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 the increasing global population and standard of living (Bringezu et al. 2017). The use of more renewable construction materials can help restrain the depletion of non-renewable resources. Forests provide renewable resources including construction materials, pulp and paper, energy, bioproducts and more (Jakes et al. 2016). Also, forests sequester carbon and forest-based products storing carbon have the highest potential to mitigate climate change (Canadell and Raupach 2008; Fargione et al. 2018; Malmsheimer et al. 2011). Considering carbon storage in wood and carbon displace from avoiding non-wood construction materials, especially in building construction, wood products are 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 increasing consumers' environmental awareness and stricter environmental regulations, documenting the environmental performance of products using life-cycle assessment (LCA) is becoming widespread and is the new normal, especially for building products (Gelowitz and McArthur 2017). Quantifying environmental performance for structural wood products such as lumber is one way to generate green building certifications that support the green building movement (Bergman and Taylor 2011; Ritter et al. 2011) and scientific documentation [e.g., environmental product declarations (EPDs)] and provide information to stakeholders including consumers, regulating agencies, and policymakers. EPD (based on the underlying LCA data) provides verified data on the environmental performance of products and services and can identify the environmental hot spots for continuous improvements in a consumer-friendly format (ISO 2006a, 2007). In addition, keeping EPDs current (EPDs required to be updated every 5 years) allows the continuous environmental improvement of products to be assessed over time (ISO 2017).

Redwood (*Sequoia sempervirens*) forests are very productive, with native-grown forests limited to northern (coastal) California and the southwestern corner of coastal Oregon in the United States (US) (Save-The-Redwood-League 2019) although plantation-grown forests are found in New Zealand. Due to naturally occurring chemicals inside the pores of redwood, the wood products made are considered weather-, insect-, and rot-resistant and are ideal for outdoor applications (Jones and O'hara 2011; Jones 2011; Scheffer and Morrell 1998). Bergman et al. (2013a) estimated the environmental impact of building decks with redwood is substantially lower compared with other alternative materials such as plastics. Moreover, structural wood products made from redwood are premium and used in many outdoor and indoor applications including decking, fencing, beams, posts, and interior furniture (Wiemann 2010). There are different categories of redwood lumber products produced based on the moisture content (i.e., varies from 19 to 127% MC dry basis) and surface conditions (i.e., rough, planed, or partially planed). Usually, redwood lumber products are sold as rough-green, rough-dry, planed-green, and planed-dry. The term "green" in the context of lumber in this study refers to freshly cut wood. With the advancement of technology, the 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 in the last several years. Therefore, it can be expected that there have been substantial changes (and most likely improvements) in the environmental performance of redwood lumber products. Moreover, there may be a large difference in the environmental performances among the individual categories of the products due to differences in the unit manufacturing operations. For example, rough-green redwood lumber likely has lower environmental impacts than planed-dry redwood lumber as the former does not need kiln (forced) drying and planing unit operations. Sahoo and Bergman (2020) provided the cradle-to-gate LCA results of redwood lumber that used to aggregate LCI for the redwood lumber industry and all categories of the products. Therefore, a detailed product-specific LCA study is necessary to understand the differences in the lifecycle impacts of individual redwood limber categories.

The objective of this study was to quantify the cradle-to-grave (cradle-to-gate and gate-to-grave) environmental impacts associated with various categories of redwood (*Sequoia sempervirens*) lumber products based on current manufacturing practices, using lumber in constructing redwood decks and disposing of the lumber in landfills that capture landfill gases like biogenic methane. This study serves two important purposes: (i) the cradle-to-gate study result was used to develop an industry average EPD for all categories of redwood lumber products and (ii) demonstrating the differences in the cradle-to-grave environmental performances of major categories of redwood lumber products based on moisture content and surface conditions.

2 Materials and methods

This study quantified environmental impacts of redwood lumber using a cradle-to-grave lifecycle assessment approach following the guidelines of ISO standards (ISO 2006b, c) and the Product Category Rule (PCR) for North American Structural and Architectural Wood Products (UL-Environment 2019a, b). An overall cradle-to-grave LCA of redwood lumber was accomplished by doing separate cradle-to-gate and gate-to-grave studies. The cradle-to-gate LCA study was used to develop an industry average EPD for the redwood lumber (AWC 2020). Primary data (especially for cradle-to-gate LCA) were collected for the production year 2017 by surveying redwood sawmills mainly with a questionnaire filled out by three redwood lumber manufacturing plants in northern California, US, followed by a site visit to each facility. The US LCI and US Ecoinvent databases (LTS 2019) and peer-reviewed literature provided secondary data including the supply of electricity and the manufacturing of fuels, lubricants, and chemicals. Also, input data used in the "gate-to-grave section (that included the transport of wood products from lumber sawmill to customers, wood structure installation, usage, and its end-of-life) of this study were taken from a previously published report (Bergman et al. 2013a). The mass balance and life cycle inventory (LCI) data were estimated based on 2017 primary data collected through survey questionnaires. The processes in the redwood lumber production system were modeled using SimaPro 9.0 software (Pré-Consultants 2020). Sahoo and Bergman (2020) provided the complete details of this study for generating LCI and cradle-to-gate LCA that was used to develop an industry-wide and product average EPD for redwood lumber. However, this study disaggregates redwood lumber into five main categories as well as LCI and extends the LCA study to cradle-to-grave to illustrate the differences in environmental impacts among the lumber products (i.e., rough-green, rough-kiln-dry, planed-green, planed-kiln-dry, and planed-air-dry). The environmental impacts were estimated using TRACI 2.1 impact assessment method (Bare 2011). For the quantification of total energy demand, we used Cumulative Energy Demand (CED) 1.10, based on the method published by Ecoinvent version 2.0, and the method was modified based on lower heating values (LHVs).

2.1 Goal and scope

Redwood lumber products have several uses including decking, fencing, and structural products. Thus, sawmills produce several categories of lumber products including categories of rough or planed and green or dry. The goal of the study was to (i) develop cradle-to-gate LCI for redwood lumber manufacturing using survey data at the unit process level and (ii) develop gate-to-grave LCI for redwood lumber using secondary data, especially for constructing decks and its disposal at the end of service life to estimate environmental impacts associated with cradle-to-gate and cradle-to-grave life-cycle stages of redwood lumber. Cradle-to-gate and cradle-to-grave studies estimated the environmental impacts including GW impact for five categories of the products.

The geographic scope of this study was the US, especially manufacturing of redwood lumber and for use on the US West Coast, where it is most predominated. This was a cradle-to-grave study, and thus, it covered all life stages of including harvest operations, production, construction, use, and end-of-life of redwood lumber (ISO 2017). A1-stage included forest management (silvicultural) and harvesting of redwood trees from the sustainably managed redwood forest (Han et al. 2015). A2 and A3 stages were log transportation and lumber production (sawing, drying, and planing), respectively. The transport of lumber to the construction site and installation was included in the A4 and A5 stages respectively. B1, C1, C2, and C3 stages included product use, demolition, transport to waste disposal site, and disposal of waste, respectively. Some of the redwood lumber sawmills in the study burn mill residues in a cogeneration unit to produce heat and electricity consumed by the sawmill internally while excess electricity was sold to the local grid (D-module of product's lifecycle stages) (ISO 2017).

2.2 Functional unit or declared unit

It is important to provide a reference to which inputs (materials, fuels, and electricity) and outputs (products/co-products and emissions) can be related. LCAs use a functional or declared unit as the reference depending on the scope. Although redwood lumber products have multiple uses, a majority of redwood lumber products are used in making decks. A functional unit of 1 m^3 of redwood lumber with a service life of 25 years was used in this analysis, and this functional unit can well represent all different use of redwood lumber. One cubic meter of green-lumber ($>50\%$ MC dry basis) and dry-lumber ($<19\%$ MC dry basis) were 360 and 380 oven-dried kg wood, respectively (Bergman 2021; Bergman et al. 2013a; Sahoo and Bergman 2020). The redwood lumber industry was interested in the lifecycle assessment of redwood lumber without differentiating the product category. It was learned from previous studies especially soft and hardwood lumber production that the differences in the environmental impacts between rough-green and planed-dry lumber products were substantial due to drying and planing unit operations (Puettmann et al. 2010a). The LCI flows and life-cycle impact assessment (LCIA) results were reported on a per-functional unit basis.

2.3 Allocation procedure

Selecting an appropriate allocation approach was an important and necessary part of this LCA study because co-products were generated during the manufacturing process in addition to the main product: redwood lumber. In the present study, all primary energy and environmental outputs were assigned to the final products and various co-products (mill residues) by mass allocation except co-generation. An energy allocation was used to assign primary inputs and environmental impacts to outputs such as heat and electricity produced in the co-generation unit. The decision was based on the fact that a large percentage of the mill residues were produced which were further used to generate heat and electricity, and a substantial portion of the electricity was exported to the commercial grid.

2.4 System boundary and unit processe

2.4.1 System boundary

Demarcating the boundary was necessary to track the material and energy flows crossing the boundary precisely. This study (Fig. 1) considered the complete life cycle (cradle-to-grave) of all the redwood lumber products, starting from raw material extraction to final disposal in a municipal solid waste (MSW) landfill with methane capture. The cradle-to-grave lifecycle was divided into (i) cradle-to-gate and (ii) gate-to-grave system boundaries. The cradle-to-gate boundary started with resource extraction and ended at the mill gate with products ready to ship. The gate-to-grave boundary started with product transport to the installation site and ends with disposal (grave). The gate-to-gate boundary uses the on-site system boundary of the sawmill and the four major unit processes involved (log yard, sawing, drying, and planing). The cradle-to-gate boundary included gate-to-gate and upstream supply chain operations (this boundary considered both on- and off-site emissions for all material and energy consumed. It began with forest management and ended with products at the sawmill gate ready for dispatch to consumers). The gate-to-cradle boundary included the downstream supply chain of redwood lumber products that included transportation of products to the installation site, construction of the structure (i.e., deck) that use redwood lumber products, use of the constructed structure for on average 25 years, demolition of the structure after the end of service life, transportation of demolition waste to a disposal site (i.e., an MSW landfill site), and disposal of the redwood

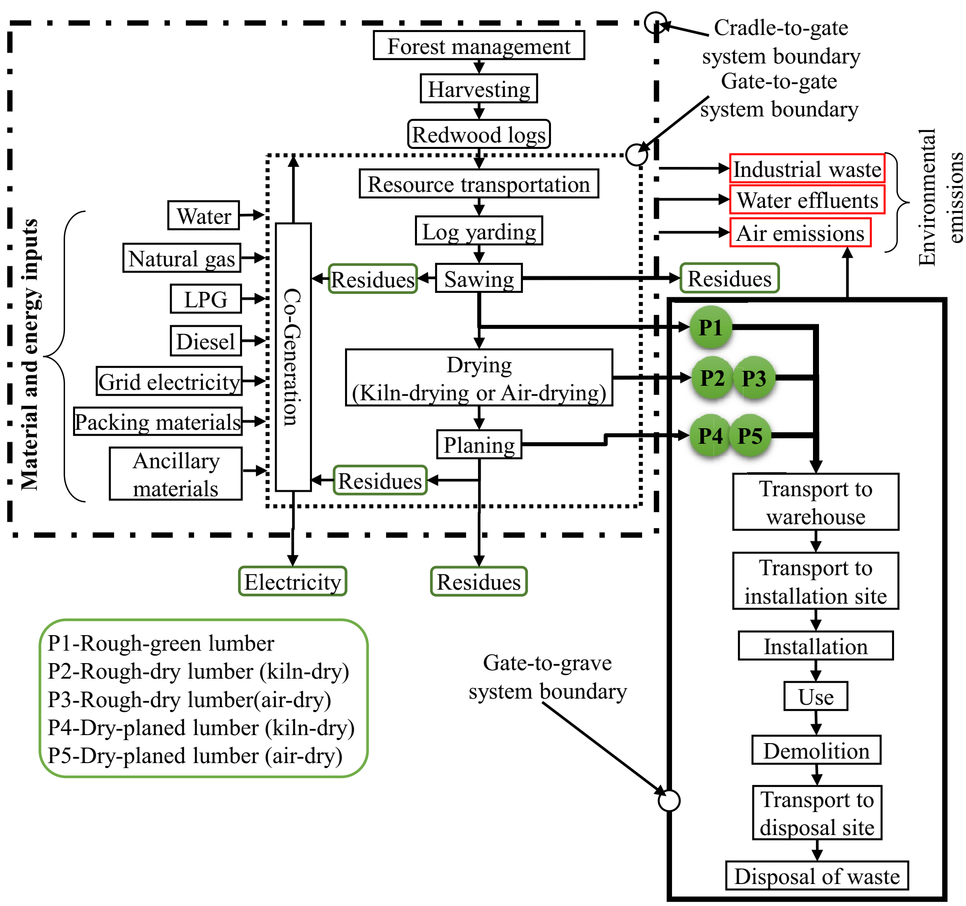


Fig. 1 System boundaries for redwood lumber manufacturing, use, and disposal

lumber construction waste. Although redwood lumber has various uses, it is predominately (~90%) used for making decks in the west coast US (Han et al. 2015). When forests are thinned or harvested, and kept as forests, they regrow and eventually recover carbon loss during harvesting both aboveground as well as belowground in the soil. Therefore, soil carbon is not considered in the analysis (Hektor et al. 2016; James et al. 2021; Johnson and Curtis 2001; Johnson et al. 2010).

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 consumed on-site. Ancillary material data such as motor oil, paint, hydraulic fluid, and packaging materials were collected and were part of the analysis.

Rough-green lumber was sold directly to customers or dried to reduce the lumber moisture content before selling. The drying of lumber was performed by either air-drying (rough-air-dry) or kiln-drying (rough-kiln-dry) based on the climate and time to fulfill customer demand. The rough-green, rough-kiln-dry, and rough-air-dry lumber was planed and sold as planed-green, planed-kiln-dry, and planed-air-dry lumber, respectively. Both drying and surfacing can be full or partial based on customer demand. Overall, there are five different categories of lumber products (Table 1).

2.4.2 Resource extraction

Redwood forests are naturally grown and unique to the coastal area of northern California, US. About 23% of the total 1.7 million acres of the redwood forest is protected including 110,000 acres of old-growth forest (Save-The-Redwood-League 2021). About 77% of total redwood forest lands are privately owned and most of the redwood forests that supply redwood logs to the sawmill in this study are sustainably managed and certified by Sustainable Forestry Initiative (SFI) and Forest Stewardship Council (FSC) (Sahoo and Bergman 2020). The primary source of data used for this study was collected from sawmills and combined, they represented more than 66% of the total annual production of the redwood lumber industry in 2017.

Table 1 Major categories of redwood lumber products and their production share in 2017

Major redwood lumber categories	% of the total production
Rough-green	58.0%
Rough-kiln-dry	5.7%
Planed-green	11.7%
Planed-kiln-dry	23.6%
Planed-air-dry	0.9%

The forest resource (i.e., logs) extraction can include growing seedlings, planting, thinning, and final harvest. LCI for redwood forest resources management included seed, fertilizer, and electricity (used in greenhouse operations) and fuel and lubricants consumed in equipment for site preparation, thinning, and harvest operations. The primary output from the forest is a log destined for the lumber mill. The coproduct, non-merchantable slash, is generally left at a landing and disposed of through mechanical activities, prescribed fire, or removed for energy purposes. Han et al. (2015) provided the full description of the redwood forest management and harvest in the US.

2.4.3 Manufacturing of redwood lumber

The main unit processes in the manufacturing of redwood lumber considered were resource transport, log yard, sawing, drying, and planing with cogeneration of electricity and heat considered as auxiliary processes.

2.4.3.1 Log (resource) transport Log transportation started from the forest landing in the woods and included loading at the landing and unloading at the sawmill. Saw-logs (127% MC) harvested from the redwood forest were transported to mills by diesel logging trucks. The weighted average distance of log (round-wood) transport by trucks was estimated to be 74.6 km (one way).

2.4.3.2 Log yard The log yard operation started with logs unloading from trucks, and then sorted into piles. Log stackers or front-end loaders transported logs from the yard to the sawmill (the debarking unit). On arrival at the log yard, logs were scaled using the appropriate scale, i.e., Scribner short in thousand bf (Fonseca 2005). The procurement of redwood logs is seasonal, i.e., during the summer months. Therefore, 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 (Bergman 2021). To prevent checking or splitting, logs stored in the log yard were sprayed with a water sprinkler. The log yard unit operation inputs included logs with bark, fuel, electricity, water, and lubricants. Outputs included logs with bark and emissions from burning the fuels used by the log handling equipment.

2.4.3.3 Sawing The first modeled step of the sawing unit operation was debarking where the bark is removed from logs in a debarker. In the sawing process, incoming redwood logs were sawn into various dimensions [Table A2 (Sahoo and Bergman 2020)] of rough-green lumber. This unit operation is typically a major source of electrical consumption for producing lumber products (Bergman et al. 2014b). Based on the customer demand, a certain volume of rough-green lumber was stacked and packaged

Table 2 GHG emissions from wood landfilled with standard methane capture (Bergman et al. 2013a)

GHG emissions	kg GHG per ODkg wood
Methane, biogenic[1]	9.00E−03
Carbon dioxide, biogenic[a]	3.03E−02
Carbon dioxide, biogenic[b]	1.16E−01
Carbon dioxide, biogenic[c]	4.95E−02

[a]Released directly into the air

[b]Released after energy recovery (70%)

[c]Release after flaring (30%)–energy not recovered

for delivery. The remaining portion of rough-green lumber was stickered for drying, either kiln drying, air drying, or moved to planing operation. Outputs from the sawing process by mass include rough-green lumber (49%), wood chips (15%), bark (12%), sawdust (5%), hog fuel (12%), and shavings (7%). Hog fuel consists of a mixture of wood residues, and some mills ground all wood residues into hog fuel. About 19% of wood residues left the system boundary and trucked off-site. The remaining (32%) wood residues were used in-house in a co-generation unit to produce heat and electricity.

2.4.3.4 Drying Second-growth redwood has a high moisture content of about 127% dry basis (Alden 1997; Bergman et al. 2014b). Air drying is typically done to bring the high moisture content down to the FSP (fiber saturation point) which is about 30%, and air drying reduces the kiln-drying effort which is an energy-intensive process (Bergman and Bowe 2010; Comstock 1975). Drying decreases the volume of lumber after they dry below the FSP (although the mass of the wood per board remains constant). Sawmills account for wood shrinkage when lumber dries (Bergman and Bowe 2010). The drying of lumber was modeled by either air-drying (rough-air-dry) or kiln-drying (rough-kiln-dry) based on the climate and time to fulfill customer demand. Of the original 100% rough green lumber produced, 30% was dried to 15–19% MC, mostly in a dry kiln. The output from this operation is either packaged and sold to the customers or moved to the next operation, i.e., planing. The inputs for this unit operation were electricity and liquid fuel for operating handling equipment and natural gas for boiler generating steam used in kiln drying. However, some of the sawmills used waste heat from the co-generation unit in the kiln for drying lumber.

2.4.3.5 Planing Redwood sawmills produced planed-green, planed-kiln-dry, and planed-air-dry lumber. Rough green and dry lumber are usually planed on all four sides, which produces planer shavings, a wood residue. Inputs into the planing process include rough (green or dry) lumber, whereas outputs include planed (green or dry) lumber (98%) and planer shavings (2%). The planer shavings were modeled as a solid fuel for on-site co-generation that generates heat and electricity which was used internally, with excess electricity exported to the grid.

2.4.3.6 Co-generation Thermal energy in the form of steam used in the sawmill especially the kiln drying process was provided by burning of either natural gas or wood residue. In this study, co-generation was considered as an auxiliary process where mill residues were burned in a wood boiler to produce steam which was further used to produce renewable electricity and heat. Renewable electricity was used in the sawmill, and excess electricity was exported to the grid. Some of the sawmills (those having co-generation units) use waste heat from co-generation in the kiln for lumber drying. However, the amount of heat generated in the co-generation was more than the sawmill's heat requirement, and thus, excess heat from cogeneration was disposed to air as waste heat. Outputs from the co-generation process were electricity, heat, solid waste (wood ash), and air emissions (e.g., CO_2, CO) from combustion. The input in the cogeneration process was wood residues generated in the sawmill, water for the boiler, and boiler chemicals.

2.4.4 Product transport

Sawmill manufactured five categories of lumber products and primarily used for making decks within the region of manufacture (U.S. West Coast). Lumber products were transported from sawmills to warehouses and then from warehouses to installation sites in a diesel engine flatbed trailer. The weighted transport distance between sawmill and warehouse and warehouse to installation site was assumed to be 300 km and 20 km, respectively (Bergman et al. 2013a).

2.4.5 Installation and use

This portion of the assessment covered the ancillary material requirements and processes involved in the installation, use, and maintenance of decking products throughout their service life of 25 years. The use phase accounted for all the material and energy inputs and processes associated with the installation, use, and maintenance. Due to the inherent natural durability of redwood, no chemicals such as preservatives were applied to the redwood decking material. However, a mass loss of 3% due to trimming and finishing during the installation of the deck was accounted for. We have assumed no additional repair and maintenance inputs during the use phase of the deck until its removal at its end of life.

2.4.6 Demolition and disposal of wood waste

At the end of service life, redwood decking was simply demolished, and wood waste was disposed of in a MSW landfill. It was assumed that redwood waste was transported to a local landfill in a diesel engine dump truck, and the average transport distance was 40 km. A certain portion of the carbon in wood breaks down anaerobically when stored in a landfill and produces landfill gas that is composed of biogenic methane and biogenic carbon dioxide. Based on the WARM model estimation for wood, Table 2 estimates the amount of methane and carbon dioxide emitted from the landfill based on the different assumptions of capturing landfill gas and utilization as energy recovery and flaring. It was assumed that about 12% (Good 2016) of wood decomposed in the landfill. The rest of the assumptions were the same as presented in Bergman et al. (2013a).

2.5 Inventory approach

Primary (mill) data were collected from redwood lumber manufacturing sawmills (for the year 2017) through a detailed survey questionnaire to generate the gate-to-gate LCI for the LCA study. Surveys tracked energy and raw material inputs, product and co-product outputs, water and air emissions, and solid waste generation. Secondary data from peer-reviewed literature and public databases were used for the upstream and downstream supply chain of redwood lumber including pre-mill gate processes (such as forestry operations which include timber harvesting and log handling and transportation) and post-mill gate processes (such as transportation of lumber products, installation, use, demolition of the structure, and disposal of wood waste). For example, the data related to upstream forest operations for redwood logs came from Han et al. (2015) and downstream operations came from Bergman et al. (2013a). Secondary data, such as diesel, gasoline, natural gas, propane, grid electricity, chemicals, and transport, were taken from the DATASMART LCI database (LTS 2019) in SimaPro.

2.6 Cutoff rules

In the primary surveys, manufacturers were asked to report total hazardous air pollutants (HAPs) specific to their wood products manufacturing process regardless of whether they were less than the 1% cutoff. However, flows with significantly lower environmental influence and less than 1% of the cumulative mass and energy of the studied system were excluded according to the PCR (UL-Environment 2019b). Wood product facilities are required to report as surrogates for all HAPs according to Title III of the Clean Air Act Amendments of 1990. All HAPs are included in the LCI; no cutoff rules apply.

2.7 Data quality

The present study collected data from representative redwood lumber manufacturers that use average technology and survey a minimum of 50% of the redwood production capacity in the US. The annual production in 2017 by the three redwood sawmills surveyed was approximately 67% of the total redwood lumber production, 605,308 m^3 (WWPA 2018) in the US which was well above the original goal. The process-specific (i.e., primary) data were collected from each sawmill through survey and follow-up calls to complement any missing data and along with site visits. Furthermore, various empirical fundamental calculations were performed for mass and energy balance to validate the data collected through the survey and identify outliers. A mass balance (from material input to material output for each sawmill), energy comparison with other wood products, and a sensitivity analysis were conducted to quantify uncertainty in data 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 a weighted-average approach. The LCI flows were estimated considering the mass allocation approach (UL-Environment 2019a), and thus, all emissions, energy use, and material consumed were assigned to the redwood lumber as well as redwood residues, including green chips, bark, sawdust, hog fuel from sawing process, and dry shavings from the planing process.

2.8 Assumptions and limitations

The data collection, analysis, and assumptions followed the protocol defined by CORRIM in "Research Guidelines for Life-Cycle Inventories" (2010). To conform to ISO 14,040 (ISO 2006b), additional considerations are listed below:

- Human labor, machinery, and infrastructure were considered to be outside system boundaries and therefore were not modeled in this analysis.
- Flow analyses of mass (logs, lumber, residues) in the process were determined on an oven-dry weight basis using the weighted-average specific gravity of 0.36 (green, 127%MC dry basis) and 0.38 (dry, 12%MC dry basis).
- The primary forest resource data were not collected but used secondary data from earlier LCA studies (Han et al. 2015) to develop the cradle analysis. The data included growing seedlings, planting, thinning, fertilization (where applicable), and final harvest.
- Secondary data from Bergman et al. (2013a) was used to build gate-to-grave LCI that includes product transporta-

tion, construction of deck using redwood lumber, use, demolition, and wood waste disposal.

- This study excluded land-use impacts, including biodiversity because redwood lumbers are coming from 2nd growth forests, and the forests were certified by Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) which is considered to be replanted, and eventually, harvested forestland returned to their previous state.
- The change in the forest carbon (increases and decreases) was not tracked but considered that the harvested trees were being sustainably managed based on the above two forest certification programs along with the California Forest Practices, one of the most stringent forest harvesting regulations in the US (Bergman et al. 2014b; Han et al. 2015).
- The study did not consider the temporal dimensions of greenhouse gas (GHG) emissions.
- Biogenic CO_2 emissions were tracked and reported, but the impact method does not count the contribution of wood-derived CO_2 emissions from burning wood fuel in the boiler toward the GW impact estimate because the wood was sourced from a sustainable source (ISO 2017).
- The carbon content for wood products was assumed to be 53% by mass of oven-dry wood (Bergman et al. 2013a).

2.9 Life-cycle impact assessment

SimaPro 9.0 software (Pré-Consultants 2020) was used to generate the LCI flows, and the LCIA was performed using the TRACI 2.1 method (Bare 2011). Ten impact categories were examined, including ozone depletion (kg chlorofluorocarbons-11 eq), global warming (GW [kg CO_2 eq]), photochemical smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogenic (CHUh), non-carcinogenic (CTUh), respiratory effects (kg PM2.5 eq, ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus) (UL-Environment 2019a).

3 Results and discussion

3.1 Mass balance for cradle-to-gate study

Table 3 summarizes the mass balance of redwood planed-dry lumber production. Using a weight-averaged approach, 2.18 m^3 [785 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. Mill residues were burned in a boiler to produce heat and electricity. Out of 405 OD kg of mill residues produced per declared unit, boilers burned 327 OD kg of mill residues on-site for thermal process energy. Overall, an average redwood log was decreased to 48.4% (380/785) of its original dry mass (with bark) during its conversion to planed-dry redwood lumber.

The conversion rate of planed dry lumber from redwood logs was similar to hardwood [43.7–46.5% (Bergman and Bowe 2008, 2012)] and softwood [42.2–50.3% (Bergman and Bowe 2010; Milota et al. 2005)] species in the US. Overall, 405 OD kg of residues were generated, and 81% (327 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 mulch and soil amendments. Redwood lumber in service stores carbon. The carbon content for redwood products was assumed to be 53% by mass of OD wood (Jones and O'hara 2011). Therefore, the carbon stored in 1 m^3 (380 OD kg) of redwood lumber was found to be equivalent to 738 kg CO_2, and this carbon storage effect continued for the life of the product.

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

	Sawing process		Co-generation	Dryer process		Planer process		All process combined		
Material (OD kg)	In	Out	In	In	Out	In	Out	In	Out	Diff
Green logs	785	–	–	–	–	–	–	785	0	−785
Green chips	–	115	93	–	–	–	–	93	115	23
Green sawdust	–	38	30	–	–	–	–	30	38	7
Green bark	–	95	76	–	–	–	–	76	95	19
Green shaving	–	55	45	–	–	–	–	45	55	11
Green hog fuel	–	95	77	–	–	–	–	77	95	19
Rough green Lumber	–	386		386	–	–	–	386	386	0
Rough dry lumber	–	–	–		386	386	–	386	386	0
Planed dry lumber	–	–	–	–	–	–	380	0	380	380
Dry shavings	–	–	6	–	–	–	6	6	6	0
Sum	785	785	327	386	386	386	386	1585	1585	−327

3.2 Material inputs and products outputs in cradle-to-gate study

Table 4 provides the product-specific and weighted-average (based on the mass balance of survey sawmills) inputs (resource, fuels and energy, chemicals, and ancillary materials) and outputs (lumber and mill residues) for the gate-to-gate lumber products manufacturing stage. Among the five categories of redwood lumber products, planed-dry lumber used maximum inputs, and rough-dry lumber used minimum inputs. A large part of the electricity and heat was generated in house (in co-generation unit) using mill residues, and thus, most mill residues were used internally while the excess was sold and leave the system. Excess heat from the co-generation unit was used to dry the lumber. Sawmills also burned some natural gas to augment heat from the wood boiler for the lumber drying process. The main material inputs were natural, i.e., redwood logs and water. Most water was for the drying, power generation, and log yard unit operations at the sawmills. Green and air dry lumber did not use heat, and therefore, the transport distance of chemicals used in the boiler was assumed to be zero.

3.3 Cumulative energy consumption

Table 5 shows the cumulative primary energy consumption in the production of 1 m^3 of redwood lumber. Cumulative

Table 4 Gate-to-gate material flow analysis of 1 m^3 of redwood lumber

Description	Unit	Rough-green	Rough-kiln-dry	Planed-green	Planed-kiln-dry	Planed-air-dry	Overall
Products out							
Lumber	m^3	1	1	1	1	1	1
Green chips (sold)	OD kg	22.51	23.76	22.89	24.16	24.16	23.03
Green sawdust (sold)	OD kg	7.35	7.76	7.48	7.89	7.89	7.52
Green bark (sold)	OD kg	18.53	19.55	18.84	19.89	19.89	18.96
Green shaving (sold)	OD kg	10.80	11.40	10.99	11.60	11.60	11.06
Dry shaving (sold)	OD kg	0.00	0.00	0.00	6.47	6.47	1.59
Green hog fuel (sold)	OD kg	18.54	19.57	18.86	19.91	19.91	18.97
Renewable electricity (exported to grid)	kWh	223.0	223.0	223.0	223.0	223.0	223.0
Resources inputs							
Water, well, in-ground	L	11.07	11.07	11.07	11.07	11.07	11.07
Water, municipal	L	45.86	67.74	73.44	95.32	73.44	62.29
Round redwood log	m^3	2.03	2.14	2.07	2.18	2.18	2.08
Fuels and energy inputs							
Diesel	L	0.85	1.19	1.51	1.85	1.51	1.19
Gasoline	L	0.03	0.10	0.08	0.15	0.08	0.07
Natural gas	Nm^3	0	8.49	0.04	8.53	0.04	2.51
Electricity (grid)	kWh	6.42	8.40	14.19	16.17	12.67	9.81
Electricity (co-generation)	kWh	21.91	28.66	48.44	55.19	43.24	33.46
Heat (biomass)	MJ	0	2519.46	0	2519.46	0	740.24
Chemicals inputs							
Oxygen scavenger (sulfite)	L	0	6.98E-03	0	6.98E-03	0	2.05E-03
Corrosion scale inhibiter	L	0	1.72E-02	0	1.72E-02	0	5.05E-03
pH adjuster	L	0	1.35E-01	0	1.35E-01	0	3.97E-02
Transport							
Resource transport	tkm	136.06	143.62	138.38	146.07	146.07	139.22
Chemicals transport	tkm	0	84.62	0	84.62	0	24.86
Ancillary material inputs							
Hydraulic fluid	kg	0.08	0.11	0.15	0.17	0.15	0.11
Motor oil	kg	0.06	0.09	0.13	0.15	0.13	0.09
Grease	kg	0.01	0.01	0.01	0.01	0.01	0.01
Plastic strapping	kg	0.01	0.01	0.12	0.13	0.13	0.05
Paint	kg	0.02	0.02	0.02	0.02	0.02	0.02
Replacement sticker	kg	0.73	1.01	1.38	1.65	1.38	1.05

energy consumption for cradle-to-gate manufacturing redwood lumber varied from 523 to 4,877 MJ/m^3 lumber based on the type of redwood lumber product. The redwood lumber product with the lowest and the highest cumulative energy demand was rough-green and planed-kiln-dry lumber products, respectively. The majority of primary energy consumption was in the lumber production (A3) stage, which varied from 51 to 94% of the cradle-to-gate cumulative energy demand. Non-renewable fossil energy was a notable part of cradle-to-gate primary energy use in the production of redwood lumber, i.e., 323 to 967 MJ/m^3 lumber. The non-renewable fossil energy used in the production of rough-green lumber was mainly due to the use of fossil fuel used mostly in the A1 (forest management and timber harvesting) and A2 (log transportation) production stages. In the other four lumber products, the non-renewable fossil energy contributes significantly more due to the use of fossil fuel, especially in the A3 production stage which was coming from the use of natural gas for heat in kiln-drying. The contribution of renewable energy in the production (A3-stage) of redwood lumber products varied between 195 and 3872 MJ/m^3 lumber (37–79% of cumulative primary energy demand), and most of those were coming from biomass (electricity and heat-related to co-generation). There was a large variation in the cumulative energy demand among the redwood lumber products. At the aggregate level (weighted-average of all redwood lumber product categories), renewable energy contributes about 69% of cradle-to-grave cumulative energy demand, and more than 99% is from biomass. Overall, primary energy consumption increased compared with the previous redwood decking study (Bergman et al. 2014b).

Compared with Bergman et al.'s (2014b) study, this study estimated a drastic reduction (i.e., ~40%) in energy from fossil but a multifold increase (~325%) in energy from renewable resources. In the cradle-to-gate analysis, we did not take the credit for the extra electricity that was generated on-site but sold off-site. In retrospect, the wood product industry generates energy in-house by burning wood fuel generated on-site (Puettmann et al. 2010b). Redwood lumber production, especially rough-green and planed-green, 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 US varies between 3000 and 6000 MJ/m^3 (Bergman and Bowe 2012; Milota and Puettmann 2017; Milota et al. 2005; Puettmann et al. 2010a, b). The low cumulative energy consumption for redwood decking occurs because of the minimal use of kiln-drying, which is the most energy-intensive part of producing a dry lumber product.

3.4 Environmental emission profile

Table 6 lists the environmental emissions for manufacturing 1 m^3 of redwood lumber for cumulative emissions for both cradle-to-gate and gate-to-grave along with direct on-site emissions. The cumulative values included all emissions which were higher than the on-site emissions, as expected. In the cradle-to-gate system boundary, biogenic CO_2 and fossil CO_2 were 16–323 and 22–59 kg/m^3, respectively, based on the type of redwood lumber. In the gate-to-cradle system boundary, biogenic CO_2 and fossil CO_2 were 86–397 and 56–87 kg/m^3, respectively, based on the type of redwood lumber. Biogenic CO_2 emissions were generated either in the mill (gate-to-gate) or in the landfill. However, the contribution of lumber production (gate-to-gate system boundary) toward total fossil CO_2 emissions (cradle-to-grave) ranged from 5 to 28% depending on the type of lumber. For example, only 5.4% and 27.6% of total cradle-to-grave fossil CO_2 emissions contributed to lumber production for rough-green lumber and planed-dry lumber, respectively. Drying and planing operations add substantial fossil CO_2 emissions in planed-dry lumber. For the cumulative case, fossil CO_2 was about 0.5–5 times the fossil CO_2 emitted for the on-site case, whereas biogenic CO_2 emissions were the same for both cases. 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. Irrespective of lumber types, more than two-thirds of total cumulative fossil CO_2 emissions were contributed by the gate-to-grave (especially product transport and disposal) portion of the lumber lifecycle stage mainly due to fuel used in transport and fugitive methane emissions from landfill.

3.5 Cradle-to-gate and cradle-to-grave life-cycle impact assessments

Table 7 shows midpoint environmental impacts (both cradle-to-gate and cradle-to-grave) for five categories of redwood lumber products without considering the credits from co-generating renewable electricity from burning mill residues. In all ten environmental impact categories, the trends are similar among the five types of redwood lumber products. Except for the fossil fuel depletion, redwood lumber's cradle-to-grave lifecycle impacts were higher than cradle-to-gate due to additional fuel use mainly during product transportation and fugitive methane emissions from landfills in the disposal of lumber products. The cradle-to-grave fossil fuel depletion impact was lower than cradle-to-gate as landfill gas was generated

Table 5 Cumulative primary energy consumption in the production for 1 m^3 redwood lumber, cradle-to-gate, mass allocation

	Rough-green				Rough-kiln-dry				Planed-green				Planed-kiln-dry				Planed-air-dry				Overall			
	A1	A2	A3	Total	A1	A2	A3	Total	A1	A2	A3	Total	A1	A2	A3	Total	A1	A2	A3	Total	A1	A2	A3	Total
Non-renewable, fossil	171.6	82.3	69.0	322.9	181.1	86.8	569.7	837.7	174.5	83.7	193.8	452.0	184.2	88.3	694.4	967.0	184.2	88.3	197.6	470.2	218.22	93.50	267.00	578.72
Non-renewable, nuclear	0.0	0.0	4.8	4.8	0.0	0.0	24.0	24.0	0.0	0.0	17.9	17.9	0.0	0.0	37.1	37.1	0.0	0.0	18.1	18.2	0.04	0.00	30.51	30.55
Renewable, biomass	0.0	0.0	189.4	189.4	0.0	0.0	3277.6	3277.6	0.0	0.0	740.0	740.0	0.0	0.0	3828.2	3828.3	0.0	0.0	750.5	750.6	0.02	0.00	1348.42	1348.44
Renewable, wind, solar, geothermal	0.0	0.0	1.9	1.9	0.0	0.0	10.4	10.4	0.0	0.0	7.4	7.4	0.0	0.0	15.9	15.9	0.0	0.0	7.5	7.5	0.00	0.00	0.68	0.69
Renewable, water	0.2	0.0	3.4	3.6	0.2	0.0	18.6	18.8	0.2	0.0	13.4	13.6	0.2	0.0	28.6	28.8	0.2	0.0	13.6	13.8	0.20	0.00	3.70	3.90
Total	171.8	82.3	268.5	522.6	181.4	86.8	3900.3	4168.5	174.7	83.7	972.5	1230.9	184.5	88.3	4604.3	4877.1	184.5	88.3	987.5	1260.2	218.49	93.50	1650.31	1962.30

Table 6 Direct emissions outputs resulting from the production of 1 m^3 of redwood lumber products, mass allocation

	1-RGL			2-RDL			3-PGL			4-PDL			5-PASL		
Substance	Cradle-to-gate (kg/m^3)	On-site (kg/m^3)	Gate-to-grave (kg/m^3)	Cradle-to-gate (kg/m^3)	On-site (kg/m^3)	Gate-to-grave (kg/m^3)	Cradle-to-gate (kg/m^3)	On-site (kg/m^3)	Gate-to-grave (kg/m^3)	Cradle-to-gate (kg/m^3)	On-site (kg/m^3)	Gate-to-grave (kg/m^3)	Cradle-to-gate (kg/m^3)	On-site (kg/m^3)	Gate-to-grave (kg/m^3)
Water effluents															
BOD5 (biological oxygen demand)	9.65E−03	5.70E−03	9.77E−03	2.36E−02	1.94E−02	2.17E−02	1.85E−02	1.44E−02	1.86E−02	3.24E−02	2.81E−02	3.05E−02	1.90E−02	1.48E−02	1.75E−02
Chloride	8.49E−01	1.36E−01	5.98E−01	2.12E+00	1.37E+00	1.52E+00	1.05E+00	3.24E−01	7.98E−01	2.32E+00	1.56E+00	1.72E+00	1.10E+00	3.31E−01	5.54E−01
COD (chemical oxygen demand)	1.44E+01	6.11E+00	1.88E+01	3.15E−02	2.28E−02	3.19E−02	2.21E−02	1.37E−02	2.65E−02	3.92E−02	3.03E−02	3.96E−02	2.29E−02	1.40E−02	2.40E−02
DOC (dissolved organic carbon)	4.50E−03	3.28E−03	8.18E−03	8.52E−03	7.23E−03	1.15E−02	8.02E−03	6.77E−03	1.17E−02	1.20E−02	1.07E−02	1.50E−02	8.27E−03	6.96E−03	1.14E−02
Oils, unspecified	1.24E−03	7.78E−04	1.26E−03	3.26E−03	2.77E−03	3.06E−03	2.38E−03	1.91E−03	2.40E−03	4.40E−03	3.91E−03	4.21E−03	2.45E−03	1.96E−03	2.29E−03
Suspended solids, unspecified	2.07E−01	1.55E−01	2.81E−01	1.68E+00	1.62E+00	1.73E+00	4.05E−01	3.52E−01	4.79E−01	1.87E+00	1.82E+00	1.93E+00	4.17E−01	3.60E−01	4.75E−01
Industrial waste[a]															
Waste in inert landfill		2.67E−01			2.67E−01			2.67E−01			2.67E−01			2.67E−01	
Waste to recycling		2.22E−01			2.22E−01			2.22E−01			2.22E−01			2.22E−01	
Solid waste[b]		1.11E−01			1.11E−01			1.11E−01			1.11E−01			1.11E−01	
Air emissions															
Acetaldehyde	6.60E−05	2.06E−05	7.18E−05	2.35E−04	1.87E−04	2.41E−04	1.06E−04	5.98E−05	1.12E−04	2.75E−04	2.26E−04	2.81E−04	1.10E−04	6.10E−05	1.16E−04
Acrolein	1.84E−05	1.29E−05	1.92E−05	1.44E−04	1.39E−04	1.45E−04	4.89E−05	4.32E−05	4.96E−05	1.75E−04	1.69E−04	1.76E−04	4.99E−05	4.40E−05	5.07E−05
Benzene	1.08E−04	5.28E−05	1.16E−04	3.12E−04	2.53E−04	3.20E−04	2.30E−04	1.74E−04	2.38E−04	4.33E−04	3.74E−04	4.41E−04	2.36E−04	1.77E−04	2.44E−04
CO	2.17E−01	5.30E−02	4.10E−01	7.46E−01	5.73E−01	9.04E−01	3.34E−01	1.68E−01	5.27E−01	8.64E−01	6.88E−01	1.02E+00	3.46E−01	1.71E−01	5.13E−01
CO_2 (biomass (biogenic))	15.98	15.96	86.33	276.11	276.09	350.36	62.39	62.37	132.74	322.52	322.50	396.77	63.28	63.26	137.53
CO_2 (fossil)	21.74	4.26	56.49	51.03	32.58	79.02	29.67	11.89	64.43	58.99	40.22	86.98	30.90	12.13	60.43

Table 6 (continued)

Substance	1-RGL Cradle-to-gate (kg/m^3)	1-RGL On-site (kg/m^3)	1-RGL Gate-to-grave (kg/m^3)	2-RDL Cradle-to-gate (kg/m^3)	2-RDL On-site (kg/m^3)	2-RDL Gate-to-grave (kg/m^3)	3-PGL Cradle-to-gate (kg/m^3)	3-PGL On-site (kg/m^3)	3-PGL Gate-to-grave (kg/m^3)	4-PDL Cradle-to-gate (kg/m^3)	4-PDL On-site (kg/m^3)	4-PDL Gate-to-grave (kg/m^3)	5-PASL Cradle-to-gate (kg/m^3)	5-PASL On-site (kg/m^3)	5-PASL Gate-to-grave (kg/m^3)
CH_4	2.62E−02	3.71E−03	3.18E+00	3.41E−02	1.03E−02	3.35E+00	3.08E−02	7.95E−03	3.19E+00	3.87E−02	1.46E−02	3.36E+00	3.23E−02	8.16E−03	3.35E+00
Formaldehyde	2.05E−04	1.34E−04	2.15E−04	2.11E−03	2.04E−03	2.12E−03	5.63E−04	4.91E−04	5.73E−04	2.47E−03	2.39E−03	2.48E−03	5.75E−04	4.99E−04	5.85E−04
Mercury	8.12E−08	6.70E−08	1.15E−07	5.87E−07	5.72E−07	6.15E−07	2.61E−07	2.47E−07	2.95E−07	7.67E−07	7.51E−07	7.95E−07	2.65E−07	2.50E−07	2.95E−07
NO_x	2.94E−01	5.56E−02	5.55E−01	5.31E−01	2.79E−01	7.46E−01	3.75E−01	1.32E−01	6.36E−01	6.12E−01	3.55E−01	8.27E−01	3.92E−01	1.35E−01	6.18E−01
Non-methane VOC	2.09E−02	1.05E−02	4.15E−02	1.07E+00	1.06E+00	1.09E+00	3.59E−02	2.53E−02	5.65E−02	1.08E+00	1.07E+00	1.10E+00	3.71E−02	2.59E−02	5.47E−02
Particulate (PM10)	1.34E−03	1.32E−03	1.49E−03	7.38E−03	7.35E−03	7.51E−03	5.00E−03	4.97E−03	5.14E−03	1.10E−02	1.10E−02	1.12E−02	5.07E−03	5.04E−03	5.20E−03
Particulate (unspecified)	1.91E−03	2.69E−04	4.93E−03	2.27E−03	5.35E−04	4.68E−03	2.28E−03	6.07E−04	5.29E−03	2.63E−03	8.74E−04	5.05E−03	2.38E−03	6.23E−04	4.94E−03
Phenol	5.59E−06	5.58E−06	5.59E−06	9.73E−05	9.73E−05	9.73E−05	2.19E−05	2.19E−05	2.19E−05	1.14E−04	1.14E−04	1.14E−04	2.22E−05	2.22E−05	2.22E−05
SO_x	1.55E−02	6.64E−03	−2.24E−01	5.91E−02	3.16E−02	−1.70E−01	4.12E−02	1.47E−02	−1.64E−01	6.99E−02	4.20E−02	−1.59E−01	2.90E−02	1.95E−02	−2.27E−01
VOC	1.66E−02	9.03E−03	2.06E−02	1.50E−01	1.42E−01	1.51E−01	4.09E−02	3.32E−02	4.48E−02	1.74E−01	1.66E−01	1.75E−01	4.18E−02	3.37E−02	4.36E−02

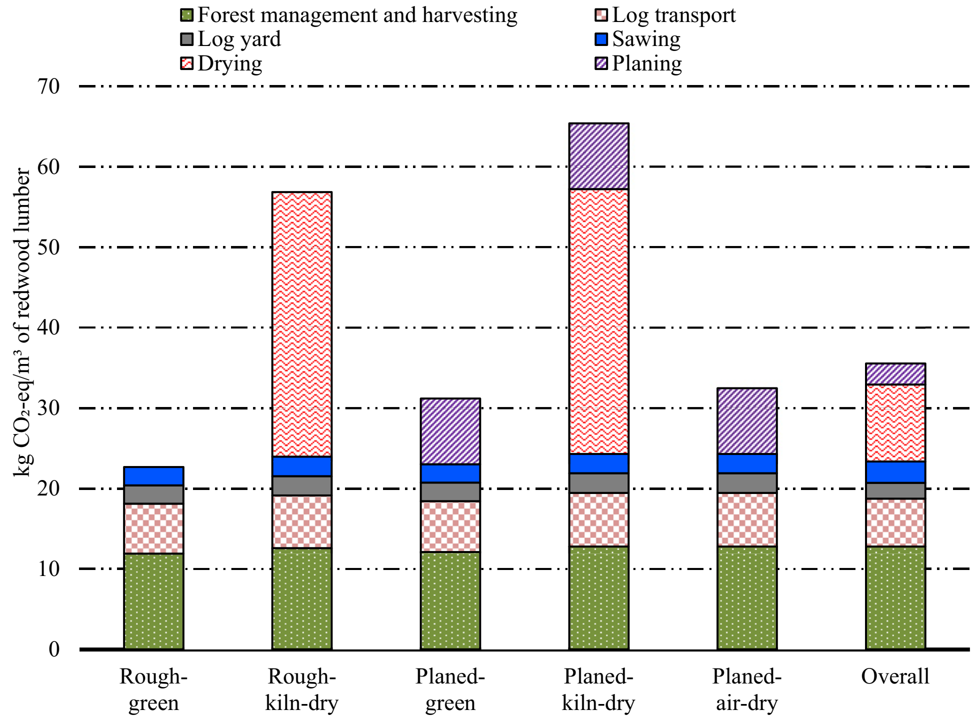
[a] Includes solid materials not incorporated into the product or co-products but left the system boundary

[b] Solid waste was boiler ash from burning wood. Wood ash is typically used a soil amendment or landfilled

Table 7 Cradle-to-gate and cradle-to-grave environmental performance of 1 m^3 redwood lumber

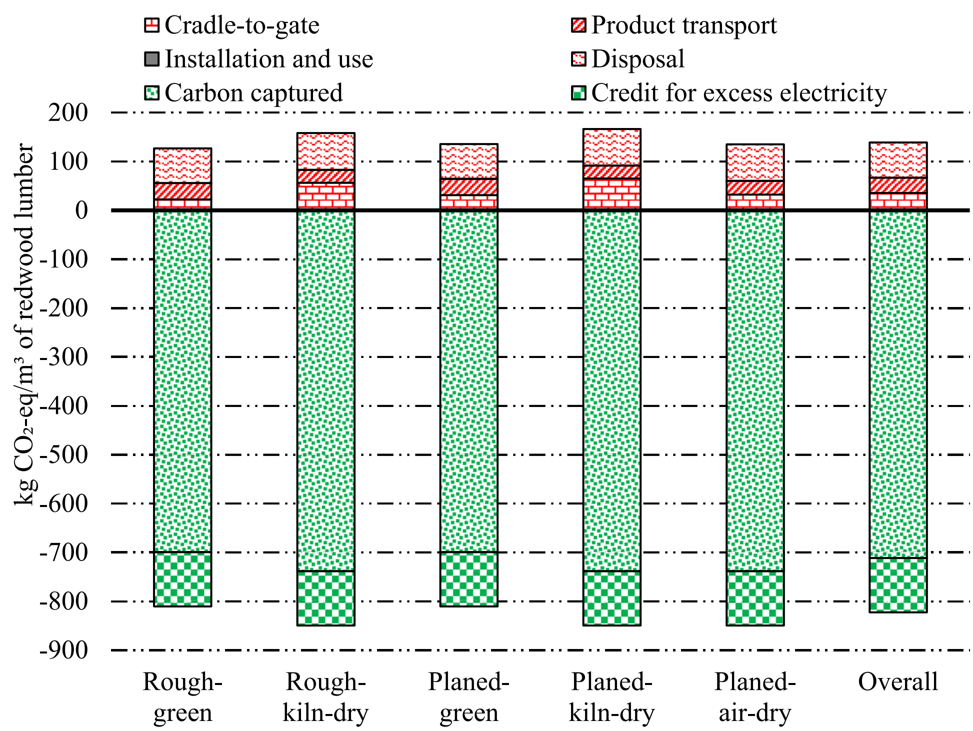
		Rough-green		Rough-kiln-dry		Planed-green		Planed-kiln-dry		Planed-air-dry		Lumber (aggregate)	
Impact category	Unit	Cradle-to-gate	Cradle-to-grave	Cradle-to-gate	Cradle-to-grave	Cradle-to-gate	Cradle-to-grave	Cradle-to-gate	Cradle-to-grave	Cradle-to-gate	Cradle-to-grave	Cradle-to-gate	Cradle-to-grave
Ozone depletion	kg CFC-11 eq	2.8E−07	3.0E−07	1.2E−06	1.3E−06	8.8E−07	3.0E−07	1.9E−06	1.9E−06	9.0E−07	9.2E−07	8.1E−07	8.3E−07
Global warming	kg CO2 eq	22.68	127.21	56.85	158.16	31.20	127.56	65.38	166.68	32.48	135.39	35.55	139.09
Smog	kg O3 eq	7.37	13.84	8.86	14.22	9.46	13.96	15.83	21.19	9.88	15.50	9.90	16.03
Acidification	kg SO_2 eq	0.24	0.22	0.30	0.22	0.31	0.22	0.52	0.44	0.33	0.26	0.32	0.28
Eutrophication	kg N eq	0.03	0.04	0.10	0.11	0.07	0.04	0.14	0.15	0.07	0.08	0.07	0.08
Carcinogenic	CTUh	4.8E−07	9.7E−07	1.2E−06	1.6E−06	1.0E−06	9.7E−07	1.8E−06	2.2E−06	1.0E−06	1.5E−06	9.3E−07	1.4E−06
Non-carcinogenic	CTUh	3.4E−06	6.8E−06	5.5E−06	7.9E−06	5.3E−06	6.8E−06	8.5E−06	1.1E−05	5.5E−06	8.1E−06	5.1E−06	8.1E−06
Respiratory effects	kg PM2.5 eq	0.01	0.00	0.06	0.04	0.03	0.00	0.08	0.06	0.03	0.02	0.03	0.02
Ecotoxicity	CTUe	75.87	130.59	119.74	154.80	123.75	131.66	193.52	228.58	128.02	167.12	114.64	163.38
Fossil fuel depletion	MJ surplus	44.87	32.95	96.81	66.97	58.70	33.66	127.62	97.77	61.24	34.46	68.98	51.60

Fig. 2 Contribution of unit operations in the cradle-to-gate GW impact of redwood lumber products



and captured in the disposal of lumber products for energy production which offset fossil fuel use. Among all redwood lumber categories, rough-green and planed-dry lumber had the lowest and highest cradle-to-gate environmental impacts and energy use, respectively. Overall, the cradle-to-gate and cradle-to-grave GW impacts were 23–65 and 127–167 kgCO_2-eq/m^3 of redwood lumber products. Only 18–39% of total redwood lumbers' GW impact was contributed by the cradle-to-gate life-cycle stage. This is consistent with the previous study (Bergman et al. 2013b). The contribution of GW impact from the gate-to-grave life-cycle stage was more than half of the total GW impact and mainly contributed by product transportation and disposal at the end-of-life. However, the cradle-to-gate lifecycle stage of redwood lumber

Fig. 3 Cradle-to-grave and net GW impacts of various redwood lumber products in the US



has a higher contribution for other environmental impact categories including ozone depletion, acidification, and fossil fuel depletion. Overall, the cradle-to-gate environmental profiles (weighted-average) of redwood lumber production (gate-to-gate) such as GW and ozone depletion were reduced by two to four times compared with the previous study (Bergman et al. 2014b) mainly because of energy and power mix improvements such as more energy came from renewable co-generation along with a notable reduction in electricity usage in sawmill operations.

Figure 2 shows the detailed contribution of different unit operations on the cradle-to-gate GW impact of redwood lumber production. Forestry management and harvesting (A1), log transport (A2), and drying and planing in lumber production (A3) are major unit operations contributing to the cradle-to-gate GW impact.

Overall, A1, A2, and drying (A3) contribution to the total GW of redwood lumber was 36%, 17%, and 27%, respectively. Because of the use of diesel in harvesting equipment and logging trucks, most GW and fossil fuel

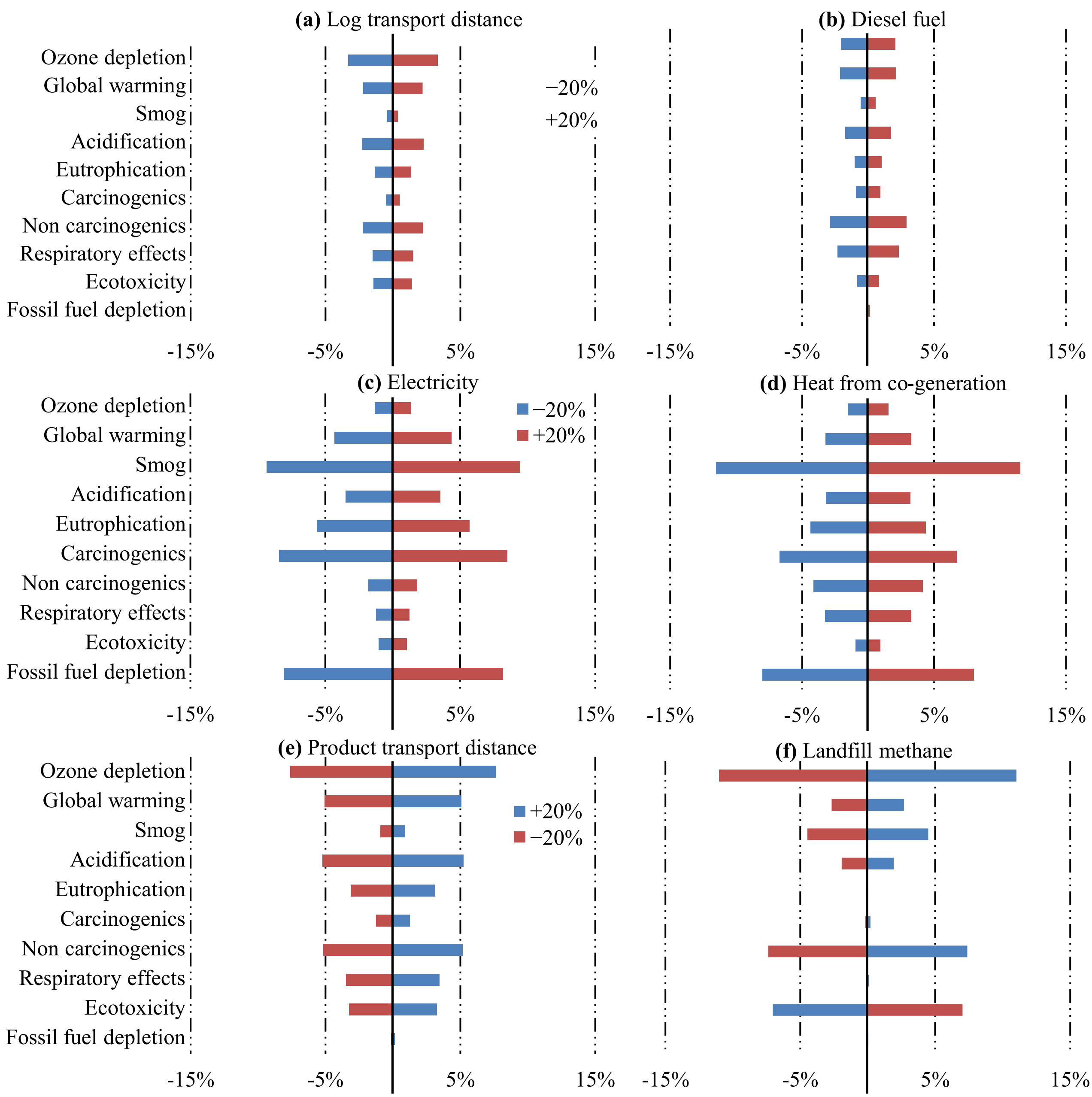


Fig. 4 Influences of variations in input parameters [(**a**) long transport distance, (**b**) diesel fuel used in the mill, (**c**) electricity used in the mill, and (**d**) heat or thermal energy used in drying lumber, (**e**) product transport distances, and (**f**) fugitive methane emissions from landfill redwood lumber] on the cradle-to-grave environmental impacts of redwood lumber (aggregate at the product level)

depletion impacts were from forestry operation and transportation of logs from forest landing to the mills. However, the use of natural gas used in drying unit operation was the major GHG emission for redwood lumber production (A3).

Figure 3 shows the GW impacts from various lifecycle stages of redwood lumber. This figure also shows the reduction in the GW impact from carbon stored in wood products and GW credits from excess renewable electricity supplied to the local grids from the co-generation unit that burns mill residues. Irrespective of the type of products, unit operations such as product transport and disposal have a substantial contribution toward the total GW impact of redwood lumber. Redwood lumbers are mainly used in decking and required minimal maintenance and consume resources in its use, e.g., semiannual washing of deck for 25 years. Thus, GW impact from product installation and use stages was negligible. Redwood lumber products disposed of in the landfill after their useful life contribute about 50% of the total cradle-to-grave GW impact.

The cradle-to-grave GW impact of redwood lumber was 127–167 $kgCO_2eq/m^3$ of lumber. However, redwood lumber products store 597 to 630 $kgCO_2eq$ per cubic meter of lumber disposed of in the landfill. Moreover, excess electricity supplied to the local grid displaced fossil electricity, i.e., 111 $kgCO_2eq$ per cubic meter of lumber. Considering the credit from renewable electricity supplied to the local grid, each cubic meter of redwood lumber can reduce GW impact by 708–741 $kgCO_2eq$. Therefore, each cubic meter of redwood lumber reduces GHG emissions by 3–5 times compared to its cradle-to-grave GHG emissions released. Thus, redwood lumber acts as a carbon sink and carbon-negative product.

4 Sensitivity analysis

Figure 4 shows the sensitivity results of six critical inputs that impacted the cradle-to-gate environmental impact of redwood lumber (weighted-average of all five product types). The percentage variations in the environmental impacts from the base case were estimated by increasing and decreasing the value of an input variable from its mean and keeping the rest of the input variables at their mean values.

Figure 4 illustrates that each input variable did not have a similar influence on all environmental impact categories. For example, variations in electricity use have a substantial impact on smog and fossil fuel depletion compared to ecotoxicity and respiratory effects. Among all impact categories, GW impact was influenced by almost all six major inputs, but a higher impact was from the product transport distance followed by electricity. Therefore, redwood lumber should be used in the area it was produced than transporting to a longer distance unless rail is used which has a much smaller impact per distance traveled than the typical tractor-trailer. Higher electricity and heat used in the production of redwood lumber have a substantial impact on smog and fossil fuel depletion. Hence, it may better to use rough green and air-dried redwood lumber than kiln-dried redwood lumber. Log transport distance has less influence on the cradle-to-grave environmental impacts, and hence, mills can procure logs from longer distances compared to this study which was only 73 km from the redwood forest to the sawmill. The sensitivity results presented here can help stakeholders such as redwood lumber manufacturers to focus on inputs and optimize the process to reduce a target environmental impact.

5 Conclusions

This study analyzed the cradle-to-grave (cradle-to-gate and gate-to-grave) environmental impacts of various categories of redwood products (such as rough-green, planed-green, rough-kiln-dry, planed-kiln-dry, and planed-air-dry lumber) in the US. The cradle-to-gate life-cycle assessment includes the LCI of (i) redwood forest management (A1), (ii) log transportation (A2), and (iii) lumber production that consists of log yard operation, debarking, sawing, drying, and planing (A3). The gate-to-grave life-cycle assessment included product transport, construction of the redwood deck and its use for 25 years, demolition of the deck, transportation of redwood lumber waste to the landfill, and decomposition of redwood in the landfill that capture 75% of methane generated from it. The primary data used in the cradle-to-gate study were collected through surveys and plant visits in the year 2017 for the participating sawmills. Data used for the gate-to-grave was taken from the available literature. The data were representative of the US redwood lumber market, and the combined production capacity of the surveyed sawmills was more than 67% of the redwood lumber market in the US.

The mass balance results for cradle-to-gate analysis showed that on average, 2.18 m^3 of redwood logs is required to produce 1 m^3 (380 dry kg) of lumber. About 48% and 52% of total log dry mass were converted to the lumber and mill residues respectively. But 81% of the total mill residues were used on-site in co-generation to produce heat and electricity. After fulfilling the electricity demand of the sawmill, the co-generation unit supplies excess electricity to the local grid (223 kWh/m^3 of lumber).

The cradle-to-gate LCIA results revealed that the lumber production stage (A3) was the greatest contributor to most of the impact categories and mostly coming from drying unit operation. However, when the whole lifecycle stages were considered, i.e., cradle-to-grave, the LCIA results showed that the product disposal stage (C3) especially landfill unit operation had the largest environmental impacts among all operations considered. There was a large difference in the cradle-to-gate environmental impacts among five categories of redwood lumber products. Rough-green and planed-kiln-dry lumber had the lowest and highest environmental impacts, respectively. Kiln-drying was the most energy-intensive among all unit operations in the production of lumber. The cradle-to-gate and cradle-to-grave GW impacts were varied from 22 to 65 and from 127 to 167 kg CO_2 eq/m^3 of redwood lumber, respectively. Considering the carbon storage in wood as part of the cradle-to-grave analysis, redwood lumber mitigates GHG emissions. The final products store 3–5 times more GHG emissions over than what is released from cradle-to-grave. Thus, redwood lumber acts as a carbon-negative product or carbon sink.

Acknowledgements We gratefully acknowledge those companies and their employees that participated in the surveys to obtain production data.

Funding Financial assistance was provided to the USDA Forest Service, Forest Products Laboratory, for this research project (19-CO-11111137–010).

References

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

Alden HA (1997) Softwoods of North America vol 102. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI

AWC (2020) Environmental Product Declaration, Redwood Lumber. American Wood Council

Bare J (2011) TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0 Clean Technol Environ Policy 13:687–696

Bergman R (2021) Drying and control of moisture content and dimensional changes. In: Wood handbook—wood as an engineering material. US Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI

Bergman R, Han H-S, Oneil E, Eastin I (2013a) Life-cycle assessment of redwood decking in the United States with a comparison to three other decking materials. The Consortium for Research on Renewable Industrial Materials (CORRIM), Seattle, WA, USA

Bergman R, Puettmann M, Taylor A, Skog KE (2014a) The carbon impacts of wood products. For Prod J 64:220–231. https://doi.org/10.13073/FPJ-D-14-00047

Bergman R, Taylor A (2011) EPD-environmental product declarations for wood products—an application of life cycle information about forest products. For Prod J 61:192–201

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

Bergman RD, Bowe SA (2010) Environmental impact of manufacturing softwood lumber in northeastern and north central United States. Wood Fiber Sci 42:67–78

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

Bergman RD, Falk RH, Gu H, Napier TR, Meil J (2013b) Life-cycle energy and GHG emissions for new and recovered softwood framing lumber and hardwood flooring considering end-of-life scenarios, vol 672. USDA Forest Service, Forest Products Laboratory, Madison, WI, USA

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

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

Canadell JG, Raupach MR (2008) Managing Forests for Climate Change Mitigation Science 320:1456–1457. https://doi.org/10.1126/science.1155458

Comstock GL (1975) Energy requirements for drying of wood products. United States Department of Agriculture, Forest Service, Forest Products Laboratory

Consortium for Research on Renewable Industrial Materials (CORRIM) (2010) Research guidelines for life cycle inventories. http://www.corrim.org/pubs/reports/2010/phase1_interim/CORRIMResProtocols.pdf. Accessed 15 Feb 2021

Fargione JE, Bassett S, Boucher T et al (2018) Natural climate solutions for the United States. Sci Adv 4:eaat1869 https://doi.org/10.1126/sciadv.aat1869

Fonseca MA (2005) The measurement of roundwood : methodologies and conversion ratios. Wallingford, UK, Cambridge, MA

Gelowitz MDC, McArthur JJ (2017) Comparison of type III environmental product declarations for construction products: material sourcing and harmonization evaluation. J Clean Prod 157:125–133. https://doi.org/10.1016/j.jclepro.2017.04.133

Global Footprint Network (2020) Earth Overshoot Day. https://www.footprintnetwork.org. Accessed 15 May 2020

Good N-D (2016) Documentation for greenhouse gas emission and energy factors used in the waste reduction model (WARM)

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. J Clean Prod 99:217–229. https://doi.org/10.1016/j.jclepro.2015.02.088

Hektor B, Backéus S, Andersson K (2016) Carbon balance for wood production from sustainably managed forests. Biomass Bioenergy 93:1–5. https://doi.org/10.1016/j.biombioe.2016.05.025

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. ISO

ISO (2017) Sustainability in buildings and civil engineering works — core rules for environmental product declarations of construction products and services. ISO

Jakes JE, Arzola X, Bergman R et al (2016) Not just lumber—using wood in the sustainable future of materials, chemicals, and fuels. JOM 68:2395–2404. https://doi.org/10.1007/s11837-016-2026-7

James J, Page-Dumroese D, Busse M et al (2021) Effects of forest harvesting and biomass removal on soil carbon and nitrogen: two complementary meta-analyses. For Ecol Manage 485:118935. https://doi.org/10.1016/j.foreco.2021.118935

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta analysis. For Ecol Manage 140:227–238. https://doi.org/10.1016/S0378-1127(00)00282-6

Johnson K, Scatena FN, Pan Y (2010) Short- and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest. For Ecol Manage 259:1262–1267. https://doi.org/10.1016/j.foreco.2009.06.049

Jones DA (2011) O'hara KL. Carbon Density in Managed Coast Redwood Stands: Implications for Forest Carbon Estimation Forestry 85:99–110. https://doi.org/10.1093/forestry/cpr063

Jones T, Meder R, Low C et al (2011) Natural durability of the heartwood of coast redwood [Sequoia sempervirens (D. Don) Endl.] and its prediction using near infrared spectroscopy. J Near Infrared Spectrosc 19:381–389

LTS (2019) DataSmart LCI package (US-EI SimaPro® Library). https://ltsexperts.com/services/software/datasmart-life-cycle-inventory/

Malmsheimer RW, Bowyer JL, Fried JS et al (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. J For 109:S7-S50

Matos GR (2017) Use of raw materials in the United States from 1900 through 2014. Reston, VA

Milota M, Puettmann ME (2017) Life-cycle assessment for the cradle-to-gate production of softwood lumber in the pacific northwest and southeast regions. For Prod J 67:331–342. https://doi.org/10.13073/FPJ-D-16-00062

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

Oliver CD, Nassar NT, Lippke BR, McCarter JB (2014) Carbon, fossil fuel, and biodiversity mitigation with wood and forests. J Sustain Forest 33:248–275 https://doi.org/10.1080/10549811.2013.839386

Pré-Consultants (2020) SimaPro 9 life-cycle assessment software package, version 9.0. Pré-Consultants

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 Fiber Sci 42:15–28

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

Ritter MA, Skog K, Bergman R (2011) Science supporting the economic and environmental benefits of using wood and wood products in green building construction. United States Department of Agriculture, Forest Products Laboratory, Madison, WI

Sahoo K, Bergman R (2020) Cradle-to-gate life-cycle assessment of redwood lumber in the United States. US Department of Agriculture, Forest Service, Forest Products Laboratory

Sathre R, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Policy 13:104–114. https://doi.org/10.1016/j.envsci.2009.12.005

Save-The-Redwood-League, (2019) A momentous year great strides toward a 100-year vision. Save The Redwood League, San Francisco, CA

Save-The-Redwood-League (2021) Coast Redwoods Facts. https://www.savetheredwoods.org/redwoods/coast-redwoods/. Accessed 15 Feb 2021

Scheffer TC, Morrell JJ (1998) Natural durability of wood: a worldwide checklist of species. Oregon State University, Forest Research Laboratory, Corvallis, Oregon

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

UL-Environment, (2019b) Part A: life cycle assessment calculation rules and report requirements. UL Environment, Washington, DC

Wiemann MC (2010) Characteristics and availability of commercially important woods vol 190. USDA Forest Products Laboratory, Madison, WI

WWPA (2018) 2018 Statistical Yearbook of the Western Lumber Industry. Western Wood Products Association, Portland, OR

Authors and Affiliations

Kamalakanta Sahoo[1,2] · Richard Bergman[1] · Troy Runge[2]

[1] Forest Products Laboratory, United States Forest Service, Madison, WI 53726, USA

[2] Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA