United States Department of Agriculture

Cradle-to-Gate Life-Cycle Assessment of Redwood Lumber in the United States

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Forest Service
Forest Products Laboratory
Research Paper FPL–RP–706
October 2020

Abstract

Global demand for renewable and sustainable materials such as wood products is growing. To support this growth, a scientific approach is necessary to illustrate the environmental benefits of wood products. This report contains a detailed cradle-to-gate life-cycle assessment method including data collection, development of life-cycle inventory, and life-cycle impact assessment for production of redwood lumber in the United States. The results illustrated that redwood lumber production has a very low carbon footprint (37.97 kg CO_2e/m^3 of lumber) and stores about 18 times more carbon compared with its cradle-to-gate carbon footprint.

Keywords: Environmental impacts, wood, LCA, life-cycle inventory, cogeneration, product, EPD, redwood

Contents

October 2020

Sahoo, Kamalakanta; Bergman, Richard. 2020. Cradle-to-gate life-cycle assessment of redwood lumber in the United States. Research Paper FPL-RP-706. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 39 p.

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Cradle-to-Gate Life-Cycle Assessment of Redwood Lumber in the United States

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1 Executive Summary

1.1 Study Goals

The goal of this study was to conduct a cradle-to-gate life-cycle assessment (LCA) and update the environmental impacts associated with redwood (*Sequoia sempervirens*) lumber production in the United States (northern California). To develop a life-cycle inventory (LCI) and perform an LCA study, the authors collected primary data from redwood lumber production facilities per Consortium on Research for Renewable Industrial Materials (CORRIM) research guidelines. Using those LCI data, an LCA was produced for redwood lumber according to the Product Category Rule (PCR) for North American Structural and Architectural Wood Products. Comparative assertions were not the goal of this study.

1.2 Methodology

This study followed the International Organization for Standardization (ISO) 14040 and 14044 standards (ISO 2006a, 2006b) to conduct an LCA study. System boundaries delineated the life cycle from the extraction of raw material inputs through product production. In this study, the declared unit was 1 m^3 of redwood lumber (either dry or green and rough or planed). An industry standard production unit (such as MBF (thousand board feet)) was converted to a metric production unit (one cubic meter) of lumber. The authors collected primary mill data through a survey questionnaire emailed to redwood lumber manufacturing facilities followed by site visits of three major redwood lumber mills representing 66.6% of the total production volume of the redwood lumber industry in 2017. This survey collected all raw material inputs (including logs, fuel, heat, and electricity), outputs (product and coproducts), and pertinent emissions to water and air as well as solid waste generation. Secondary data, such as forestry operations and forest management, were from peer-reviewed literature per CORRIM guidelines, which included public LCA databases and other LCA studies. The mass and energy balances were calculated using primary and secondary data. The LCI flows and life-cycle impact assessment (LCIA) results were generated using LCA modeling software populated by the DATASMART database, which conformed with internationally accepted standards. The study used a mass-allocation approach to assign LCI and environmental impacts for the products and coproducts. The LCIA was performed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 and cumulative energy demand (CED) methods.

1.3 Life-Cycle Inventory

Cradle-to-gate LCI flows for manufacturing redwood lumber were presented by three life stages: (1) forestry operations [A1], (2) transportation of logs from forests to the sawmill [A2], and (3) lumber production including, sawing, drying, and planing [A3]. The unit process modeling approach was followed for conducting LCA. Lumber production was the most energy-intensive process among all followed by forestry operations and log transportation. Using lower heating values, the total cumulative primary energy consumption for cradle-to-gate production of redwood lumber was 1.93 GJ/m^3 of lumber. Most energy came from renewable resources (70.17%), whereas a small portion of energy needs came from nuclear (0.84%), and the remaining 29.00% came from fossil resources.

1.4 Life-Cycle Impact Assessment

The following seven impact categories were examined: 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 NO_x-eq), abiotic depletion potential for fossil resources (ADP fossil) (MJ), and fossil fuel depletion (MJ surplus). The LCI also provided additional information such as the use of primary energy resources consumption [energy consumption from nonrenewable, renewable (wind, hydro, solar, and geothermal), and nuclear fuels and renewable and nonrenewable resource consumption], water use, and indicators describing waste.

1.5 Key Findings

Contrary to most wood product production, emissions from the forest resources stage were relatively large compared with manufacturing emissions. The cradle-to-gate LCI results showed that 37.97 kg of fossil CO_2 was released in the production of 1 m^3 of redwood lumber. The carbon content for wood products is assumed to be 50% by mass

Table 1—Cradle-to-gate life-cycle impacts of 1 m^3 of redwood lumber production in the United States

Impacts	Units	Total
Impact category		
Global warming potential – TRACI 2.1	kg CO_2e	37.97
Global warming potential – w/ biogenic CO_2	kg CO_2e	37.97
Depletion potential of the stratospheric ozone layer	kg CFC11e	8.13E–07
Acidification potential of soil and water sources	kg SO_2e	0.35
Eutrophication potential	kg Ne	0.07
Formation potential of tropospheric ozone	kg O_3e	10.74
Abiotic depletion potential for fossil resources (ADP fossil)	MJ, NCV	511.45
Fossil fuel depletion	MJ surplus	73.97
Primary energy consumption		
Nonrenewable, fossil	MJ	559.82
Nonrenewable, nuclear	MJ	16.22
Renewable, biomass	MJ	1,335.13
Renewable, wind, solar, geothermal	MJ	6.94
Renewable, hydro	MJ	12.65

of oven-dried (OD) wood (Bergman and others 2014b), and 1 m^3 of redwood lumber stores 697 kg CO_2e. Lumber production (Module A3) consumed more than 84% of total cradle-to-gate primary energy. Because of large renewable energy inputs including electricity and heat from cogeneration by mill residues, the environmental impacts of redwood lumber production were lower compared with the environmental impacts of downstream operations (Modules A1 and A2). Moreover, cogeneration using mill residues generated 294 kWh of renewable electricity/m^3 of redwood lumber produced, from which about 76% was exported to the commercial grid.

About 70% of the total primary energy used in redwood lumber production comes from renewables, especially biomass (69% of total primary energy used in lumber production). About 48% of carbon in the logs is stored in lumber products, and a substantial part of the biogenic carbon is returned to the atmosphere by burning wood residues.

1.6 Sensitivity Analysis

A sensitivity analysis was completed per ISO 14040 to model the effects of raw material transport distance and consumption of energy including electricity, natural gas, diesel, and biomass for redwood lumber production. Overall, the variations in the environmental impacts from a 20% increase or decrease in electricity or heat or fuel used to produce redwood lumber were small (less than 10%). Similarly, a 20% increase or decrease in the transport distance of logs can increase or decrease the seven environmental impacts of redwood lumber by only 1% to 7%.

1.7 Interpretation

The results of this study provide the cradle-to-gate environmental impacts of redwood lumber production (Table 1). The authors compared energy inputs from the current study (2017 data) to the earlier CORRIM study of 2010 data on gate-to-gate redwood lumber. About a 43% increase in the use of primary energy was observed in this study compared with the previous study. Despite the increase in energy usage in this study compared with the previous study, there was a large decrease in the environmental impacts including GW because of the use of renewable resources. In this study, the energy generated by woody biomass constituted most of the total energy consumed and was more than four times higher than in the previous study. Similarly, the amount of energy used from the fossil-based source was one-half of the previous study. Compared with the previous study, there was a substantial decrease in environmental impacts of produced redwood lumber for major category indicators. This was caused by a considerable increase in the use of renewable electricity, especially on-site cogeneration of electricity using mill residues generated from the mills themselves.

1.8 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). Any opinions, findings, conclusions, or recommendations expressed in this article do not necessarily reflect the views of the contributing entities.

Abbreviations

BF	board feet
CLR	cubic lumber recovery
EPDs	environmental product declarations
GWP	global warming potential
ISO	International Organization for Standardization
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LF	lineal foot
LRF	lumber recovery factor
m^3	cubic meter
MBF	thousand board feet
MMBF	million board feet
odkg	oven-dry weight wood in kilograms
PCR	product category rules
tkm	tonne – kilometers

2 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 and others 2017). The demand for construction materials is predicted to grow because of global population growth and an increased standard of living (Bringezu and others 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 and others 2011). Combining carbon storage and carbon displacement by avoiding fossil-fuel-intensive construction materials, especially in buildings, is one of the most efficient options to mitigate climate change (Sathre and O'Connor 2010, Bergman and others 2014b, Oliver and others 2014). Because of environmental awareness and regulations, documenting the environmental performance of building products using LCA is becoming widespread and is the new accepted approach. Quantifying environmental performance for structural wood products is one way to generate green building certifications (Bergman and Taylor 2011), provide 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 2017).

Redwood (*Sequoia sempervirens*) lumber is used primarily for decking, fencing, and structural products in the western United States, and its demand has increased since the Great Recession in 2008 because of the growing housing market. Bergman and others (2013, 2014a) estimated the environmental impact of redwood decking (specifically the size 38 by 138 mm) compared with other alternative materials. However, with changes in the manufacturing process, sawmill size, and sawlog procurement distances, input resources especially electricity and drying requirements to produce redwood lumber of various dimensions have gone through substantial changes.

This report focuses on all redwood lumber products, including rough-green, rough-dry, planed-green, and planed-dry lumber produced in the northern California region. These products fall under the United Nations Standard Products and Services Code (UNSPSC) of 30103601 (wood beams), 30103605 (wood planks), 30103607 (wood joists), and 30152002 (wood fencing). Redwood lumber products fall under the building products category of sawn timber (lumber). The Construction Specification Institute (CSI) codes (UL Environment 2018) for these products are 06 10 00 (rough carpentry), 06 11 00 (wood framing), 06 15 00 (wood decking), 06 16 23 (subflooring), 06 16 33 (wood board sheathing), 06 17 43 (rim boards), 06 20 00 (finish carpentry), 06 22 00 (millwork), 06 26 00 (board paneling), 06 42 13 (wood board paneling), 06 43 00 (wood stairs and railings), 06 48 00 (wood frames), 09 64 29 (wood strip and plank flooring), 06 22 00 (millwork), 06 46 00 (wood trim), and 06 49 00 (wood screens and shutters). This report describes the energy and materials through a cradle-to-gate LCI on the major unit processes in redwood lumber manufacturing. The LCI data covered forest management and harvesting through to the final product at the sawmill gate. The environmental impacts GW, ozone depletion, acidification, smog, and eutrophication are discussed. In 2014, a similar study (but for planed-dry redwood decking) was performed with a similar goal and scope (Bergman and others 2014a).

Primary data were collected by surveying three redwood sawmills representing more than 66.6% of total redwood industry annual production (0.605 million m^3) primarily with a questionnaire and site visits to determine their material use and energy consumption for the 2017 calendar year (Appendix A). Peer-reviewed literature provided secondary data. Material balances, using data from primary and secondary sources, were constructed with a spreadsheet algorithm. The values were averaged after weighting by mill annual production to obtain an industry average. Inputs included logs, fuels, electricity, packaging materials, and (boiler) chemicals necessary for lumber production. Mill outputs included lumber and coproducts such as chips, sawdust, planer shavings, bark, and hog fuel. Redwood lumber production also consumed electricity and heat from cogeneration using mill residues generated during the lumber production process.

The data collection was performed under "CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products", undated, but current in the fall of 2012, a scientifically sound and consistent process established by CORRIM. It follows ISO 14040 standards and the PCR for North American Structural and Architectural Wood Products (UL Environment 2018, 2019). This process will guide the preparation of a redwood lumber EPD.

3 Goal and Scope

3.1 Goal and Objectives

3.1.1 Goals

The primary goal of this study was to generate a gate-to-gate LCI of redwood lumber manufacturing and link these data to develop a cradle-to-gate environmental profile of redwood lumber. The cradle-to-gate LCA followed data and reporting requirements as outlined in the PCR (UL Environment 2018) that guides the preparation of a business-to-business EPD.

3.1.2 Intended Audience

The primary audience for the results of this LCA report is redwood lumber producers in the United States, LCA practitioners, green building developers, and consumers.

3.1.3 Comparative Assertions

This report does not include product use (B1-B7) and end-of- life (C1-C4) phases, which are required for comparative assertions relative to substitute products. For consistency with ISO 14044 guidelines and principles and compliance with the Wood Products PCR (UL Environment 2018, 2019), the LCA boundary would need to be expanded to include the use and end-of-life phases, if future comparative studies are intended and disclosed to the public.

3.2 Scope of Considered System

3.2.1 Functional and Declared Unit

The purpose of the functional unit is to provide a reference to which all inputs and outputs are related and quantify the service delivered by the product system. The functional unit is used for EPDs covering the complete life cycle (i.e., cradle-to-grave) of a product. But a declared unit is used for EPDs that do not cover the complete life cycle (i.e., cradle-to-gate) of the product. In accordance with the PCR and ISO standards, the declared unit is one cubic meter (1.0 m^3) for redwood lumber (includes green-rough, dry-rough, dry-planed, etc.). The detailed product types are shown in Table 2 packaged for shipment at the mill gate. This analysis did not take the declared unit to the use stage; therefore, no service life was assigned. The cradle-to-gate LCI for redwood lumber was generated by examining the manufacturing data from sawmills located in northern California collected by survey for the year 2017 and subsequent site visits. The datasets for upstream manufacturing of forestry and harvesting operations were collected from previously published material (Han and others 2015).

Table 2—Types of redwood lumber products produced in 2017

Type of lumber product	Contribution (%)
Rough-green	58.02
Partially rough-green	6.62
Partially rough-dry	5.73
Partially rough-kiln-dry	0.19
Planed-green	5.06
Planed-dry	9.29
Planed-partial-dry	14.16
Planed-air-seasoned	0.92
Total	100

3.2.2 System Boundary

The cradle-to-gate system boundary is shown in Figure 1. The system boundary includes three information modules: (A1) forest management and resource harvesting; (A2) resource and material transportation from suppliers to the mill; and (A3) redwood lumber manufacturing process. The system boundary begins with the regeneration of the forest in the northern California region (A1) and ends with various types of redwood lumber packaged at the plant gate (A3). The system boundary includes forest operations, which may include growing seedlings in a nursery, planting the seedlings, managing the forest (may include precommercial and commercial thinning) and fertilization, and final harvesting with the logs brought to a forest landing. Trucks were used for the transportation of all resources (A2) including saw logs and other raw materials for lumber production (Fig. 1).

The sawmill complex is divided into five processes: log yard, sawmill, dryer, planing, and energy generation (optional). The study recognized five steps (A3) necessary to produce redwood lumber. Excluded from the system boundaries were fixed capital equipment and facilities, transportation of employees, land use, delivery of redwood lumber to a construction site, construction, maintenance, use, and final disposal. Disposal of on-site waste from production manufacturing was included in the system

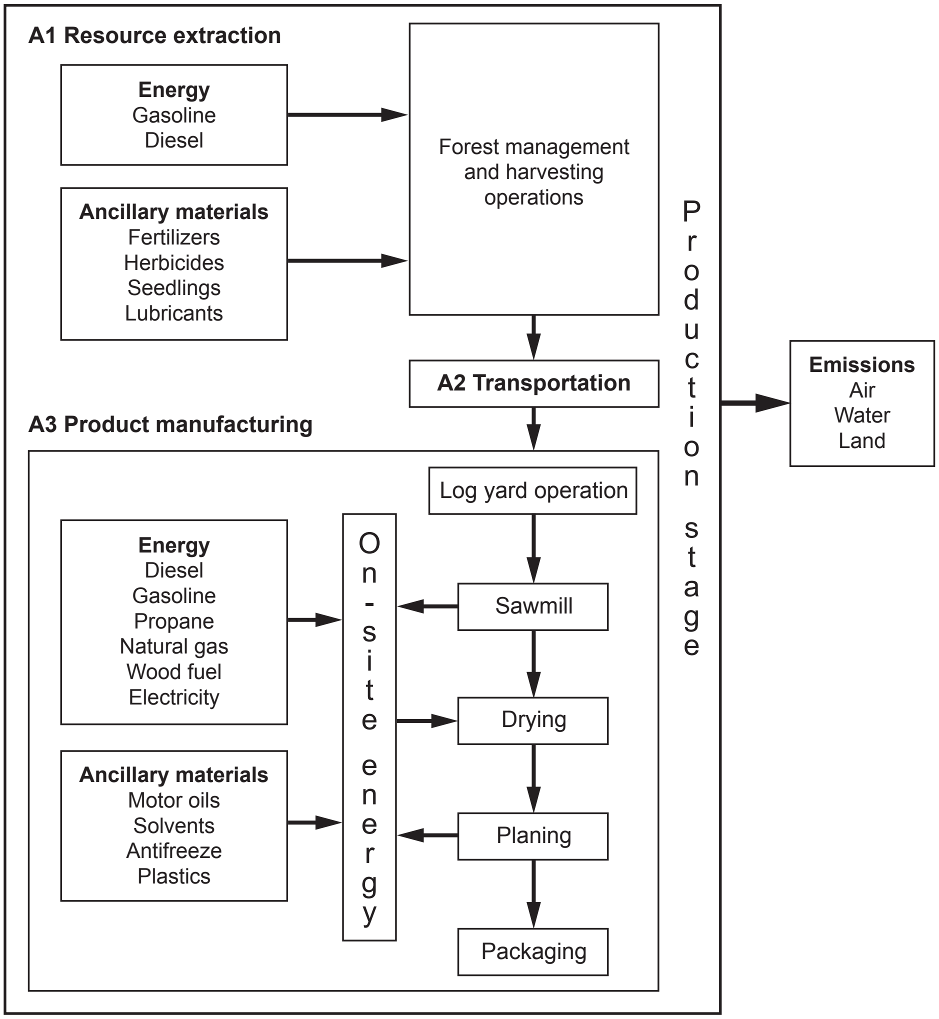

Figure 1. Cradle-to-gate system boundary for redwood lumber production, northern California.

Table 3—System boundary inclusions and exclusions for the cradle-to-gate system of redwood lumber production

Included	Excluded
Production of upstream processes for all resources, raw materials, fuels, and energy for redwood lumber production used in forestry operations and redwood lumber manufacturing	Fixed capital equipment and facilities
Transportation of (raw) materials throughout the cradle-to-gate manufacturing life stages	Transportation of employees
Packaging	Construction, maintenance, use, and end-of-life treatments

boundary. Table 3 lists the inclusions and exclusions within the system boundaries of this study.

3.2.3 Allocation Rules

Allocation is the method used to partition the environmental load of a process when several products or functions share the same process. There are various methods of allocation rules and according to UL PCR, "mass" was deemed as the most appropriate parameter for allocation (UL Environment 2018). Processing of the log at the sawmill involved multiple unit processes with multiple outputs (i.e., primary products and coproducts). The mass allocation approach was used to partition the environmental burden of the manufacturing system among all outputs. When applying mass allocation, the environmental burden of the manufacturing system is "shared" between the primary product (e.g., redwood lumber) and the coproducts of production (e.g., chips, sawdust, planer shavings, etc.) based on their mass ratio. The sawing of logs into rough green lumber produced the following coproducts: bark, sawdust, chips, and chipper fines. The planing unit operation produces shavings, trim ends, and other wood waste.

3.2.4 Cut-Off Rules

The cut-off criteria for all activity stage flow considered within the system boundary conform with ISO 21930 section 7.1.8 as well as UL PCR. The mass/energy of flow less than 1% of the cumulative mass/energy of the model flow was excluded, provided its environmental relevance was minor. The cut-off rules were not applied to hazardous and toxic material flows, all of which were included in the LCI. No material or energy input or output was knowingly excluded from the system boundary.

3.2.5 Data Collection

Surveys were used to collect the LCI data in accordance with CORRIM guidelines and ISO 14044 standards. This study collected production and emissions data provided by redwood lumber producers in northern California (representing more than 66% of the total annual production of the redwood lumber industry in 2017).

Secondary data on fuels and electrical grid inputs were taken from the U.S. LCI Database and European datasets modified specifically to be representative of U.S. operations (LTS 2017). Three mills provided data for 2017 redwood lumber and coproduct production, raw material and fuel use, electricity consumption, and on-site emissions. The primary data in the survey indicated that the majority (81%) of the lumber was sold as green or air-dried (Table 2). Data were collected from representative mills in the northern California region. In 2017, about 0.694 million m^3 of redwood lumber was produced in the United States or northern California. Responses from the mills through the survey were compared for consistency, and follow-up questions by mill visits, phone calls, and e-mails were used to clarify the responses.

3.2.6 Calculation Rules

Redwood sawmills reported logs in log scale units of Scribner. Based on U.S. industry measures, we used the conversion of 1,000 board feet (MBF) of green and dry wood lumber equal to 2.36 and 1.83 m^3, respectively, because wood shrinks as it dries from its green state to its final dry state and after it is planed (Bergman 2010, Bergman and others 2013). For this study, the conversion of volume from MBF to cubic meters for each dimensional product is presented in Table B1 in Appendix B. All flow analyses of the product and coproducts in the process were determined on an OD weight basis. Following CORRIM guidelines, overall wood mass balance was determined for material input to material output, which was within 1% using an average OD density (wood only) of 380 OD kg per m^3. Whenever missing data occurred for survey items, they were checked with plant personnel to determine whether it was an unknown value or zero; if unknown, it was not included in the weighted average calculations. Missing data were carefully noted so they were not averaged as zero. The survey results for each unit process were converted to a production basis: per cubic meter of log for the log yard, per cubic meter of rough-green lumber for the sawmill, per cubic meter of rough-dry lumber for drying, and per cubic meter of planed-dry lumber for planing. The values reported by each mill were combined into a production weighted average for each input (Eq. 1). Thus, the value from a large mill had more weight. This approach resulted in a sawmill complex that represents a composite of the mills surveyed and maintained confidentiality. SimaPro, version 8.5.2 (Pré-Consultants 2017) was used as the accounting program to track all of the environmental inputs and outputs crossing the system boundary. Missing data were defined as data not reported in surveys by the redwood lumber facilities.

$$W_1 = \frac{Y_1}{Y_1 + Y_2 + Y_3} = \frac{Y_1}{Y_{\text{total}}} \tag{1}$$

where

W_1 is weighing factor for sawmill 1,

Y_{total} is total annual production of "Y" mills, and

Y_1 is annual production of sawmill 1.

3.2.7 Biogenic Carbon

Biobased materials such as wood contain biogenic carbon, and carbon accounting must follow the requirements set out in ISO 21930 Section 7.2.7 and 7.2.12. Per ISO 21930, biogenic carbon enters the product system (removal) as primary or secondary material. Carbon removal is considered a negative emission. The biogenic carbon leaves the system (emission) either as a product, one of the coproducts, or directly to the atmosphere when combusted on site for energy. These mass flows of biogenic carbon from and to nature were listed in the LCI and expressed in kg CO_2. In the LCIA, the LCI flow of biogenic carbon removal was characterized by a factor of –1 kg CO_2e/kg CO_2 of biogenic carbon in the calculation of the GW impact category. Likewise, the LCI flow of biogenic carbon emission was characterized by a factor of +1 kg CO_2e/kg CO_2 of biogenic carbon in the calculation of GW. Emissions other than CO_2 associated with biomass combustion (e.g., methane or nitrogen oxides) were characterized by their specific radiative forcing factors in the calculation of GW impact.

The UL PCR 2019 specifies TRACI as the default LCIA method for global warming potential (GWP), a 100-year time horizon (UL Environment 2018). The TRACI method does not account for the removals or emissions of biogenic CO_2. Therefore, we manually calculated the component of the GW related to biogenic carbon separately. We have reported the GWP indicator both with and without the biogenic CO_2 component for maximum transparency.

The results for GWP and biogenic CO_2 are reported as follows:

- GWP_{TRACI}: includes greenhouse gas (GHG) emissions from the combustion of fossil resources and GHG emissions other than CO_2 from the combustion of biogenic resources (TRACI method)
- GWP_{BIO}: adds the net emissions of biogenic carbon to the GW (TRACI method + net biogenic carbon)
- LCI flows of biogenic carbon emissions and removals

4 Description of Industry

The redwood lumber industry is a subset of the very broad forest products industry, which also produces various dimensions of lumber mainly for decking, furniture, fencing, and structural products. The redwood lumber industry is limited to only northern California as redwood trees only grow in this region of the United States.

4.1 Categories of Products and Coproducts

The main product from redwood sawmills is lumber. Other products (coproducts) are also made when logs, which are round in cross section, are processed into lumber, which is rectangular in cross section. These coproducts (mill residues) include bark, chips, sawdust, and shavings. In addition, logs arrive at the mill with much of the tree's bark intact. The bark is removed by debarkers and used for fuel or sold for energy or landscaping. Another product of the mill is hog fuel (wood fuel), which can be strictly bark or a mix of bark and other coproducts depending on how individual mills classify it. These coproducts are either sold or used as fuel for on-site cogeneration and process energy for kiln-drying.

4.2 Annual Operating and Production Statistics of the Industry (U.S., Total, Regional)

Redwood sawmills are only located in northern California because of the availability of the resource. In 2017, redwood sawmills produced about 0.605 million m^3 lumber (294 million board feet), which represented 100% of the U.S. market.

4.3 Conversion Efficiencies

The sawing (to produce rough-green lumber) had a weighted average lumber recovery factor (LRF) of 8.23 BF lumber/ft^3 (0.69 m^3/m^3) incoming log or overrun of 69%. The cubic recovery ratio (CRR) was 0.48 m^3 lumber/m^3 log. When the overall process was considered (to produce planed-dry lumber), the CRR was 0.46 m^3 lumber/m^3 log.

4.4 Typical Emission Control Measures by Plant Type

The use of pollution control devices was recorded for two surveyed sawmills and included devices such as baghouses and electrostatic precipitators.

4.5 General Types of Wastes and Emissions

The air emissions reported by most mills included dust, particulate matter (PM), volatile organic compounds (VOCs), and hazardous air pollutants (HAPs). Mills classed as major sources under EPA rules are required to report methanol, formaldehyde, phenol, acetaldehyde, propionaldehyde, and acrolein, which are on EPA's HAPs list. If boilers are included, then there are some sulfur dioxide and oxides of nitrogen (NO_x) emitted. There were emissions recorded in the surveys by two redwood sawmills.

5 Description of Product

Lumber (Fig. 2) can include a variety of products ranging from boards to beams and timbers. Dimensional lumber (nominal 2 by 6 for decking) was the main product (about 39% in 2017) produced at the mills in this study. Dimensional lumber and studs are structural products that consist mainly of lumber that is nominally 2 in. thick and 4 to 12 in. wide (standard 38 mm thick by 89 to 286 mm wide). Redwood lumber products with various dimensions are shown in Table B2 in Appendix B.

5.1 Dimensions

In the United States, sizes of dimensional lumber are given in nominal customary units of inches. They are referred to as 2 by 4, 2 by 6, 2 by 8, 2 by 10, and 2 by 1. Studs are typically sold as 2 by 4 or 2 by 6. These numbers represent the nominal size of the lumber. The actual size of the lumber

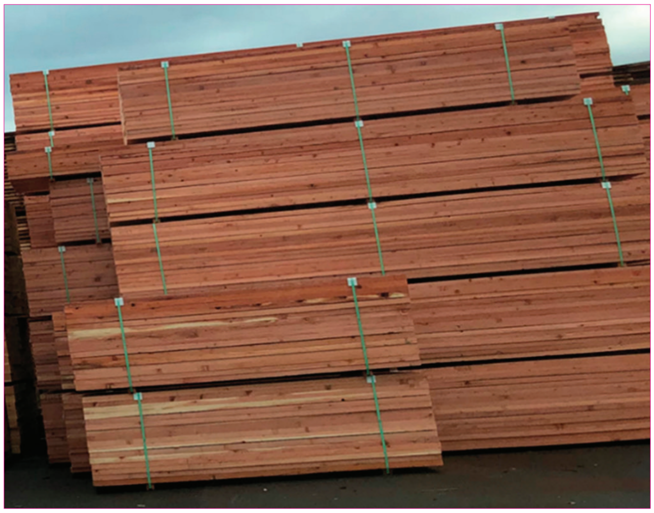

Figure 2. Redwood lumber strapped for shipping.

can vary depending on the stage of processing. A 2 by 4 might be 41 mm thick and 94 mm wide (1.61 in. thick by 3.7 in. wide) when green. This condition is called "rough-green" in this report. After drying, the actual dimensions might change to 39 mm thick by 90 mm wide (1.55 in. thick by 3.55 in. wide). This condition is called "rough-dry" in this report. The dimensions after final finishing (planing) are 38 mm thick by 89 mm wide (the grading rules specify 1.5 by 3.5 in. as the final actual size). This condition is called "planed-dry" in this report. The board is referred to as a 2 by 4 at each of the three conditions even though the physical size changes. The planed-dry size is the same for all mills. The rough-green and rough-dry sizes vary among mills and depend on the sawing efficiency. The planed-dry thickness for dimensional lumber is usually 38 mm but depending on final use can be as much as 89 mm (up to 3.5 in). The widths are 89, 140, 184, 235, and 286 mm (3.5, 5.5, 7.25, 9.25, and 11.25 in. in grading rules) for 2 by 4, 2 by 6, 2 by 8, 2 by 10, and 2 by 12, respectively (NIST 2015). Most (78%) of the lumber sawn by mills in the survey was 38 mm thick, and 22% was in other sizes, mostly 64 by 140 mm, 64 by 184 mm, and 89 by 89 mm (nominal 3 by 6, 3 by 8, and 4 by 4). The assumption was made that the processing inputs and emissions created when producing these sizes were similar to the more conventional dimensional lumber sizes because they were produced simultaneously at the same facilities. Mills specializing in thicker products might use different techniques; therefore, the study results should not be applied in those situations. Table B1 was used to convert the volume of lumber from MBF to cubic meters, which was estimated based on the information provided in Nielson and others (1985) and FPL (2010).

5.2 Wood Species

Redwood is a unique species growing naturally along the coastal area of northern California. There are three types of redwood: coast redwood (*Sequoia sempervirens*), giant sequoia (*Sequoiadendron giganteum*), and dawn redwood (*Metasequoia glyptostrobides*) (Save The Redwoods League 2019). Coast redwood is the only commercial species, and it grows in the cool climate that makes up the coastal regions of northern California. In this study, the specific gravity of redwood considered was 0.36 and 0.38 for green and dry lumber, respectively.

5.3 Moisture Content

Redwood lumber products are sold as rough-green, rough-dry, planed-green, and planed-dry. The average moisture content (MC) of the rough-green lumber was about 127% on a dry basis (db) produced in the sawmill. Fully kiln-dry lumber leaving the sawmill was about 19% MC (db). The MC of partially dry lumber (both rough and planed) was between 127% and 19% (db) depending mostly on customer requirements (i.e., final targeted MC).

6 Life-Cycle Inventory Analysis

The LCI in this section presents the unit process flows by 1 m^3 wood product out. The LCI was calculated based on 2017 production and the corresponding flows of materials during that period. No data gaps were recorded.

6.1 A1 – Resource Extraction

Forestry extraction (operations) can include growing seedlings, planting, thinning, and final harvest. The specific processes involved are reforestation (which can include seedling production, site preparation, planting, and fertilization) and harvesting (which includes felling, skidding, processing, and loading for both commercial thinning and final harvest operations). The weighted average allocation to different processes considers inherent differences in site productivity and energy usage by different kinds of logging equipment. Inputs to the forest resources management LCI include seed, electricity used during greenhouse operations, fertilizer used during seedling production and stand growth, and the fuel and lubricants needed to power and maintain equipment for site preparation, thinning, and harvest operations. The primary output product for this analysis is a log destined for the lumber mill. The coproduct, nonmerchantable slash, is generally left at a landing and disposed of through mechanical activities or prescribed fire. For a full description of the redwood forestry data and LCA results, see Han and others (2015). In Han and others (2015), the collected primary data on forest management and harvesting operations using landowner surveys in northern California collectively represented 90% of redwood decking production. The forest operations survey developed representative timber harvest and raw material collection data including measures of all material inputs such as labor use and fuel and lubrication per unit of collection activity. Three major types of harvesting systems were surveyed: ground-based, skyline, and helicopter. These three harvesting systems were further subdivided based

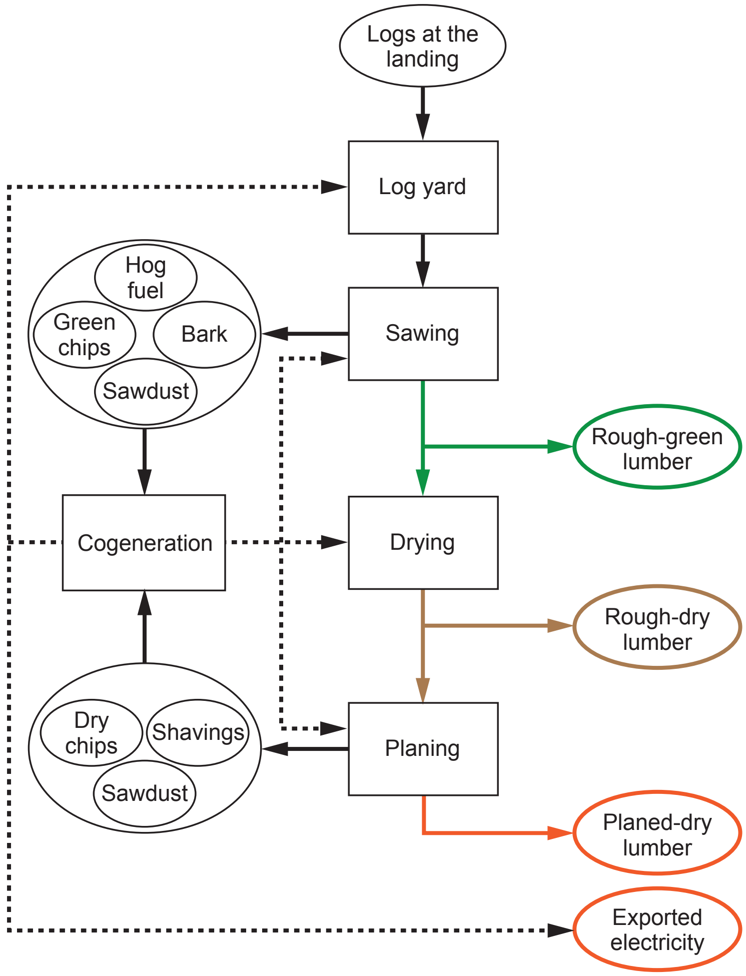

Figure 3. Diagram of the relationship between processes used to create redwood lumber from logs (dotted line indicates the renewable electricity generated with the on-site cogeneration unit and supplied to unit operations in the sawmill with excess exported to the local grid).

on the equipment type used and the harvest methods applied (uneven-aged and even-aged). In calculating output variables, results were weighted by the number of acres in each management intensity. Weighted average harvest volume was forwarded to the wood product manufacturing modules for incorporation in their LCA.

6.2 A2 – Transport of Raw Materials from the Extraction Site

Delivery of logs and materials to the mills is by truck. The mills took possession of the logs when they were delivered to the log yard. The weighted average distance of log (roundwood) transport by logging trucks was estimated to be 74.6 km (one way).

6.3 A3 – Product Manufacturing

Lumber manufacturing was divided into four main unit processes: log yard, sawing, drying, and planing. A boiler provided steam for drying if needed. Figure 3 shows the relationship between the processes and the woody inputs to and from each process. The log yard not only served as a receiving area for logs, it also provided surge capacity. In other words, it acted as a buffer to store a large volume of logs so that the mill could operate if the delivery of logs was interrupted. The log yard included the transport of logs within the mill, unloading logs, grading logs, storing logs, and moving them to the merchandizer or debarker at the sawmill. The inputs to the log yard were logs on a truck at the harvest site and fuels, mostly diesel, used in the machinery to move logs within the yard. The output from the log yard was logs at the sawmill.

Sawing process included debarking, sawing, chipping, and grinding required to convert the logs to rough-green lumber and coproducts. The process started with debarking after which the logs were sawed on a head rig. The head rig created lumber, flitches, and cants. The flitches and cants passed through resaws and edgers and were cut into lumber. The lumber was then sorted and stacked. The bark was ground and either sold or used as fuel. The saws created sawdust, which was either sold or used as fuel. The slabs

Table 4—Wood mass balance for redwood lumber manufacturing, cradle-to-gate

Input or output	Units oven-dry	per m^3 redwood lumber	Percentage
Inputs			
Roundwood (including bark)	kg	785	100
Total inputs	kg	785	100
Outputs			
Primary product			
Redwood lumber	kg	380	48
Coproducts			
Green chips	kg	115	15
Green sawdust	kg	38	5
Green bark	kg	95	12
Green shaving	kg	55	7
Green hog fuel	kg	95	12
Dry shavings	kg	6	1
Total outputs	kg	785	100
Used for on-site cogeneration	kg	327	42

and edgings that were not large enough to saw into lumber were chipped.

Drying process included the kilns, which received green lumber stacked on carts with wood spacers (stickers) between the layers. The stickers allowed air to flow between the layers in the dryer. Depending on customer needs, the stickered lumber was only air-dried (i.e., seasoned) or not at all. However, force-drying by dry kilns often occurred if only a little. The dry kilns were batch processes. In the batch kiln, the lumber was dried to a targeted MC typically using a kiln schedule. It was then moved to the dry shed or planer infeed. Some kilns were heated using steam generated by burning wood (i.e., mill residues).

Planing makes the lumber a uniform size and creates a smooth surface. It includes unstacking, planing, grading, end trimming, sorting, and packaging. Occasionally, some lengthwise sawing is done in the planing process. The process includes moving the packages and loading for shipment.

6.3.1 Mass Balance

The main material component used in the production of redwood lumber was the logs that were primarily coming from redwood forests managed by the sawmill or private owners. The average density of green logs was 360 OD kg/m^3 (volume green, weight OD). There were various types of lumber products produced when considering MC and surface of the lumber with primary product outputs of rough-green lumber, rough-dry lumber, planed-green lumber, planed-dry lumber, and planed-air-seasoned lumber. Intermediate products included rough-green lumber. Coproducts included bark, sawdust, pulp chips, trim ends, chipper fines, and planer shavings. The green, dry, and air-seasoned lumber had an average MC of 127%, 19%, and 30% (db), respectively. There was also redwood lumber, which was partially dry at 25% MC (db). All wood fiber flows in the redwood lumber system were determined on an OD basis. To estimate the wood mass balance for redwood lumber production, the following technical parameters and assumptions were applied. The annual production of lumber products (surfaced-dry, surfaced-green, and rough-green) was reported by mills in MBF. Table B1 in Appendix B can be used to convert MBF to cubic meters (Nielson and others 1985, Glass and Zelinka 2010). The average wood input density resulted in 360 kg/m^3 for green lumber and 380 kg/m^3 for dry lumber (Miles and Smith 2009, FPL 2010). The average green MC for mixed wood was estimated to be 100% MC (db). In this study, it’s assumed that the MC of bark and sawdust was the same as the MC of the sapwood. Table 4 provides a mass balance for redwood lumber manufacturing for 1 m^3 of redwood lumber product for the three-mill study sample. Of the roundwood (including bark) entering a sawmill, 48% of it by mass was processed into lumber.

6.3.2 Equipment: Type and Fuel Consumption

The equipment used in the manufacturing process falls into two broad categories, stationary machines and rolling stock (wheeled machinery, such as forklifts, for moving materials within a production facility). Stationary machinery in the sawing unit process included debarkers, circular or pony and head rig band saws, resaws, edgers, sorters, scanners, stackers, and conveyors and other handling equipment. Stationary equipment in the planing unit process included unstackers, moisture meters, planers, trim saws, sorters, scanners, stackers, and conveyors and other handling equipment. Stationary equipment was powered electrically.

Rolling stock, such as loaders, were used to move logs in the log yard unit process, to move packages of lumber from the one-unit process to another, and to load the final product for transport. Rolling stock was mainly powered by diesel but also to a smaller extent by gasoline and propane.

6.3.3 On-Site Heat and Power Production

The heat generated in the sawmill for lumber drying was either natural-gas-fired or excess heat from the cogeneration process where mill residues were burned in the wood boilers to make steam. The combustion of wood fuel and its emissions were included in the analysis. The unit process for a wood boiler was previously surveyed and reported in Puettmann and Milota (2017). In either case, the wood almost always came from mill residues produced on site. A weighted average of 24% of total electricity cogenerated on site was consumed in the sawmill, and 76% was sold to the local grid. Some of the exhaust steam from the cogeneration (combined heat and power) plant was used in the wood drying process. Only 11% of the heat produced in the cogeneration was needed for lumber drying, and the rest was waste heat, which decreased the overall efficiency of this aspect of the manufacturing operation. All exhaust steam was condensed and then returned to the wood boiler for further use. The environmental burdens from the cogeneration were allocated to the electricity produced and part of the heat consumed during the lumber drying operation. Waste heat from the cogeneration unit did not carry any of the impacts. In summary, the electricity and usable heat carried 88% and 12% of total impacts, respectively, and this allocation was based on the energy content of products and efficiency of prime mover, which converted steam to electricity. It was estimated that 1.11 kg of OD wood residues produced 1 kWh of electricity and 2.49 MJ of useful heat (excluding waste heat) to be used in the kiln for lumber drying. Most redwood lumber products are sold as green, and hence the requirement of the heat was minimal. The boilers used 100% self-generated fuel, and excess wood fuel was sold. The fuel supplied to the wood boilers was 28.4% green chips, 9.3% sawdust, 23.4% green bark, 15.6% planer shavings, and 23.4% hog fuel (Table 5).

6.3.4 Log Yard Operations

The log yard unit process begins with logs plus the attached bark on a truck at the harvest site and ends with logs plus the attached bark delivered to the infeed sawing process (i.e., debarker). Logging trucks arrive at the log yard and are unloaded by diesel-powered wheeled loaders with log grapples (also referred to as on-site loaders and haulers or rolling stock). The unloading machines are a part of the log yard unit process.

The log truck might be weighed in and out; however, all mills reported log input on a volume basis, either board feet or cubic feet. When the log trucks are unloaded, the logs are either piled in a storage deck or they are spread out, graded visually, and then transferred to the log deck. The logs are stored in decks for months to years. Having an inventory in the decks allows the mill to keep running even when log deliveries are temporarily interrupted because of weather, fire, or other supply issues. Generally, water is sprayed on the logs piles to keep them wet to maintain freshness and prevent stain and cracking. The logs are then removed from the deck and taken to the debarker at the infeed of the sawmill. Logs entering are reported on a volume basis, eastside Scribner. Log scale is a century-old method of measuring logs in which measurements of diameter and length are used to predict the board feet of lumber to be recovered from the log. Because of technology changes and changes in average log diameter, log scale greatly underestimates the board feet currently recovered. The log scale quantities reported were converted to cubic volume using a factor of 5.81 m^3/MBF. Diesel and gasoline were used as fuel for rolling stock (wheeled machinery, such as loaders, forklifts, and lumber carriers) for log unloading and moving logs through the process. Lube oil, hydraulic oil, grease, and antifreeze were also used in rolling stock. Lubricants and solvents for cleaning are also used in stationary equipment. A small amount of electricity is used in the log yard for lighting and instrumentation (Table 6).

6.3.5 Sawmill Operations – Production of Rough Green Lumber

The sawing process begins when logs with bark are received from the log yard and ends when rough sawn green lumber is stacked on stickers and packaged for sale or transported to the drying process. Additionally, chips, sawdust, bark, and hog fuel are created in the sawing process, all in green condition. Table 7 shows the products from and inputs to this process. Coproduct masses are listed in bone dry. The allocation was based on bone-dry mass. Bone-dry and OD terms are used interchangeably.

A combination of decks and conveyors move the logs and lumber through the system. Logs are first debarked. Dimensional lumber mills often have a scanning system to optimize bucking to match the log characteristics, whereas stud mills, with a more restricted product line, buck to stud lengths. The logs are then scanned before sawing so that the location of the saw cuts made by the headrig will maximize the value of the product from the log. A variety of lumber sizes are produced by the headrig. Additional sawing machine centers include resaws and edgers. Most mills have a curved resaw (curve saw) so that logs with mild sweep can be sawn more efficiently. These additional machine centers create lumber that will meet the grading rules. Additional scanning occurs at the machine centers to optimize recovery. Pieces may pass through more than one saw.

After sawing, the lumber usually flows from all machine centers to a single sorting line. Here the pieces are graded, scanned, and trimmed to length. The length trim is done if

Table 5—Inputs to wood boiler per bone dry kilogram of wood fuel combusted[a]

Description	Value	Unit	Allocation (%)
Product			
Cogeneration electricity, at sawmill, kWh, U.S.	1	kWh	88
Cogeneration heat, at sawmill, for drying, MJ, U.S.	2.49	MJ	12
Wood ash, at boiler, at mill, kg, U.S. v1.2	0.0212	kg	
Resource			
Water, process, surface	0.34	kg	
Water, process, well	0.27	kg	
Water, process, surface	0.88	kg	
Water, process, well	0.27	kg	
Material/fuel			
Chips, redwood, green, kg, C-U.S.	0.3151	kg	
Sawdust, redwood, green, kg, C-U.S.	0.1029	kg	
Hog fuel, redwood, green, kg, C-U.S.	0.2596	kg	
Bark, green, kg, C-U.S.	0.2593	kg	
Shavings, dry, kg, C-U.S.	0.1732	kg	
Diesel, loaders and haulers	0.0219	L	
Gasoline, loaders and haulers	8.94E–04	L	
Propane, loaders and haulers	4.38E–05	L	
Engine oil, in engines of loaders and haulers	1.34E–05	kg	
Engine oil, stationary equipment	5.55E–06	kg	
Hydraulic fluid for loaders and haulers	2.11E–05	kg	
Hydraulic oil for stationary equipment	7.77E–06	kg	
Transmission fluid, loaders and haulers	5.00E–05	kg	
Ethylene glycol, at plant	4.44E–07	kg	
Solvent, at plant/U.S.	1.19E–06	kg	
Solvent, at plant/U.S.	5.55E–08	kg	
Water treatment, at plant/U.S.	7.44E–07	kg	
Boiler streamline treatment	1.37E–04	kg	
Oils, mobile equipment	4.07E–06	kg	
Oils, stationary equipment	2.22E–06	L	
Urea, as N, at regional storehouse	1.11E–05	kg	
Disposal, ash, to unspecified landfill	3.50E–03	kg	
Disposal, solid waste, unspecified, to unspecified landfill, RNA	8.42E–03	kg	
Metal, to recycling, RNA	8.06E–06	kg	
Electricity/heat			
Electricity, at grid, U.S.	9.10E–02	kWh	
Natural gas, combusted in industrial boiler/U.S.	1.53E–03	m^3	
Emissions to air			
Acetaldehyde	1.17E–06	kg	
Acrolein	8.96E–07	kg	
Benzene	1.88E–07	kg	
Carbon monoxide, biogenic	3.59E–03	kg	
Carbon dioxide, biogenic	1.95E+00	kg	
Wood (dust)	6.24E–04	kg	
Formaldehyde	1.40E–05	kg	
HAPs, hazardous air pollutants	6.96E–06	kg	
Hydrogen chloride	1.30E–06	kg	
Lead	1.94E–07	kg	
Mercury	2.03E–09	kg	
Methane, biogenic	2.48E–05	kg	
Methanol	8.82E–06	kg	
Nitrogen oxides	1.22E–03	kg	

Table 5—Inputs to wood boiler per bone dry kilogram of wood fuel combusted[a]—con.

Description	Value	Unit	Allocation (%)
Emissions to air—con.	1.22E–03	kg	
Particulates, <10 µm	5.23E–04	kg	
Particulates, <2.5 µm	1.54E–04	kg	
Phenol	6.89E–07	kg	
Propanol	5.71E–08	kg	
Sulfur dioxide	8.56E–05	kg	
VOC, volatile organic compounds	9.72E–04	kg	
Dinitrogen monoxide (nitrous oxide)	3.25E–06	kg	
Naphthalene	6.40E–08	kg	
Other organic	2.34E–07	kg	
Emissions to water			
Suspended solids, unspecified	9.27E–07	kg	
BOD5, biological oxygen demand	2.33E–06	kg	

[a]3.6 MJ = 1 kWh.

Table 6—Inputs and outputs for the log yard process. Values are per cubic meter of redwood logs leaving log yard and delivered to the sawmill for northern California, USA

Description	Value	Unit	Allocation (%)
Product			
Roundwood sawlogs, redwood, green, at sawmill, m^3, CA-U.S.	1	m^3	100
Resource			
Water, process, unspecified natural origin/kg	22.46	L	
Material/fuel			
Roundwood sawlogs, redwood, green, at log yard m^3, CA-U.S.	1	m^3	
Diesel, combusted in industrial equipment NREL/U.S. U	5.65E–01	L	
Gasoline, combusted in equipment NREL/U.S. U	1.74E–03	L	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for hydraulic fluid)	1.24E–02	kg	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for motor oil)	2.12E–02	kg	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for oil and grease)	4.42E–04	kg	
Electricity/heat			
Cogeneration renewable electricity	0.50	kWh	
Electricity, low voltage WECC, U.S. only | market for | cut-off, U	0.15	kWh	
Emissions to water			
COD, chemical oxygen demand	1.07E–05	kg	
Oils, unspecified	7.69E–06	kg	
Zinc	1.20E–04	kg	

Table 7—Unit process inputs and outputs for sawing to produce 1 m^3 of rough-green redwood lumber for northern California, USA

Description	Value	Unit	Allocation (%)
Product			
Sawn lumber, redwood, rough, green, m^3, CA-U.S.	1	m^3	49
Bark, redwood, green, kg, CA-U.S.	107.53	kg	15
Chips, redwood, green, kg, CA-U.S.	35.12	kg	5
Sawdust, redwood, green, kg, CA-U.S.	88.50	kg	12
Shavings, redwood, green, kg, CA-U.S.	51.61	kg	7
Hogged fuel, redwood, green, kg, CA-U.S.	88.58	kg	12
Material/fuel			
Roundwood sawlogs, redwood, green, at sawmill, m^3, CA-U.S.	2.03	m^3	
Diesel, combusted in industrial equipment NREL/U.S. U	0.20	L	
Gasoline, combusted in equipment NREL/U.S. U	0.03	L	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for hydraulic fluid)	6.98E–02	kg	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for motor oil)	3.25E–02	kg	
Polyethylene, HDPE, granulate, at plant/U.S.- U.S.-EI U (a proxy for plastics)	8.57E–03	kg	
Alkyd paint, white, 60% in H_2O, at plant/RER with U.S. electricity U	8.31E–04	kg	
Tap water, at user/RER with U.S. electricity U	4.22E–01	kg	
Surfaced-dried lumber, at planer mill, CA-U.S./kg/U.S. - stickers	8.12E–01	kg	
Electricity/heat			
Cogeneration renewable electricity	19.32	kWh	
Electricity, low voltage WECC, U.S. only | market for | cut-off, U	5.66	kWh	
Emissions to water			
COD, chemical oxygen demand	4.91E–05	L	
Oils, unspecified	5.08E–07	L	

the end of a piece has a grade-limiting defect and its value can be raised by trimming. The pieces are then sorted for length and width. Finally, the lumber is stacked on stickers (spacers) in units that are removed from the sawmill by a diesel-powered forklift. Redwood lumber is used as rough-green, partially rough-green, partially rough-dry, planed-green, planed-dry, planed-partial-dry, and planed-air-seasoned. The rough-green lumber stacks are stored outdoors for air-drying to decrease the MC of lumber (e.g., nearly 35% MC db) before sending, if needed, to the kiln- (force) drying operation. A large portion of rough-green lumber stacks are packed for customer delivery.

Lumber was reported in board feet for each lumber size. Board feet reported values were then converted to cubic meters as described in section 4.1 of this report using the actual lumber dimensions reported by each mill. All mills reported actual dimensions (target size) for each rough-green lumber size. One cubic meter of redwood lumber was produced from 2.03 m^3 of logs. Products were more accurately measured than logs, and lumber made up 49% of the wood leaving the sawmill. The balance of the wood leaving (51%) was chips, sawdust, bark, wood fuel, and hog fuel (Table 7). These coproducts were used for on-site cogeneration (~42% of incoming logs) and were sold to be used as mulch (9%).

Diesel, gasoline, and liquefied petroleum gas were used as fuel for rolling stock for moving lumber from the process. Lube oil, hydraulic oil, grease, and antifreeze were also used in rolling stock. Lubricants and solvents for cleaning were also used in stationary equipment. Some plastic and metal strapping were used. Electricity was used in the sawmill to operate motors, instrumentation, and lighting (Table 7).

6.3.6 Drying Operations – Production of Rough-Dry Lumber

Redwood sawmills adopt either air-drying or kiln-drying or a combination of both depending on the target MC required by the customers. Air-drying is slow and may require a long time to dry. Sometimes target MC cannot be achieved because of local weather conditions. The sawmill's inventory of a specific product, local climate, and weather conditions also dictate the type of lumber drying arrangements. The kiln-drying process begins with rough sawn green or partially air-dry lumber placed at the kiln and ends with rough-dry lumber either delivered to the planer or sold as rough-dry lumber. There is approximately 7% volume loss caused by shrinkage and a corresponding increase in specific gravity.

Dry kilns are chambers 16 to 40 m long, usually with a left side and a right side. There is a set of tracks on each side

Table 8—Unit process inputs and outputs for drying 1 m^3 of rough-dry redwood lumber (values are per cubic meter of rough-dry redwood lumber for northern California, USA)

Description	Value	Unit	Allocation (%)
Product			
Sawn lumber, redwood, rough, dry, m^3, CA-U.S.	1	m^3	100
Material/fuel			
Sawn lumber, redwood, rough, green, m^3, CA-U.S.	1.07	m^3	
Diesel, combusted in industrial equipment NREL/U.S. U	0.09		
Gasoline, combusted in equipment NREL/U.S. U	0.02	L	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for hydraulic fluid)	5.62E–03	kg	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for motor oil)	9.25E–03	kg	
Tap water, at user/RER with U.S. electricity U	4.45E–01	kg	
Electricity/heat			
Cogeneration renewable electricity	2.72	kWh	
Electricity, low voltage WECC, U.S. only | market for | cut-off, U	0.80	kWh	
Heat, on-site boiler (natural gas fired)	94.72	MJ	
Exhaust heat from cogeneration boiler	733.19	MJ	
Emissions to water			
COD, chemical oxygen demand	0.00E+00	kg	
Oils, unspecified	8.85E+01	kg	
Emissions to air			
Particulates, nonboiler	1.13E–05	kg	
VOC, volatile organic compounds	3.05E–02	kg	

so lumber can be rolled through the kiln on carts. Each side holds a track of lumber approximately 2.4 to 3 m (two units) wide and 4 to 5 m (two to three units) high. For the surveyed sawmills, the exhaust steam generated from either the cogeneration plant or natural gas-fired boilers was used to supply heat for the kiln-drying process. There are fans that circulate air through the sticker slots between the layers of lumber. Steam heat exchangers (heating coils) provide the energy to heat the air to the desired temperature. The humidity is controlled by ventilators that open to release moist warm air and take in ambient air. The humidity can be raised by releasing live steam into the chamber. The temperature and humidity in the kilns are controlled to a drying schedule, a series of dry-bulb and wet-bulb temperatures designed to remove moisture as quickly as possible without damaging the wood (Simpson 1991, Bergman 2010). For redwood, the maximum drying temperature ranged from about 80 to 100 °C. A portion of the rough-dry lumber (graded, trimmed, sorted, stacked, and packed using plastic straps) was sold to the customers, whereas the rest went to the planing process.

Nonwood materials were tracked too. Almost all water used for the facility was allocated to the log yard and cogeneration plant; a very small amount was used in the sawing and planing operations. Diesel, gasoline, and liquefied petroleum gas were used as fuel for forklifts and modified front end loaders, which were used for moving lumber into the kiln, out of the kiln, and to the planer. Lube oil, hydraulic oil, grease, and antifreeze were used in rolling stock. Lubricants and solvents for cleaning were also used in stationary equipment. Electricity, 3.52 kWh/m^3 (Table 8) sourced from cogen and grid, was used in the dryer to operate motors, instrumentation, and lighting. The kiln emissions were created when the wood was dried.

6.3.7 Planing Operations – Production of Packaged Planed-Dry Lumber

The planing process begins with units of rough-green or rough-dry or partially rough-dry lumber placed at the infeed and ends with packaged planed or partially planed lumber loaded for shipment (Table 9). Additionally, planer shavings are created in the planing process. Redwood lumber is planed relatively lightly as indicated by the small amount of planar shavings generated (6.47 OD kg/m^3) compared with that of other lumber products (Bergman and Bowe 2008, 2010, 2012; Puettmann and others 2010). The planed lumber is graded, trimmed, sorted, and stacked before packaging.

The product is packaged in units that are composed of lumber of a single thickness, width, and (usually) length. Lath is placed between some layers in the unit to prevent the side pieces from falling when the consumer opens the unit. The units are usually covered with a paper wrap. End paint might be applied, and the unit might be stenciled. The units are banded with plastic strapping. Runners are placed under the units to allow access for the forklift tines. The packaged units are then placed on trucks for transport.

Table 9—Unit process inputs and outputs for producing 1 m^3 of planed-dry redwood lumber for northern California, USA

Description	Value	Unit	Allocation (%)
Product			
Sawn lumber, redwood, plane, dry, m^3, CA-U.S.	1	m^3	98.33
Planer shavings, dry, kg, CA-U.S.	6.47	kg	1.67
Material/fuel			
Sawn lumber, redwood, rough, dry, m^3, CA-U.S.	1.02	m^3	
Diesel, combusted in industrial equipment NREL/U.S. U	0.09	L	
Gasoline, combusted in equipment NREL/U.S. U	0.02	L	
Natural gas, combusted in industrial equipment NREL/RNA U	0.01	L	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for hydraulic fluid)	2.09E–02	kg	
Lubricating oil, at plant/U.S.- U.S.-EI U (a proxy for motor oil)	2.39E–02	kg	
Polyethylene, HDPE, granulate, at plant/U.S.- U.S.-EI U (a proxy for plastics)	4.70E–02		
Tap water, at user/RER with U.S. electricity U	4.53E–01	kg	
Electricity/heat			
Cogeneration renewable electricity	10.28	kWh	
Electricity, low voltage WECC, U.S. only | market for | cut-off, U	3.01	kWh	
Emissions to water			
Suspended solids, unspecified	1.13E–06	kg	
COD, chemical oxygen demand	1.57E–05	kg	

The planer used water for cooling machinery and dust control. Diesel, gasoline, and liquefied petroleum gas were used as fuel for rolling stock for moving lumber from the process to truck, rail, or ships. Lube oil, hydraulic oil, grease, and antifreeze were used in rolling stock. Lubricants and solvents for cleaning were also used in stationary equipment. Electricity, 13.29 kWh/m^3, was used in the planer to operate motors, instrumentation, and lighting.

6.4 Secondary Data Sources

Table 10 lists the secondary LCI data sources used in this LCA study for raw material inputs, ancillary materials and packaging, transportation of materials and resources, fuels and energy for manufacturing, water sources, and waste streams.

7 Life-Cycle Impact Assessment

The LCIA phase establishes links between the LCI results and potential environmental impacts. The LCIA calculates several impact indicators including GW, eutrophication, and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are subsequently summarized. Environmental impacts are determined using the TRACI method (Bare 2011). Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning comparison indicator values are not valid. Additionally, each impact indicator value is stated in units that are not comparable with others. For the same reasons, indicators should not be combined or added. Additionally, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. The primary fuels are categorized into nonrenewable (fossil and nuclear) and renewable (biomass, geothermal, solar, wind, hydro). Table 11 summarizes the source and scope of each impact category reported in this report, which is required to be in conformance with the PCR.

Cradle-to-gate environmental performance results for all reporting indicators are listed in Table 12 for redwood lumber. The LCIA results in Table 12 show the absolute values for A1-resource extraction, A2-transportation, and A3-redwood lumber production. About 41% of the CO_2 equivalent emissions (GWP) came from producing lumber (15.75 kg CO_2 eq), with 40% assigned to forestry operations (15.16 kg CO_2 eq). Transportation, which is primarily the transport of logs to the sawmill, was 7.06 kg CO_2 eq or 19% of the cradle-to-gate GWP impact.

Table 12 also provides indicators related to energy use, material resource consumption, and renewable secondary fuels (RSF) generated. The total cradle-to-gate energy use was 1,931 MJ/m^3. This value is 43% higher than that in the previous study (Bergman and others 2014a), which reported a value of 1,340 MJ/m^3 for planed-dry redwood decking. The total cradle-to-gate renewable and nonrenewable energies are 1,335 and 609.2 MJ, respectively. Most of the freshwater use is in the A3 life-cycle stage. Freshwater use was recorded for log sprays and cogeneration boiler use (195.5 L/m^3).

Table 10—Secondary data sources (LTS 2017) and data quality assessment

	LCI data source	Geography	Year	Data quality assessment
A1: Raw material inputs				
Inputs				
Wood resource	*Database:* CORRIM dataset *Process:* Roundwood, redwood, average, at forest road, CA-U.S	North America – region specific	2005–2019	*Technology:* Good. Process models region-specific technology. *Time:* Good. Some data are less than 10 years old. *Geography:* Very good. Data are representative of regional production.
A2: Raw material transportation				
Inputs				
Trucking	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Transport, combination truck, diesel-powered NREL/U.S. U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Good. Data are less than 10 years old. *Geography:* Very good. Data are representative of North American trucking.
A3: Manufacturing				
Energy inputs				
Electricity	*Database:* US EI 2.2 (DataSmart, LTS 2017)	North America – region specific	2018	*Technology:* Very good. Process models average electricity technology specific to regional grids. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of regional electricity generation.
Gasoline	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Gasoline, combusted in equipment NREL/US U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American propane production and combustion.
Diesel	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Diesel, combusted in industrial equipment NREL/US U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American diesel production and combustion.
Biomass combustion	*Database:* CORRIM data *Process:* Wood combusted, at boiler, at mill, kg, US	North America	2015	*Technology:* Very good. Process represents combustion of biomass in an industrial boiler. *Time:* Very good. Data are within two years. *Geography:* Very good. Data are representative of North American biomass combustion.
Ancillary materials and packaging				
Hydraulic fluid and lubricants	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Lubricating oil, at plant/US- US-EI U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American processes.
Antifreeze	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Ethylene glycol, at plant/US - US-EI U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American processes.
Solvents	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Hexane, at plant/ US- US-EI U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American production and combustion.
Plastic strap	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Polyethylene, HDPE, granulate, at plant/ US- US-EI U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American processes.
Greases and oils	*Database:* US EI 2.2 (DataSmart, LTS 2017) *Process:* Lubricating oil, at plant/US- US-EI U	North America	2018	*Technology:* Very good. Process models average North American technology. *Time:* Very good. Data are less than 5 years old. *Geography:* Very good. Data are representative of North American processes.

Table 11—Selected impact indicators, characterization models, and impact categories

Reporting category per tables E1–E5 in ISO 21930	Indicator name	Abbreviation	Unit
Core mandatory impact indicators	Global warming potential, fossil	GWP_{TRACI}	kg CO_2e
Core mandatory impact indicators	Global warming potential, w/ biogenic[a]	GWPBIO	kg CO_2e
Core mandatory impact indicators	Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e
Core mandatory impact indicators	Acidification potential of soil and water sources	AP	kg SO_2e
Core mandatory impact indicators	Eutrophication potential	EP	kg PO_4e
Core mandatory impact indicators	Formation potential of tropospheric ozone	SFP	kg O_3e
Core mandatory impact indicators	Abiotic depletion potential for fossil resources (ADP fossil)	ADPf	MJ, NCV
Core mandatory impact indicators	Fossil fuel depletion	FFD	MJ surplus
Use of primary resources	Renewable primary energy carrier used as energy	RPRE	MJ, NCV
Use of primary resources	Renewable primary energy carrier used as material	RPRM	MJ, NCV
Use of primary resources	Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV
Use of primary resources	Renewable primary energy carrier used as material	NRPRM	MJ, NCV
Secondary material, secondary fuel and recovered energy	Secondary material	SM	kg
Secondary material, secondary fuel and recovered energy	Renewable secondary fuel	RSF	MJ, NCV
Secondary material, secondary fuel and recovered energy	Nonrenewable secondary fuel	NRSF	MJ, NCV
Secondary material, secondary fuel and recovered energy	Recovered energy	RE	MJ, NCV
Mandatory inventory parameters	Consumption of freshwater resources;	FW	m^3
Indicators describing waste	Hazardous waste disposed	HWD	kg
Indicators describing waste	Nonhazardous waste disposed	NHWD	kg
Indicators describing waste	High-level radioactive waste, conditioned, to final repository	HLRW	kg or m^3
Indicators describing waste	Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	kg or m^3
Indicators describing waste	Components for re-use	CRU	kg
Indicators describing waste	Materials for recycling	MR	kg
Indicators describing waste	Materials for energy recovery	MER	kg
Indicators describing waste	Recovered energy exported from the product system	EE	MJ, NCV
Additional inventory parameters for transparency	Biogenic carbon removal from product	BCRP	kg CO_2e
Additional inventory parameters for transparency	Biogenic carbon emission from product	BCEP	kg CO_2e
Additional inventory parameters for transparency	Biogenic carbon removal from packaging	BCRK	kg CO_2e
Additional inventory parameters for transparency	Biogenic carbon emission from packaging	BCEK	kg CO_2e
Additional inventory parameters for transparency	Biogenic carbon emission from combustion of waste from renewable sources used in production processes	BCEW	kg CO_2e
Additional inventory parameters for transparency	Carbon emissions from combustion of waste from nonrenewable sources used in production processes	CWNR	kg CO_2e

[a]ISO 21930 requires a demonstration of forest sustainability to characterize carbon removals with a factor of –1 kg CO_2e/kg CO_2. ISO 21930 Section 7.2.1 Note 2 states the following regarding demonstrating forest sustainability: “Other evidence such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) can be used to identify forests with stable or increasing forest carbon stocks.” Canada’s UNFCCC annual report table 6-1 provides annual NET GHG Flux Estimates for different land use categories. This reporting indicates nondecreasing forest carbon stocks and thus the source forests meet the conditions for characterization of removals with a factor of –1 kg CO_2e/kg CO_2.

Table 12—Cradle-to-gate environmental performance of 1 m^3 redwood lumber based on mass allocation for northern California, USA

Reporting category and indicator name	Abbreviation	Unit	Total	A1	A2	A3
Core mandatory impact indicator						
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	37.97	15.16	7.06	15.75
Global warming potential – w/ biogenic CO_2	GWPBIO	kg CO_2e	37.97	–1,424.19	7.06	1,455.10
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	8.13E–07	6.11E–09	2.69E–10	8.07E–07
Acidification potential of soil and water sources	AP	kg SO_2e	0.35	0.20	0.04	0.11
Eutrophication potential	EP	kg Ne	0.07	0.01	0	0.06
Formation potential of tropospheric ozone	SFP	kg O_3e	10.74	6.28	1.15	3.31
Abiotic depletion potential for fossil resources (ADP fossil)	ADPf	MJ, NCV	511.45	205.42	88.02	218.01
Fossil fuel depletion	FFD	MJ surplus	73.97	31.48	13.50	28.99
Use of primary resources						
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	1,354.71	0.23	0	1,354.49
Renewable primary energy carrier used as material	RPRM	MJ, NCV	7,942.00	0	0	7,942.00
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	576.04	218.26	93.50	264.28
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	0	0	0	0
Secondary material, secondary fuel and recovered energy						
Secondary material	SM	kg	0	0	0	0
Renewable secondary fuel	RSF	MJ, NCV	0	0	0	0
Nonrenewable secondary fuel	NRSF	MJ, NCV	0	0	0	0
Recovered energy	RE	MJ, NCV	0	0	0	0
Mandatory inventory parameters						
Consumption of freshwater resources	FW	m^3	0.159	0.00	0.00	0.159
Indicators describing waste						
Hazardous waste disposed	HWD	kg	0	0	0	0
Nonhazardous waste disposed	NHWD	kg	9.63	0.00	0.00	9.63
High-level radioactive waste, conditioned, to final repository	HLRW	m^3	1.43E–07	1.01E–10	0	1.43E–07
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	3.71E–08	2.10E–11	0	3.70E–08
Components for re-use	CRU	kg	0	0	0	0
Materials for recycling	MR	kg	0.057	0	0	0.057
Materials for energy recovery	MER	kg	0	0	0	0
Recovered energy exported from the product system	EE	MJ, NCV	0.000	0	0	0.000

8 Interpretation

As defined by ISO, the term life-cycle interpretation is the phase of the LCA in which the findings of either the LCI or the LCIA, or both, are combined consistently with the defined goal and scope to reach conclusions and recommendations. This phase in the LCA reports the significant issues based on the results presented in the LCI and LCIA of this report. Additional components report an evaluation that considers completeness, sensitivity, and consistency checks of the LCI and LCIA results, conclusions, limitations, and recommendations.

8.1 Identification of the Significant Issues

The objective of this element is to structure the results from the LCI or LCIA phases to help determine the significant issues found in the results and presented in previous sections of this report. A contribution analysis was applied for the interpretation phase of this LCA study. Contribution analysis examines the contribution of life-cycle stages (A1 and A3), unit process contributions in a multi-unit manufacturing process, and specific substances that contribute an impact.

8.2 Life-Cycle Phase Contribution Analysis

For GW impact, 41% of the CO_2 equivalent emissions come from producing redwood lumber (A3), with 40% and 19% assigned to extraction (A1) and transportation (A2), respectively (Table 13). Within A3, 70% of GWP impact was from the contribution from lumber drying. Lumber production (A3) represented the highest impacts for the ozone depletion and fossil fuel depletion environmental impact categories. Resource extraction (A1) represented the highest impacts in various impact categories including eutrophication and formation potential of tropospheric ozone. From cradle to gate, freshwater use was also almost exclusively consumed during the A3 life-cycle stage (Table 13). Most of the renewable fuels were used in the A3 life-cycle stage (Tables 14 and 15). Renewable fuels represented 69% of total cradle-to-gate (A1-A3) energy use (Table 15). Nonrenewable fossil fuel consumption cradle-to-gate was 38%, 16%, and 46% for A1, A2, and A3, respectively (Table 14). Within the resource extraction (A1) life-cycle stage, ~100% of the total energy was nonrenewable fuels (Table 15). Biomass energy was primarily used in cogeneration and drying lumber in kilns (A3) and represented 82% of the total energy for A3 (Table 15). In summary, cradle-to-gate total energy for producing redwood lumber, which includes fuel for process heat and equipment and electricity, comes from 29% fossil fuels, 0.84% nuclear, 69.15% renewable biomass fuel, and 0.66% hydro (Table 15).

8.3 Uncertainty Analysis

The uncertainty and sensitivity analyses aim to assess the reliability of the results. Some degree of uncertainty is present in the results because of the variation among different data providers. The uncertainty analysis investigates input data variations within the sample of production facilities. The uncertainty analysis investigates input data variations within the sample of production facilities. Statistics for key inventory results, i.e., electricity, diesel, natural gas, and wood fuel, are shown in Table 16. The standard deviation for each of these factors was calculated based on the sample data and was used to perform sensitivity analysis on these parameters.

In the sensitivity analysis, significant inventory parameters were altered to investigate the effect on the LCIA results. In this case, the electricity input, the diesel and gasoline inputs, the natural gas input, and the biomass fuel input were increased and decreased by 20%. The change in LCIA results is presented in Table 17. It shows that a 20% change of inputs especially electricity, natural gas, and diesel has only minor effects on the results. However, the use of woody biomass as fuel can substantially affect certain indicators including ozone depletion potential and primary energy use (renewable energy).

8.4 Limitations

This LCA was created using industry average data for upstream materials. Variation can result from differences in supplier locations, manufacturing processes, manufacturing efficiency, and fuel type used. This LCA does not report all the environmental impacts caused by the manufacturing of the product but rather reports the environmental impacts for those categories with established LCA-based methods to track and report. Unreported environmental impacts include (but are not limited to) factors attributable to human health, land-use change, and habitat destruction. To assess the local impacts of product manufacturing, additional analysis is required.

This LCA report documents the results of a cradle-to-gate analysis and is not a comparative assertion, which is defined as an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. This LCA does not make any statements that the product covered by the LCA is better or worse than any other product.

9 Treatment of Biogenic Carbon

Forests are understood as a natural system with multiple functions, the production function of timber being one of them. Therefore, natural growth and decay processes, including natural disturbances, are not attributable to the production function of forests and are therefore not considered in LCA. Harvesting operations lead to temporal decreases in forest carbon pools in the respective stand. Impacts on forest carbon pools resulting from the sustainable or unsustainable management of forests, however, cannot be defined or assessed on the stand level but require the consideration of carbon pool changes on the landscape level, i.e., the level on which management decisions are made. Resulting from the fundamental principle of sustainable forest management to preserve the production function of forests, total forest carbon pools can be considered stable (or increasing) under sustainable forest management. This is because temporal decreases of forest carbon pools resulting from harvesting on one site are compensated by increases of carbon pools on other sites, forming together the forest area under sustainable forest management.

It is acknowledged that excessive extraction of slash, litter, or roots for the purpose of bioenergy generation can lead to decreases in forest carbon pools. These activities, however, are not causally linked to the extraction of timber for the material use of wood. Effects on forest carbon pools related to the extraction of slash, litter, or roots are not attributable to the material use of wood and are therefore not considered in this document.

To reflect the biogenic nature of wood, its renewability, and its potential carbon neutrality, the system boundary between

Table 13—Cradle-to-gate redwood lumber LCIA contribution analysis results for A1-resource extraction, A2-transporation, and A3-redwood lumber production

Reporting category and indicator name	Abbreviation	Unit	Total	A1	A2	A3
Core mandatory impact indicator						
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	100%	40%	19%	41%
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	100%	1%	0%	99%
Acidification potential of soil and water sources	AP	kg SO_2e	100%	52%	11%	37%
Eutrophication potential	EP	kg Ne	100%	46%	9%	45%
Formation potential of tropospheric ozone	SFP	kg O_3e	100%	57%	10%	33%
Abiotic depletion potential for fossil resources (ADP fossil)	ADPf	MJ, NCV	100%	39%	17%	44%
Fossil fuel depletion	FFD	MJ surplus	100%	38%	16%	45%
Use of primary resources						
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	100%	0%	0%	100%
Renewable primary energy carrier used as material	RPRM	MJ, NCV	100%	0%	0%	100%
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	100%	38%	16%	46%
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	—	—	—	—
Secondary material, secondary fuel and recovered energy						
Secondary material	SM	kg	—	—	—	—
Renewable secondary fuel	RSF	MJ, NCV	100%	0%	0%	100%
Nonrenewable secondary fuel	NRSF	MJ, NCV	—	—	—	—
Recovered energy	RE	MJ, NCV	—	—	—	—
Mandatory inventory parameters						
Consumption of freshwater resources	FW	m^3	100%	0%	0%	100%
Indicators describing waste						
Hazardous waste disposed	HWD	kg	—	—	—	—
Nonhazardous waste disposed	NHWD	kg	100%	0%	0%	100%
High-level radioactive waste, conditioned, to final repository	HLRW	m^3	100%	0%	0%	100%
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	100%	0%	0%	100%
Components for re-use	CRU	kg	—	—	—	—
Materials for recycling	MR	kg	100%	0%	0%	100%
Materials for energy recovery	MER	kg	—	—	—	—
Recovered energy exported from the product system	EE	MJ, NCV	—	—	—	—

Table 14—Cradle-to-gate redwood lumber LCIA energy use contribution analysis results by fuel type for A1-resource extraction, A2-transporation, and A3-redwood lumber production

	Unit	Total	A1	A2	A3
Nonrenewable, fossil	MJ	100.00%	38.98%	16.70%	44.32%
Nonrenewable, nuclear	MJ	100.00%	0.25%	0.00%	99.75%
Nonrenewable, biomass	MJ	100.00%	0.04%	0.00%	99.96%
Renewable, biomass	MJ	100.00%	0.00%	0.00%	100.00%
Renewable, wind, solar, geothermal	MJ	100.00%	0.07%	0.00%	99.93%
Renewable, water	MJ	100.00%	1.60%	0.00%	98.40%

Table 15—Cradle-to-gate redwood lumber LCIA energy use contribution analysis results for A1-resource extraction, A2-transporation, and A3-redwood lumber production

	Unit	Total	A1	A2	A3
Nonrenewable, fossil	MJ	29.00%	99.88%	100.00%	15.33%
Nonrenewable, nuclear	MJ	0.84%	0.02%	0%	1.00%
Nonrenewable, biomass	MJ	0.00%	0%	0%	0%
Renewable, biomass	MJ	69.15%	0.01%	0%	82.48%
Renewable, wind, solar, geothermal	MJ	0.36%	0%	0%	0.43%
Renewable, water	MJ	0.66%	0.09%	0%	0.77%
		100.00%	100.00%	100.00%	100.00%

Table 16—Uncertainty analysis of selected inventory results

Inventory parameter	Units	Sample mean	Standard deviation	Sample minimum	Sample maximum
Electricity – A3 input	kWh	58.16	17.88	32.28	72.05
Diesel – A3 input	L	2.49	0.60	1.65	2.98
Gasoline – A3 input	L	0.08	0.06	0.00	0.12
Natural gas – A3 input	m^3	2.47	4.41	0.00	9.35
Wood fuel – A3 input	kg	104.59	78.98	0.00	167.51
Transport distance – A2 input	t-km	73.25	19.36	46.69	88.55

nature and the product system under study is defined as follows:

- Wood entering the product system from nature accounts for the energy content and the biogenic carbon content as material inherent properties.
- All technical processes related to forestry operations intended to produce timber (e.g., stand establishment, tending, thinning(s), harvesting, establishment, and maintenance of forest roads) are considered within the system boundary and are subject to coproduct allocations as outlined in the reference PCR (UL Environment 2019).
- Potential implications caused by the unknown origin of wood or unsustainably produced timber are considered.
- Human-induced impacts on forest carbon pools resulting in deforestation are included. In this study, the redwood forests that supplied logs to the sawmills are Sustainable Forestry Initative (SFI) and Forest Stewardship Council (FSC) certified and managed sustainably. Deforestation does not occur in the redwood forests from which the logs were procured.

Because the degradation of forest carbon pools resulting from unsustainable management of forests cannot be attributed to a specific log but is a process on a landscape level, the effect of forest degradation is considered by not assuming carbon neutrality. In the case of land-use changes from forests to other land uses (e.g., deforestation), the loss of carbon in the forest carbon pools are to be considered. Consideration of the biogenic carbon neutrality of wood is valid for North American wood products because national level inventory reporting shows overall increasing and/or neutral forest carbon stocks in recent years (FAO 2015, Oswalt and others 2019, Sahoo and others 2019).

Using this method to determine a value, –1,439 kg CO_2e (A1) was removed in the production of 1 m^3 of redwood lumber (Table 18). That same 1 m^3 of lumber stores 190 kg of carbon or +697.3 kg CO_2e (C3/C4). The coproducts produced during lumber production account for an additional +142.5 kg CO_2e (A3) for a total "emission" in wood product leaving the system boundary of +839.2 kg CO_2e. The combustion of wood fuel emitted 600.2 kg CO_2e. In summary, total removals were –1,440.30 kg CO_2e and total "emissions" were +840.12 kg CO_2e from cradle-to-gate (A1–A3) (Table 18). In accordance with ISO 21930, emission from packaging (BCEK) is reported in A5 and emission from the main product is reported in C3/C4. The system boundary for this LCA only includes module A1–A3.

10 Discussion

In 2014, Bergman and others (2014a) performed a gate-to-gate LCA of dry redwood lumber, which was generally used to make decking, and used 2010 survey data collected from redwood sawmills from the same region. Table 19 shows the comparison between the previous study by Bergman and others (2014a) and this study (2017 data). There was a 30% increase in total primary energy use in the production of redwood lumber in this study (1,738 MJ/m^3) compared

Table 17—Sensitivity analysis (mass allocation)

			Log transport distance		Diesel		Gasoline		Electricity		Natural gas		Woody biomass	
Impact indicator	Unit	Baseline results	–20%	+20%	–20%	+20%	–20%	+20%	–20%	+20%	–20%	+20%	–20%	+20%
GWP_{TRACI}	kg CO_2e	37.81	–6.40%	6.40%	–1.71%	1.71%	–0.08%	0.08%	–3.08%	3.12%	–3.23%	3.23%	–2.17%	2.18%
ODP	kg CFC11e	7.42E–07	–0.01%	0.01%	–0.16%	0.16%	–0.01%	0.01%	–5.70%	5.77%	–0.03%	0.03%	–9.11%	9.12%
AP	kg SO_2e	0.38	–3.77%	3.77%	–2.22%	2.22%	–0.09%	0.09%	–3.65%	3.70%	–0.24%	0.24%	–3.50%	3.51%
EP	kg Ne	0.03	–3.08%	3.08%	–2.49%	2.49%	–0.10%	0.10%	–3.08%	3.11%	–0.39%	0.39%	–4.57%	4.58%
SFP	kg O_3e	1.11E+01	–3.56%	3.56%	–2.49%	2.49%	–0.10%	0.10%	–2.54%	2.57%	–0.21%	0.21%	–3.77%	3.77%
ADPf	MJ, NCV	526.52	–5.73%	5.73%	–1.66%	1.66%	–0.09%	0.09%	–3.24%	3.28%	–3.26%	3.26%	–2.17%	2.18%
FFD	MJ surplus	82.27	–5.63%	5.63%	–1.59%	1.59%	–0.08%	0.08%	–3.33%	3.37%	–3.47%	3.47%	–2.13%	2.13%
RPRE	MJ, NCV	1,353.03	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	–7.89%	7.98%	0.00%	0.00%	–12.60%	12.61%
NRPRE	MJ, NCV	609.27	–5.26%	5.26%	–1.54%	1.54%	–0.08%	0.08%	–3.53%	3.57%	–3.13%	3.13%	–2.67%	2.67%

Table 18—Biogenic carbon inventory parameters

Additional inventory parameters	Abbreviation	Unit	Total	A1	A2	A3	A5	C3/C4
Biogenic carbon removal from product	BCRP	kg CO_2	–1439.35	–1439.35	—	—	—	—
Biogenic carbon emission from products (including residues and lumber)	BCEP	kg CO_2	839.17	—	—	142.51	—	696.67
Biogenic carbon removal from packaging	BCRK	kg CO_2	–0.95	—	—	–0.95	—	—
Biogenic carbon emission from packaging	BCEK	kg CO_2	0.95	—	—	—	0.95	—
Biogenic carbon emission from cogeneration [internal heat and electricity use]	BCEW	kg CO_2	192.49	—	—	192.49	—	—
Biogenic carbon emission from cogeneration (external electricity)	BCEW	kg CO_2	407.68	—	—	407.68	—	—
Net biogenic carbon emission		kg CO_2	0					

Table 19—LCIA comparison between previous data (Bergman and others 2014a, based on 2010 industry surveys) and current study data (based on 2017 industry surveys) on redwood lumber production in northern California, USA

Impact category	Unit	Current study based on 2017 production data[a]	Past study based on 2011 production data[a]	Percentage change
Ozone depletion potential	kg CFC11e	8.07E–07	3.69E–06	–78
Global warming potential, fossil	kg CO_2 eq	22.81	57.4	–60
Eutrophication potential	kg N eq	5.79E–02	2.34E–02	148
Smog potential	kg O_3 eq	4.46	6.61	–33
Nonrenewable fossil and nuclear	MJ	357.78[b] (361.01[c])	1,023	–65
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	1,354.49[b] (1,377.16[c])	317	327
Freshwater	L	195.53	29.26	568

[a]For comparison purposes, cumulative values of A2 and A3 stages of the redwood lumber life cycle were considered.
[b]Cumulative energy demand for the A2 and A3 stages were estimated considering lower heating value.
[c]Cumulative energy demand for the A2 and A3 stages were estimated considering higher heating value.

with the previous gate-to-gate study (1,340 MJ/m^3 using the higher heating value of all fuel–energy inputs) (Bergman and others 2014a). Moreover, in this study, there was a 65% decrease in the use of nonrenewable and a 327% increase in the use of renewable energy compared with the previous study. In this study, the residues generated from the sawmill were burned in the cogeneration unit to produce renewable electricity, which was mostly used on-site at the sawmill (24% of total electricity production) and the rest was exported to the local grid. A part of the total heat exhausted from the cogeneration unit was used for drying redwood lumber (12% of the total heat generated) with excess heat released to the environment, i.e., waste heat. Despite higher total energy use, the total cradle-to-gate GHG emissions were decreased by 78% because of the use of renewable electricity and heat from woody biomass. There was a 568% increase in water usage because of electricity produced in cogeneration being used internally.

11 Completeness and Consistency Checks

The completeness and consistency checks and sensitivity help to establish and enhance confidence in the study. These improve the reliability of the results of the LCA study, including the significant issues identified in the interpretation.

The objective of the completeness check is to ensure that all relevant information and data needed for the interpretation are available and complete. Three selected information modules (harvesting and forest management, resource and material transportation, and manufacturing of redwood lumber) were checked for data completeness including all elements such as raw and ancillary material input, energy input, transportation, water consumption, product and coproduct outputs, emissions to air, water, and land, and waste disposal. All the input and output data were found to be complete, and no data gaps were identified.

Table 20—Wood conversion

To convert from	to	Multiply by
Board feet log scale, international rule 1/4	m^3	0.0002
Board feet rough-green or rough-dry lumber	m^3	Varies by lumber size, based on actual dimensions
Board feet planed lumber	m^3	0.00162 for 2 by 6; varies by lumber size

The objective of the consistency check is to determine if the assumptions, methods, models, and data are consistent with the goal and scope of the study. Through a rigorous process, consistency is ensured to fulfill the goal of the study in terms of assumptions, methods, models, and data quality including data source, accuracy, data age, time-related coverage, technology, and geographical coverage.

12 Conclusions

The cradle-to-gate LCA for redwood lumber includes the LCI of forest resources, which relies on secondary and tertiary data, and the LCI of manufacturing, which relies on primary survey data and secondary data for process inputs such as natural gas, diesel, and electricity. The survey results were from representative operations in the northern California region that produce redwood lumber. The survey data were representative of the lumber sizes and production volumes consistent with trade association production data. By surveying 0.403 million m^3 of redwood lumber production, this study represents 66.6% of the total U.S. production for 2017, which was 0.605 million m^3.

Using methods of drying wood that are less energy-intensive than heated kilns can result in large decreases in environmental impacts. Because redwood sawmills use minimal kiln-drying (and when they do, the source for heating is from woody biomass), GHG emissions from the forest extraction (resources) are large relative to that from manufacturing (Puettmann and Wilson 2005, Puettmann and others 2010). In addition, on-site emissions to land and water are small. Mill on-site airborne emissions originated mainly at the boiler and dryer. Electrical energy use was greatest in the sawmill with overall energy use and on-site emissions dominated by the drying process.

Energy consumption was mostly consistent with the previous redwood decking study except for items such as higher woody biomass consumption and cogeneration electricity production (Bergman and others 2013, 2014a). Still, woody biomass consumption drove the high percentage of energy consumption for the product manufacturing stage for both studies. For this study, lumber production (A3) consumed 84% of the total energy, whereas 11% went to forest operations and 5% to transport. Energy generated by renewable fuels, such as woody biomass, represented about 69% of the total energy from cradle to gate. Total nonrenewable fuel use was 29% of the total energy from cradle to gate. For nonrenewable fuel contribution, forestry operations and raw material transportation consumed 39% and 17%, respectively (Table 13).

13 Critical Review

13.1 Internal Review

The purpose of the internal review of this LCA report was to check for errors and conformance with the PCR prior to submittal for external review. The technical and editorial comments of the reviewers were carefully considered and, in most instances, incorporated into the final document. The USDA Forest Service, Forest Products Laboratory (FPL), addressed the internal review comments, as appropriate, and maintains a record of all comments and responses for future reference.

13.2 External Review

The external review process was intended to ensure consistency between the completed LCA and the principals and requirements of the International Standards on LCA (ISO-14044) and the PCR for North American Structural and Architectural Wood Products (UL Environment 2018). Following FPL's internal review evaluation, documents were submitted to UL Environment for independent external review. The independent external review performed by UL Environment was conducted by Dr. Thomas P. Gloria, Ph.D., Industrial Ecology Consultant.

13.3 Units

Table 20 gives some information about converting from board feet to cubic meters.

14 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.C. 2011. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy. 13(5): 687-696.

Bergman, R. 2010. Chapter 13. Drying and control of moisture content and dimensional changes. In: General Technical Report FPL-GTR-190. Wood handbook—Wood as an engineering material. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Bergman, R.D.; Bowe, S.A. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science. 40(3): 448-458.

Bergman, R.; Bowe S. 2010. Environmental impact of manufacturing softwood lumber determined by life-cycle inventory. Wood and Fiber Science. 42(CORRIM Special Issue): 67-78.

Bergman, R.; Bowe S. 2012. Life-cycle inventory of manufacturing hardwood lumber in the southeastern United States. Wood and Fiber Science. 44(1): 71-84.

Bergman, R.; Taylor, A. 2011. EPD-environmental product declarations for wood products—an application of life cycle information about forest products. Forest Products Journal. 61(3): 192-201.

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. https://corrim.org/lcas-on-wood-products-library/ Corvalis, OR: Consortium for Research on Renewable Industrial Materials.

Bergman, R.D.; Oneil, E.; Eastin, I.L.; Han, H.S. 2014a. Life cycle impacts of manufacturing redwood decking in northern california. Wood and Fiber Science. 46(3): 322-339.

Bergman, R.; Puettmann, M.; Taylor, A.; Skog, K.E. 2014b. The carbon impacts of wood products. Forest Products Journal. 64(7-8): 220-231.

Briggs, D.G. 1994. Forest products measurements and conversion factors: with special emphasis on the US Pacific Northwest. Seattle, WA: College of Forest Resources, University of Washington.

Bringezu, S.; Ramaswami, A.; Schandl, H.; O'Brien, M.; Pelton, R.; et al. 2017. Assessing global resource use: a systems approach to resource efficiency and pollution reduction. International Resource Panel. Nairobi, Kenya: United Nations Environment Programme.

Canadell, J.G.; Raupach, M.R. 2008. Managing forests for climate change mitigation. Science. 320 (5882): 1456-1457.

FAO. 2015. Global forest resources assessment 2015. FAO Forestry Paper No. 1. Rome, Italy: The Food and Agriculture Organization of the United Nations.

FPL. 2010. Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Glass, S.V.; Zelinka, S.L. 2010. Chapter 4. Moisture relations and physical properties of wood. In: FPL-GTR-190. Wood handbook—Wood as an engineering material. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Han, H.S.; Oneil, E.; Bergman, R.D.; Eastin, I.L.; Johnson, L.R. 2015. Cradle-to-gate life cycle impacts of redwood forest resource harvesting in northern California. Jouranl of Cleaner Production. 99: 217-229.

ISO. 2006a. ISO-14040. Environmental management: life cycle assessment; Principles and Framework. Geneva, Switzerland: International Organization for Standardization.

ISO. 2006b. ISO-14044. Environmental Management: Life Cycle Assessments: requirements and guidelines. Geneva, Switzerland: International Organization for Standardization.

ISO. 2017. ISO-21930. Sustainability in buildings and civil engineering works — core rules for environmental product declarations of construction products and services. Geneva, Switzerland: International Organization for Standardization.

LTS. 2017. DataSmart LCI package (US-EI SimaPro® Library). https://ltsexperts.com/services/software/datasmart-life-cycle-inventory/. Huntington, VT: Long Trail Sustainability.

Malmsheimer, R.W.; Bowyer, J.L.; Fried, J.S.; Gee, E.; Izlar, R.; Miner, R.A.; Munn, I.A.; Oneil, E.; Stewart, W. 2011. Managing forests because carbon matters: integrating energy, products, and land management policy. Journal of Forestry. 109(7S): S7-S50.

Matos, G.R. 2017. Use of raw materials in the United States from 1900 through 2014, Fact Sheet. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

Miles, P.D.; Smith, W.B. 2009. Specific gravity and other properties of wood and bark for 156 tree species found in North America. Res. Note NRS-38. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 35 p.

Nielson, R.; Dobie, J.; Wright, D. 1985. Conversion factors for the forest products industry in western Canada. Vancouver, B.C., Canada: Forintek Canada Corp., Western Laboratory.

NIST. 2015. American softwood lumber standard: voluntary product standard PS 20-15. Gaithersburg, MD: U.S. Department of Commerce National Institute of Standards and Technology. 51 p.

Oliver, C.D.; Nassar, N.T.; Lippke, B.R.; McCarter, J.B. 2014. Carbon, fossil fuel, and biodiversity mitigation with wood and forests. Journal of Sustainable Forestry. 33(3): 248-275.

Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. 2019. Forest resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 223 p.

Pré-Consultants. 2017. SimaPro life-cycle assessment software package, version 8.5.2. Amersfoort, the Netherlands: Pré-Consultants.

Puettmann, M.E.; Milota, M. 2017. Life-cycle assessment for wood-fired boilers used in the wood products industry. Forest Products Journal. 67(5-6): 381-389.

Puettmann, M.E.; Wilson, J.B. 2005. Life-cycle analysis of wood products: cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science. 37(CORRIM Special Issue): 18-29.

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

Sahoo, K.; Bergman, R.; Alanya-Rosenbaum, S.; Gu, H.; Liang, S. 2019. Lifecycle assessment of forest-based products: a review. Sustainability. (11): 4722.

Sathre, R.; O'Connor, J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science & Policy. 13(2): 104-114.

Save The Redwoods League. 2019. A momentous year: great strides toward a 100-year vision. Annual Report 2018-19. San Francisco: Save The Redwoods League. https://www.savetheredwoods.org/wp-content/uploads/Annual-Report-2018-19-web.pdf.

Simpson, W.T. 1991. Dry kiln operator's manual. Agric. Handbook AH-188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

UL Environment. 2018. Product category rules for building-related products and services in: Brazil, China, Europe, India, Japan, Korea, North America, South East Asia. Part A: Life Cycle Assessment calculation rules and report requirements. UL Environment, Washington, DC.

UL Environment. 2019. Product category rule (PCR) guidance for building-related products and services: Part B: Structural and architectural wood products EPD requirements. Washington, DC: UL Environment.

15 Glossary of Terms

Allocation: A way of dividing emissions and resource use among the different products of a process. The partitioning can be made on a weight basis, energy content, or economic value.

Board foot (BF): The basic unit of measurement for lumber. One board foot is equal to a 1-in. board, 12 in. wide and 1 ft long (1 in. = 25.4 mm, 1 ft = 0.31 m).

Cradle-to-gate: LCA model that includes the upstream part of the product life cycle, i.e., all steps from raw material extraction to product at the factory gate.

Cubic recovery: A measure of the actual cubic volume of lumber recovered from the original net cubic log scale volume.

Declared unit: Quantity of a wood building product for use as a reference unit, e.g., mass, volume, for the expression of environmental information needed in information modules.

Functional unit: Expresses the function of the studied product in quantitative terms and serves as basis for calculations. It is the reference flow to which other flows in the LCA are related. It also serves as a unit of comparison in comparative studies.

Life-cycle assessment (LCA): Method for the environmental assessment of products covering their life cycle from raw material extraction to waste treatment.

Life-cycle inventory (LCI): LCA study that goes as far as an inventory analysis but does not include impact assessment.

Life-cycle impact assessment (LCIA): Phase of an LCA study during which the environmental impacts of the product are assessed and evaluated.

Lumber recovery factor (LRF): The volume of lumber recovered (in board feet) per cubic foot of log processed.

Overrun: The volume of lumber actually obtained from a log in excess of the estimated volume of the log, based on the log scale.

Product category rules (PCR): Set of specific rules, requirements, and guidelines for the development of type III environmental declarations for one or more product categories (ISO 14025, ISO 21930).

System boundary: A set of criteria that specifies which unit processes are part of a product system (adapted from ISO 14044).

Appendix A—Production Facility Survey Questionnaires

CORRIM SURVEY

The Consortium for Research on Renewable Industrial Materials (CORRIM)

Redwood lumber-2017

Thank you for giving us the opportunity to work with you on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be an excellent marketing tool for the redwood lumber industry particularly in the green building industry. A growing demand for building projects that use products with lower environmental burdens and energy-efficient materials has spurred a green movement in the construction industry.

As a member of the U.S. forest products industry, you know that using wood is a sensible choice because wood is renewable and often poses fewer burdens to the environment than substitute materials. Many consumers do not understand this. With your input, we can test the theory that redwood lumber poses less negative impacts to the environment than substitute materials such as plastic, concrete, steel and others do. Completed projects of this type have shown that wood products to be a sustainable and sound environmental choice over non-wood product alternatives.

This questionnaire focuses on annual production, annual energy use and generation, annual material inputs and outputs, and annual environmental emissions for redwood lumber manufactured in California. Regarding the questionnaire, our focus is on process information because this data is vital for precise and accurate results. Additional details may be requested later. We realize that you may not have all the information requested, but the data you are able to provide will be appreciated.

Strict confidentiality will be maintained for all companies that supply data

Company Name: ________________________________

Facility Address: ________________________________

____

Contact Person: ________________________________

Telephone: (   )   **Fax:** (   )_______

Contact email: ________________________________

Please direct questions and send complete questionnaires to:
Kamalakanta (KK) Sahoo
USDA FS Forest Products Laboratory
One Gifford Pinchot Dr
Madison, WI 53726-2398
Phone (608) 231-9272 / Fax (608) 231-9508
Email: ksahoo@fs.fed.us

PART I: OPERATION OVERVIEW
GENERAL INFORMATION (Please provide responses for all requested information)

1. **Reporting Year: ________ Starting Month: ________ Ending Month: ________**

2. **Log scale: Dolye, International, Scribner, Weight basis (circle one)**

3. **How many days did your mill operate for the selected reporting year? _________Days/Year**

4. **How many production shifts per day for the selected reporting year? __________Shifts/Day**

5. **Does your mill have the following:**

❑ log storage ○ dry deck ○ sprinkled deck ○ pond ○ other: _______________ ❑ log handling ○ log sorter/merchandizer ○ debarker ❑ sawmill ○ head rig(s): how many:_____ ○ band saw: how many:_____ ○ circular saw: how many:_____ ○ resaws: how many:______ ○ edgers: how many:______ ○ edger optimizer ○ trimmer optimizer ○ trimmer ○ sorter, # bins:______ ○ sticker stacker ○ emission control device(s)	❑ dryers and kilns ○ air drying yard: Capacity_________ ○ conventional steam: Capacity________ ○ high temperature steam: Capacity________ ○ direct-fired: Capacity________ ○ dehumidification: Capacity________ ○ transfer car system: Capacity________ ❑ boiler ○ wood-fired boiler ○ gas-fired boiler (natural or propane) ○ oil-fired boiler ○ cogeneration facility (electricity) ○ emission control device(s) ❑ planers ○ planer ○ in-line moisture meter ○ grading station ○ trimmer ○ end paint/seal ❑ other mill equipment

PART II: TOTAL MILL MATERIAL & ENERGY INPUTS & OUTPUTS

6. **Average log diameter: ____________ inches**

7. **Range of log diameter: ______to______ inches**

8. **Average log length: ______________feet**

9. **Volume of incoming logs during the reporting year: _____________ thousand bf**

10. **Volume of logs sold to outside firms during the reporting year: _________ thousand bf**

11. **Volume of logs sent to your sawmill during the reporting year: ________ thousand bf**

Please complete the following table to provide your facilities annual lumber production levels for the reporting year by product size. Please add more rows if necessary. Note – only report rough green lumber production by size for products when sold or transferred from your facility. We will be completing a mass balance (logs in vs. lumber and co-products out) for your mill, so we first need to know your lumber production – so if it leaves your facility, we need to track it. *We provided an example in the table of a mill that produces annually 60 million bf of nominal 2x6s. The numbers for 2x6 lumber are the focus of this project but we need values for the other sizes to determine the mass balance accurately.*

ANNUAL MILL PRODUCTION

Nominal Lumber Size	MMbf for reporting yr.	Surfaced-Green (MC=30%)[1]	Rough-Dry (MC=15%)[1]	Surfaced-Dry (MC=15%)[1]	Rough Green (Sold or transferred only) (MC=30%)[1]	Price ($/Mbf)	Percentage (%)
2x6	e.g. 45	X, MC=35%				e.g.600	75%
2x6	e.g. 10		X, MC=19%			e.g.700	16.7%
2x6	e.g. 5			X, MC=19%		e.g.900	8.3%
Total	e.g. 60	e.g.45	e.g. 10	e.g. 5		e.g.640	100%
Please complete for your mill below (add more rows if required)							
1x4							
1x4							
1x4							
5/4x6							
5/4x6							
5/4x6							
2x4							
2x4							
2x4							
2x6							
2x6							
2x6							

[1] **Change MC as appropriate** More rows on next sheet (over)

Nominal Lumber Size	MMbf for reporting yr.	Surfaced-Green (MC=30%)[1]	Rough-Dry (MC=15%)[1]	Surfaced-Dry (MC=15%)[1]	Rough Green (Sold or transferred only) (MC=30%)[1]	Price ($/Mbf)	Percentage (%)
2x8							
2x8							
2x8							
2x10							
2x10							
2x10							
2x12							
2x12							
2x12							
2x14							
2x14							

2x14							
4x4							
4x4							
4x4							
4x6							
4x6							
4x6							
4x8							
4x8							
4x8							
Other							
Other							
Other							
Other							
Other							
Other							
Total							100%

[1] Change MC as appropriate

ANNUAL RESOURCE TRANSPORTATION DATA: (transporting material to and from your sawmill)

Material	No. of deliveries	Average net weight of load (tons)	Average one-way distance (miles)	Transportation type (choose one)	Percent empty backhaul
Logs				Rail/Trucking	
Purchased wood fuel (if any)				Rail/Trucking	
Boiler Chemicals				Small/Large Truck	

12. For each of the co-products produced at your plant, please indicate the weight (tons) of **annual** production for the reporting period that are shipped to other users, used internally as fuel or for the production of another co-product at your facility, stockpiled for future use or land filled (estimates are acceptable). If zero, enter a dash (-). Please state units if other than tons like cubic yards. The final column (Total Quantity) should equal the sum of the individual rows.

Estimate amount of wood residue produced per thousand bf of redwood lumber ______tons/Mbf

Co-products and By-Products	Moisture Content (wet basis)	Sold (Shipped)	Used Internally (as fuel)	Used Internally (other uses)	Landfill	Inventory	Total Quantity
	(%)	tons	tons	tons	tons	tons	tons
Chips, green							
Sawdust, green							
Bark, green							
Edging strips, green							

Shavings, green							
Hogged material, green							
Sawdust, dry							
Shavings, dry							
Hogged material, dry							
Other							

13. If you have installed emission control devices at your mill, please list them by type and the equipment controlled by the device.

	Boiler #1	Boiler #2	Sawmill	Dry Kiln	Planermill	Logyard
Type of Device						
Equipment controlled						
Electrical Use[1], kWh						
Type of emissions controlled						

14. Are you processing material from other facilities (e.g. kiln drying lumber or planing rough green or kiln dried lumber from other mills)?

_________Yes; ___________No;

If Yes, please specify the quantity per process for the selected reporting year:

Kiln drying lumber from other mills (MMbf/yr) _______
Planing rough green lumber from other mills (MMbf/yr) _______
Planing kiln-dried lumber from other mills (MMbf/yr) _______

Short description of redwood lumber production process:

The sawmill complex is divided into six process units: (1) log yard, (2) sawing, (3) drying, (4) planing, (5) boiler or co-generation equipment (energy generation) and (6) emission control (if applicable)
- Log yard includes all log handling from receiving logs at mill gate up to breakdown of the log
- Sawing includes the breakdown of the logs into rough green lumber.
- Drying includes stickering, the dry kilns, loading area, and unloading (storage) and air yards.
- Planing includes the unstacker, planer, and packaging areas. Each of these includes transportation to the next unit process or plant gate.
- Boiler/co-generation equipment (energy generation) includes fuel storage, transportation, boiler, turbines and steam distribution system.

ANNUAL TRANSPORTATION FUEL USE ON-SITE (includes all fuels for yard equipment, forklifts, and carriers)

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		1. Log yard	2. Sawing	3. Drying	4. Planing	5. Boiler/Co-gen	
Off-road diesel							Gallons
Fuel Oil #6							Gallons
Propane							Gallons
Gasoline							Gallons
Electricity							kWh
Other							

ANNUAL BOILER FUEL AND ELECTRICTY USE: (boilers, cogeneration units, etc.)

Boiler Fuel	Total Quantity	Units	Moisture content (if applicable)
Wood			
Wood boiler fuel produced on-site		Tons	
Purchased wood boiler fuel		Tons	
Fossil Fuel			
Natural Gas		Thousand ft^3	
Fuel oil #1(kerosene)		Gallons	
Fuel oil #2 (heating oil)		Gallons	
Fuel oil #6		Gallons	
Propane		Gallons	
Electricity for entire facility		kWh	
Other			

Annual electricity use for the following processes (**Estimation by percentage or number is ok**)

Process	kWh	% of total
1. Log yard		
2. Sawing		
3. Kiln drying		
4. Planing		
5. Boiler/Co-generation		
Total		100%

ANNUAL WATER USE

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		1. Log yard	2. Sawing	3. Drying	4. Planing	5. Boiler/Co-gen	
Input							
Surface water							Gallons
Groundwater							Gallons
Municipal water							Gallons
Output							
Water discharged							Gallons
Water recycled							Gallons

What percent of water is recycled? ________%

ANNUAL ANCILLARY MATERIALS

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		1. Log yard	2. Sawing	3. Drying	4. Planing	5. Boiler/Co-gen	
Hydraulic Fluid							Gallons
Motor Oils							Gallons
Greases							Pounds
Gasoline							Gallons

Steel strapping							Pounds
Plastic strapping							Pounds
Paint							Gallons
Corrugated cardboard							Pounds
Replacement stickers							Pounds

ANNUAL INDUSTRIAL (SOLID) WASTE (material requiring disposal outside of mill)

Type	Pounds	Percent Landfilled
Pallets (not re-used)		
Fly Ash		
Bottom ash		
General refuse (do not include above materials)		
Recycled material		
Other		

ANNUAL AIR EMISSIONS: (*Provide stack test if available*)

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		1. Log yard	2. Sawing	3. Drying	4. Planing	5. Boiler/ Co-gen	
Dust							Pounds
Total Particulate							Pounds
PM2.5							Pounds
PM10							Pounds
Carbon monoxide (CO)							Pounds
Carbon dioxide (CO_2)							Pounds
Acetone							Pounds
Acetaldehyde							Pounds
Formaldehyde							Pounds
Hazardous Air Pollutants (HAPS)							Pounds
Methanol							Pounds
Nitrous oxides (NOx)							Pounds
Phenol							Pounds
Propionaldehyde							Pounds
Sulfur dioxide (SO_2)							Pounds
Total VOCs							Pounds
Others (please list all known):							Pounds
Other							Pounds
Other							Pounds
Other							Pounds
Other							Pounds

ANNUAL BOILER CHEMICALS

Boiler Chemicals	Total Quantity	Units
Oxygen scavenger Name_______________		Gallons
Corrosion inhibitors Name_______________		Gallons
Scale inhibitors Name_______________		Gallons
pH adjusters Name_______________		Gallons
Anti-foams Name_______________		Gallons
Sludge conditioners Name_______________		Gallons

ANNUAL WATER EFFLUENT: *(Provide water discharge test if available)*

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		1. Log yard	2. Sawing	3. Drying	4. Planing	5. Boiler/ Co-gen	
BOD[1]							Pounds
COD[2]							Pounds
Chlorine							Pounds
Oil							Pounds
Suspended solids							Pounds
Dissolved solids							Pounds
Phenols							Pounds
Others (please list all known):							Pounds

[1] Biological oxygen demand
[2] Chemical oxygen demand

DRY KILN INFORMATION (dry kilns are the most energy intensive process for making lumber)

Part of this study will be reviewing energy reduction potentials associated with kiln-drying, the most energy intensive aspect of lumber production. Please provide the following details on each of your kilns. If all or some kilns are identical simply write "same as Kiln No. X" below the appropriate kiln number. Attach a separate sheet if there are more than 5 kilns.

Dry Kilns	1	2	3	4	5
Kiln Capacity (Mbfm)					
Energy Systems					
Direct-fired (Y/N)					
Fuel type (gas, oil, biomass, etc.)					
Capacity (BTU's / hr.)					
Total HP electrical motors (blower, make-up air etc.)					
Radiant Heating (coils) (Y/N)					
Type (steam, hot oil, hot water)					
Kiln Configuration					

(side loading, single track, double track)					
Average age of kilns or year installed					
Fan Configuration (line shaft, cross shaft)					
No. of fan motors					
Dry Kilns (continued)	1	2	3	4	5
Total HP for Kiln					
Humidification System (yes/no)					
If **yes**, state type (live steam, water spray)					
Vent Heat Exchangers present (Yes/No)					
Drying Practices					
Initial Moisture Content					
Average length of time material remains in air-drying yard (days)					
Average Kiln Drying Time for all material (hrs)					
Pre-sorting (Yes/No)					
If **Yes**, state type of sorting (by MC, grade, other)					
Final Moisture Content					

Glossary

Baghouse: Air pollution device which forces gases through a filter thereby capturing gas born particles.
By-product: Material produced during manufacturing that is recycled or used “within system boundaries.”
Bottom ash: Residual by-product of burning coal. Porous, grainy, roughly sand sized particles.
Co-product: A material produced from manufacturing and "sold outside of the system boundary."
Cyclone: A device that uses centrifugal forces to collect waste material.
Dust: Dispersion particles formed in grinding a solid; particles may be small enough to temporarily suspend in the air.
Edgings: Pieces of board produced after lumber passes through an edger to achieve desired width.
Electrostatic Precipitator (esp): A type of precipitator which changes the electrical charge on a particle so that it can be captured by electrostatic forces.
Emissions: Expulsion of pollutants to air from a source.
Fly ash: Particulate impurities that come from burning coal and other materials.
General refuse: Waste collected from the facility that is mixed with dirt and cannot be sent to the boiler.
HAPs: Hazardous Air Pollutants (carbon oxides, nitrogen oxides, sulfur oxides).
Inorganic material: Material such as sand and other non-solubles.
Industrial waste: Material produced during manufacture requiring disposal out of the “system boundary.”
Packaging material: Steel strapping, plastic lumber covers, cardboard corners, plastic or paper wrap.
Particulates: By-products of combustion or milling; can be solid or liquid state.
PM10: Standard for measuring solid and liquid particulates in suspension in the atmosphere; particulates are defined here as less than 10 micrometers in diameter.
Product: The primary material produced from manufacturing and "sold outside of the system boundary."
Recycled material: Material collected from the manufacturing facility operation that is re-used.
VOCs: Volatile Organic Compounds- produced in incomplete combustion of carbon based compounds; does not include methane; examples are oil based paints and gasoline fumes.

Appendix B—Conversion Factors and Redwood Lumber Product Dimensions

Table B1—Conversion factor used to convert thousand board feet (MBF) to cubic meters for redwood lumber based on size and type (moisture content and extent of planing)[a]

Nominal dimensions[b]	Rough-green	Partially rough-green	Partially rough-dry	Partially rough-kiln-dry	Planed-green	Planed-dry	Planed-partial-dry	Planed-air-seasoned
1 by 2	2.333	1.887	1.748	1.748	1.440	1.327	1.364	1.364
1 by 3	2.318	1.946	1.815	1.815	1.575	1.475	1.516	1.516
1 by 4	2.333	1.987	1.859	1.859	1.642	1.549	1.592	1.592
1 by 5	2.324	1.983	1.855	1.855	1.642	1.549	1.592	1.592
1 by 6	2.318	2.023	1.889	1.889	1.728	1.622	1.668	1.668
1 by 7	2.327	2.028	1.893	1.893	1.728	1.622	1.668	1.668
1 by 8	2.322	2.011	1.882	1.882	1.700	1.604	1.649	1.649
1 by 9	2.328	2.014	1.884	1.884	1.700	1.604	1.649	1.649
1 by 10	2.324	2.038	1.899	1.899	1.751	1.637	1.683	1.683
1 by 12	2.326	2.046	1.911	1.911	1.767	1.659	1.706	1.706
2 by 2	2.380	1.910	1.770	1.770	1.440	1.327	1.364	1.364
2 by 3	2.364	1.969	1.837	1.837	1.575	1.475	1.516	1.516
2 by 4	2.380	2.011	1.881	1.881	1.642	1.549	1.592	1.592
2 by 4 (1-1/2 by 3-1/2 actual)	2.380	2.011	1.881	1.881	1.642	1.549	1.592	1.592
2 by 4 (1-5/8 by 3-5/8 actual)	2.380	2.011	1.881	1.881	1.642	1.549	1.592	1.592
2 by 5	2.371	2.006	1.877	1.877	1.642	1.549	1.592	1.592
2 by 6	2.364	2.046	1.910	1.910	1.728	1.622	1.668	1.668
2 by 6 (1-1/2 by 5-1/2 actual)	2.364	2.046	1.910	1.910	1.728	1.622	1.668	1.668
2 by 7	2.373	2.051	1.915	1.915	1.728	1.622	1.668	1.668
2 by 8	2.368	2.048	1.903	1.903	1.728	1.604	1.649	1.649
2 by 10	2.371	2.061	1.921	1.921	1.751	1.637	1.683	1.683
2 by 12	2.372	2.069	1.933	1.933	1.767	1.659	1.706	1.706
2 by 12 (1-1/2 by 11-1/2 actual)	2.372	2.069	1.933	1.933	1.767	1.659	1.706	1.706
3 by 3	2.349	2.058	1.922	1.922	1.767	1.659	1.706	1.706
3 by 4	2.364	2.080	1.960	1.960	1.795	1.721	1.769	1.769
3 by 4 (2-5/8 by 3-5/8 actual)	2.364	2.080	1.960	1.960	1.795	1.721	1.769	1.769
3 by 5	2.355	2.075	1.955	1.955	1.795	1.721	1.769	1.769
3 by 6	2.349	2.120	1.994	1.994	1.891	1.803	1.854	1.854
3 by 6 (2-1/4 by 5-5/8 actual)	2.349	2.120	1.994	1.994	1.891	1.803	1.854	1.854
3 by 7	2.358	2.124	1.998	1.998	1.891	1.803	1.854	1.854

Table B1—Conversion factor used to convert thousand board feet (MBF) to cubic meters for redwood lumber based on size and type (moisture content and extent of planing)[a]—con.

Nominal dimensions[b]	Rough-green	Partially rough-green	Partially rough-dry	Partially rough-kiln-dry	Planed-green	Planed-dry	Planed-partial-dry	Planed-air-seasoned
3 by 8	2.353	2.121	1.985	1.985	1.890	1.782	1.832	1.832
3 by 8 (2-1/4 by 7-1/2 actual)	2.353	2.121	1.985	1.985	1.890	1.782	1.832	1.832
3 by 10	2.355	2.135	2.005	2.005	1.915	1.819	1.870	1.870
3 by 12	2.357	2.143	2.017	2.017	1.930	1.842	1.893	1.893
4 by 4	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 4 (3-1/2 by 3-1/2 actual)	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 4 (3-3/8 by 3-3/8 actual)	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 4 (3-5/8 by 3-5/8 actual)	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 5	2.371	2.121	2.006	2.006	1.872	1.807	1.857	1.857
4 by 6	2.364	2.167	2.046	2.046	1.970	1.893	1.946	1.946
4 by 6 (3-1/2 by 5-1/2 actual)	2.364	2.167	2.046	2.046	1.970	1.893	1.946	1.946
4 by 6 (3-5/8 by 3-3/8 actual)	2.364	2.167	2.046	2.046	1.970	1.893	1.946	1.946
4 by 7	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 8	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 10	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
4 by 12	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
6 by 6	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
6 by 8	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
6 by 10	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
6 by 12	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
8 by 8	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
8 by 10	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
10 by 10	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
10 by 12	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
12 by 12	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857
Others	2.380	2.126	2.010	2.010	1.872	1.807	1.857	1.857

[a]This table was generated following these references (Nielson and others 1985, Briggs 1994, FPL 2010).
[b]Nominal measurements for dimensional lumber can be converted to standard metric measurements of the following:
1 in. = 19 mm; 2 in. = 38 mm; 3 in. = 64 mm; 4 in. = 89 mm; 5 in. = 114 mm; 6 in. = 140 mm; 7 in. = 159 mm;
8 in. = 184 mm; 9 in. = 210 mm; 10 in. = 235 mm; 12 in. = 286 mm.

Table B2—Redwood lumber dimensions and their volume contributions in 2017

Nominal dimensions[a]	Contribution (%)
1 by 2	0.0481
1 by 4	0.1831
1 by 6	0.2671
1 by 8	0.0499
2 by 2	0.1045
2 by 3	0.1535
2 by 4	15.8846
2 by 6	38.6600
2 by 8	13.2711
2 by 10	0.9331
2 by 12	9.1201
3 by 4	0.0003
3 by 6	4.2728
3 by 8	8.2682
4 by 4	6.1805
4 by 6	0.9549
4 by 8	0.5789
4 by 10	0.0077
4 by 12	0.0666
6 by 6	0.6748
6 by 8	0.1090
6 by 10	0.0200
6 by 12	0.0927
8 by 8	0.0506
8 by 10	0.0004
10 by 10	0.0012
10 by 12	0.0001
12 by 12	0.0011
Others	0.0454

[a]Nominal measurements for dimensional lumber can be converted to standard metric measurements of the following: 1 in. = 19 mm; 2 in. = 38 mm; 3 in. = 64 mm; 4 in. = 89 mm; 6 in. = 140 mm; 8 in. = 184 mm; 10 in. = 235 mm; 12 in. = 286 mm.