On-Site Energy Consumption and Life-Cycle Environmental Impacts of Sawmills in California

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Abstract

Addressing climate change is a global priority. Life-cycle assessment (LCA) quantifies the carbon footprint of products and can provide strategies for climate change mitigation. This novel study analyzed the energy consumption of softwood sawmills and used attributional LCA to estimate cradle-to-gate environmental impacts of softwood lumber manufactured in California. Using a representative sample size, 16 California sawmills (capturing ~88% of lumber production) were surveyed. Sawmills' energy consumption was characterized and evaluated by fuel type and on-site energy generation for annual lumber output in thousand board feet (MBF). Electric energy (194 kWh/MBF), with 85 percent of it coming from on-site generation and diesel fuel (5.55 L/MBF), was the main hot spot in the energy analysis. For cradle-to-gate environmental impacts, LCA of 1 m^3 of lumber was conducted on three lumber types. Using the survey data and secondary data specific to western US forest industry operations and raw material transportation, a cradle-to-gate life-cycle inventory was developed. For different impact categories, environmental impact indicators per cubic meter were reported and discussed; for instance, 36 to 48.4 kg CO_2 eq for global warming, 0.34 to 0.61 kg SO_2 eq for acidification, and 60.1 to 94.4 MJ surplus for fossil fuel depletion. As expected, planed-dry lumber had the highest environmental impacts per cubic meter. Energy analysis and environmental hot spots in lumber manufacturing were discussed in connection with carbon emission reduction strategies by the California forest products industry. California sawmills have adapted climate change mitigation strategies including on-site combined heat and power generation from renewable and sustainable wood residues, as evident in the results.

Mitigating climate change requires reducing greenhouse gas (GHG) emissions, which can be achieved by using and promoting products with lower GHG impacts (IPCC 2022). Using wood products to replace alternatives with equal functionality has been shown to reduce GHG emissions (Bergman et al. 2014, Geng et al. 2019). Several countries like Austria, Finland, Sweden, Australia, Canada, the United Kingdom, and the United States are adopting policies (direct or indirect) to increase the use of wood in the construction industry as a sustainable building material (Wang et al. 2014, Hildebrandt et al. 2017, Vihemäki et al. 2019). These policies, when implemented, would create substantial new demand for wood products (Nepal et al. 2021). For example, by 2050, global demand for timber is expected to rise threefold from 2020 consumption levels (Gresham House 2020, FAO 2022). Consequently, there is a growing concern for how to meet increasing demand for timber products without overexploiting forest resources. This implies a need for better insights into the performance of forest products industries and examining ways in which

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the timber sector can improve its resource efficiency and contribute toward meeting climate change mitigation targets (Loeffler et al. 2016a, Adhikari and Ozarska 2018, Brashaw and Bergman 2021).

Timber products are renewable and often considered environmentally sustainable. However, wood products have environmental impacts associated with their life-cycle stages, like any other product. The processing of felled trees into roundwood and various intermediate to final products consumes energy and emits GHGs to the atmosphere, which are two major sources of environmental impacts. Studies have indicated that primary wood product industries such as sawmills consume large quantities of electricity, mostly in the sawing unit process (Gopalakrishnan et al. 2005, Quesada-Pineda et al. 2016, Adhikari and Ozarska 2018). In addition, forestry operations, transportation of raw materials, and use of fossil fuels and chemicals generate emissions with associated environmental impacts.

In the United States, the Pacific Coast states have significantly large softwood lumber production capacity, with Oregon and Washington leading production and California establishing itself among the top 10 US lumber-producing states (OFRI 2020). After years of declining lumber production, California's timber industry is recovering. Among California's primary forest products industries, the sawmill sector is the largest in terms of sales and timber volumes processed. During 2016, lumber and sawn products accounted for 65 percent of the total sale of primary wood products from the California forest products industry (Marcille et al. 2020). The 32 sawmills operating that year in California contributed nearly 2 billion board feet of lumber, which accounted for >6 percent of softwood lumber production and >4 percent of lumber consumption in the United States (Marcille et al. 2020). California's forest industries include wood product manufacturers, forestry, logging workers, and supporting firms, which directly contributed to 57,891 jobs and $3.6 billion in labor income in the state (Marcille et al. 2020).

In many western US sawmills, a large part of total energy demand (>70%) is derived from renewable resources, mostly from sawmill residue and logging slash used for generation of process heat and power (Loeffler et al. 2016b, Sahoo and Bergman 2020). With expanding production and capacity utilization in California's wood products industry and growing importance of the renewable energy benefits, it is essential to inform policymakers, industry, and the public of the industry's energy requirements and environmental impacts. With a recovering timber industry and increasing demand for wood for mass timber from the building sector, California is looking forward to expanding its wood products manufacturing sustainably while minimizing potential environmental impacts (Cabiyo et al. 2021, Redmore et al. 2021).

A widely acknowledged and accepted approach for analyzing environmental impacts of products is to conduct an attributional life-cycle assessment (LCA). LCA methodology is guided by the International Organization for Standardization (ISO) standards (ISO 14040, 14044 2006). LCA is the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 2006). The life cycle can include all life stages from cradle to grave, i.e., raw material extraction and transportation, product manufacturing and transportation, use, and end of life. As per ISO framework, LCA consists of four phases: (1) goal and scope definition, establishing the functional or declared unit, system boundary, and choices to ensure consistency in other phases; (2) life-cycle inventory (LCI) analysis, compiling and quantifying the inputs and outputs for the processes included in the scope; (3) life-cycle impact assessment (LCIA), which converts LCI flows into potential environmental impacts associated with various processes in the product life cycle; and (4) interpretation of results for decision making. Each stage of the process involves several options that could influence the result. LCA can identify a wide range of environmental impacts, but global warming has emerged as the most critical impact category (Hoegh-Guldberg et al. 2018, Armstrong McKay et al. 2022, Canadell et al. 2023). The choice of impact categories depends on the goals of the study.

In the context of California and the larger US Pacific Coast region, LCA studies have been conducted on forest harvesting (Johnson et al. 2005, Han et al. 2015, Oneil and Puettmann 2017) and wood products manufacturing such as softwood lumber (Puettmann, 2020a) and redwood (*Sequoia sempervirens*) lumber (Sahoo and Bergman 2020, Sahoo et al. 2021). Often, these analyses are based on data from small groups of sawmills within a region or a single wood species. Therefore, analyses at state level are needed. The state-level analysis of energy consumption of the US sawmill industry has been conducted by Loeffler et al. (2016a: Arizona, Colorado, and New Mexico; 2016b: Montana). The focus of these two studies remains on-site energy consumption and sawmill emissions. A similar analysis of California sawmills is yet to be conducted, and the present study addresses this research gap.

The goal of this study was to analyze energy consumption and life-cycle environmental impacts of softwood lumber production using a larger sample of California's sawmills. Using a representative sample of on-site energy consumption data of sawmills, this study also examined sawmills' performance and opportunities to improve their energy profile. The purpose of this survey was to expand the collection of energy-use data for the sawmills that was conducted through a separate effort by University of Montana in response to a request from the California Department of Forestry and Fire Protection (CAL FIRE). Further, the study expanded to include quantification of life-cycle environmental impacts on a cubic meter lumber basis and LCA results of the sawmills were grouped on the basis of type of lumber—planed dry (PD), planed green (PG), rough green (RG)—manufactured by the sawmills as a primary output or final product.

Methods

Study area and sawmill survey

For this analysis, the state of California formed the geographic boundary (Fig. 1). California has around 32 million acres of forest land, of which 16 million acres are used for timber production, mainly softwood sawtimber, which held a total volume of live trees of 102 billion ft^3 (2.89 billion m^3) in 2019 (USDA 2019, Marcille et al. 2020). During the period from 2001 to 2019, these forests offset 6.2 percent of the state's carbon emissions (Christensen et al. 2021). The

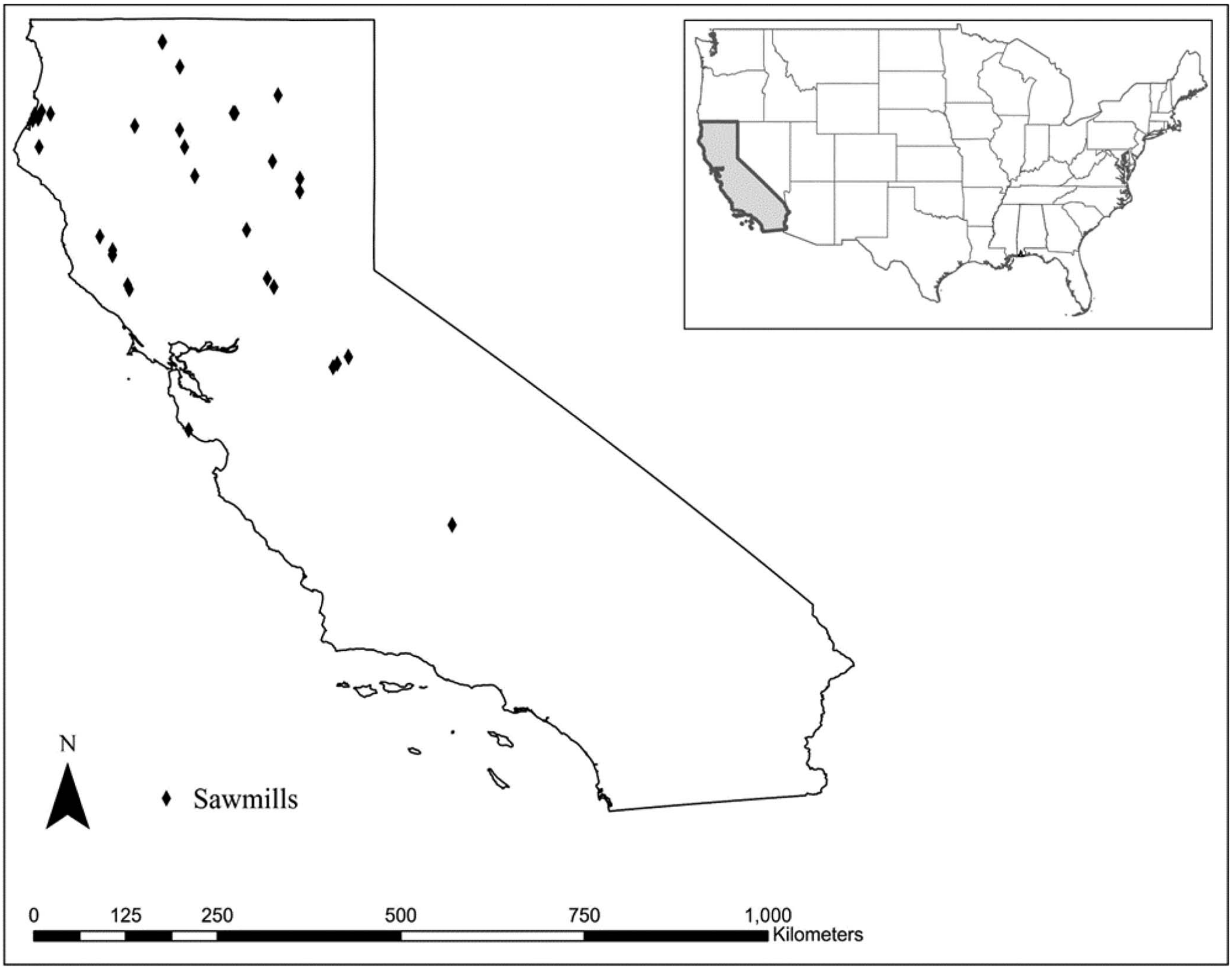

Figure 1.—Forest product facility locations in California 2016 (Forisk Consulting, 2024).

primary wood species harvested in California in 2016 were white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), redwood (*S. sempervirens*), sugar pine (*Pinus lambertiana*), and incense cedar (*Calocedrus decurrens*), which accounted for >98 percent of harvested timber (Marcille et al. 2020). Table 1 displays California's 2016 harvested volumes by species and their associated weighted average specific gravities used in this analysis.

In 2016, 80 primary wood product facilities, which included 32 sawmills and 23 forest-based bioenergy facilities, received 1.57 billion board feet Scribner of harvested sawlogs (Marcille et al. 2020). About 82 percent of the total sawlog harvest (1.29 billion board feet) were received by 32 sawmills that were the subject of the survey in this analysis. Responses were received from 16 of the 32 sawmills operating in 2016, which represented 1.14 billion board feet, i.e., nearly 88 percent of California's sawlog harvest (1.29 billion board feet; Table 1).

The sawmill survey collected information on volume of roundwood sawlogs purchased and lumber tally output of the sawmills. The survey was intended to collect on-site energy consumption data from sawmills to find out their annual energy use profile and the intensity of energy used to convert sawlogs into lumber products. Survey design followed those used by Loeffler et al. (2016a, 2016b) to collect on-site energy consumption data, which also provides baseline comparisons across several US states (see Supplemental Information Part A for survey questions).

On-site energy consumption data were collected by the University of Montana. Sawmills were asked to provide information about usage of fuel for their rolling stock (e.g., forklifts), hog fuel, natural gas, heating oil, propane, and electricity including both grid power and electricity generated on-site.

Sawmills' performance and energy analysis

Sawmills reported on-site energy consumption values and associated lumber production in thousand board feet (MBF) lumber tally. MBF is the commonly used measure of wood volume in the United States. For sawmills' efficiency, lumber recovery or distinctly lumber overrun (LO) was calculated by dividing the MBF lumber tally output by MBF log scale input. LO tends to be an inexact measure of sawmill efficiency, but it is easily calculated (Keegan et al. 2010). Log scales estimate the amount of lumber that could be produced from the harvested timber or log (Spelter 2004,

Table 1.—Percent distribution of wood species harvested in California in 2016.

Wood species	Harvest (MBF)	Percent of harvest (%)	Specific gravity (green)	Specific gravity (12% MC)[a]
White fir (*Abies concolor*)	429,840	27.4	0.37	0.39
Douglas-fir (*Pseudotsuga menziesii*)	371,210	23.6	0.45	0.48
Ponderosa pine (*Pinus ponderosa*)	357,207	22.7	0.38	0.40
Redwood (*Sequoia sempervirens*)	218,373	13.9	0.34	0.35
Sugar pine (*Pinus lambertiana*)	112,962	7.2	0.34	0.36
Incense-cedar (*Calocedrus decurrens*)	54,438	3.5	0.35	0.37
Other species	27,200	1.7	—	—
Weighted average	—	—	0.38	0.41
Total	1,571,230	100	—	—

[a] MC = moisture content.

Fonseca 2005, Keegan et al. 2010, Blatner et al. 2012). There tends to be differences between log scale and lumber tally for all sawmills (Ray et al. 2007, Keegan et al. 2010). The MBF output of sawmills was also converted into cubic meters on the basis of the lumber type they primarily produce. This was considered necessary for international readers because MBF is a nonmetric unit and is mainly used in the United States. Three main lumber types were produced and conversion factors for each were applied: 2.36, 1.73, and 1.67 m^3/MBF for RG, PG, and PD lumber, respectively (Sahoo and Bergman 2020). The energy data per cubic meter of lumber produced were compiled as supplemental information (Supplemental Figs. S1 and S2 Part B).

Performance of sawmills was evaluated by grouping them into two groups according to their annual lumber output: G1 sawmills ($n = 7$) producing >100,000 MBF lumber output, and G2 sawmills ($n = 9$), which produce <100,000 MBF lumber output. Fuel and energy inputs per MBF lumber for all respondent sawmills were analyzed on the basis of the energy usage and lumber production data collected in the survey. Because the average annual production of lumber was very high for some sawmills and very low for others, a lumber production weighted average of each energy input was calculated on the basis of the reported energy consumption values for each sawmill (Eq. 1):

$$W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

where W is the weighted average of the reported fuel and energy values by sawmills, n is number of sawmills (16), w_i is the weight factor (i.e., fraction of each sawmill's lumber production to respondent's total lumber production), and X_i is each sawmill's reported fuels and associated energy value. By taking this approach, energy input values from a large sawmill were given more weight and the original information remained confidential (Puettmann 2020a, 2020b; Sahoo et al. 2021). The survey data were collected for all energy sources consumed inside the sawmill. Energy used outside the sawmill, including transportation of raw materials, and finished wood products were not recorded and therefore excluded in the energy analysis. The data were converted to Système International (SI) units to ensure that results are standardized for performing the LCA, and that they allow consistent comparisons with future studies (Table 2).

Life-cycle assessment

Goal and scope.—The main objective of this study was to identify the primary contributors of selected environmental impacts associated with wood product manufacturing in California. To assess the environmental impacts, sawmills were grouped by lumber product. The sawmills in this analysis produce different types of lumber, which can be rough or planed, as well as green or dry. We grouped the sawmills on the basis of the three primary types of lumber produced: RG, PG, and PD lumber. Sawmills in this analysis do not produce rough dry lumber.

The specific goal of this cradle-to-gate attributional LCA was to assess the environmental impacts of RG, PG, and PD lumber production stages covering harvesting operations (A1), raw material (log) transportation (A2), and product manufacturing in sawmills (A3) modules. As mentioned earlier, lumber conversions in the United States tend to be difficult to discern because lumber dimensions are measured in nominal dimensions and not actual dimensions, so we needed to consider what the final lumber type is. In addition, wood shrinks as it dries (Bergman 2021). Therefore, we used separate conversions of volume from MBF of RG, PG, and PD lumber tally to cubic meters of lumber that were estimated in a LCA of redwood lumber production in California (Sahoo and Bergman 2020, Sahoo et al. 2021). Table 3 shows the type of lumber output, their share in total production, and MBF-to-cubic-meter conversion applied for each lumber type.

Declared unit.—The declared unit of the cradle-to-gate LCA was 1 m^3 of the final product leaving the sawmills. Declared unit focuses on a single product and it is used when not covering the whole life cycle of a product (i.e.,

Table 2.—Energy content of the fuel and electricity inputs reported in the analysis.

Energy inputs	Reported unit	Multiplication factor to convert to SI unit[a]	SI unit	MJ per SI unit
Diesel	Gallon	3.78	L	10.24[b]
Gasoline	Gallon	3.78	L	34.84[b]
Propane	Gallon	3.78	L	25.37[b]
Natural gas	Dekatherms	28.3	m^3	38.32[b]
Wood residue	Bone dry tons	0.907	Bone dry tonnes	20.9[c]
Electricity	kWh	1	kWh	3.6

[a] SI = Système International.

[b] EPA 2021.

[c] Puettmann and Milota 2017.

Table 3.—Percent distribution of types of lumber produced in California sawmills in 2016.

Type of lumber produced	Percent share in total production (number of sawmills)	Conversion (MBF/m^3)
Rough-green lumber	13 ($n = 4$)	2.36
Planed-green lumber	26 ($n = 4$)	1.73
Planed-dry lumber	61 ($n = 8$)	1.67

cradle to gate). Further, it was preferred to use SI units as the basis for reporting the flows of material and energy across the system boundary for the LCI and the results of LCIA (ISO 21930 2017). The conversion required for lumber volume from MBF to cubic meters of lumber is further described in the LCI section and *Table 3*.

System boundary.—The survey collected only on-site energy consumption at sawmills in California (*Fig. 1*); therefore, it was necessary to extend the LCA system boundary to include upstream information modules of forest operations and raw material transportation off-site of the sawmills. *Figure 2* presents the cradle-to-gate system boundary included in this LCA. Transportation of manufactured lumber and any subsequent secondary manufacturing, their end uses, and disposals at the end of their service life were not included in the system boundary. The unit processes in sawmills were identified on the basis of their primary lumber output (e.g., RG, PG, PD). However, on-site fuel and energy consumption collected in the survey did not distinguish among different sawmill unit processes (e.g., debarking, sawing, drying, and planing), and therefore represents the combined operations of sawmills and total fuels consumed.

Cradle-to-gate LCI.—Primary data from the sawmill survey, secondary data from published LCA studies, and the DATASMART LCI package available in SimaPro software were used to develop a LCI of California lumber products (LTS 2021). For constructing the LCI, informational modules of A1, A2, and A3 corresponded in this analysis to forest management (resource) activities, raw material transportation, and sawmill operations, respectively (ISO 14025 2006, ISO 21930 2017). The LCI of forest management and harvesting operations (A1) was based on previously published work from California (Johnson et al. 2005, Han et al. 2015, Oneil and Puettmann 2017). LCI for the A1 module included regional representation of forest management practices (seedling, site preparation, and planting) and harvesting activities (felling, processing, skidding, loading for further transportation).

For LCI of sawlog transportation (A2), the average distance to sawmills was estimated to be 103 km on the basis of the values reported in several studies from the California region (Johnson et al. 2005, Oneil and Puettmann 2017, Puettmann 2020a, Sahoo et al. 2021). LCIs of sawmill operations (A3) for the three lumber types were developed from the survey input and output data grouped into RG, PG, and PD lumber, respectively (Table 4).

On-site energy consumption data and mass flows were normalized to declared unit (1 m^3). The mass flows were tracked to estimate the inputs required to produce a cubic meter of lumber. The mass balance analysis showed that 1.82, 2.16, and 2.31 m^3 of sawlogs were required to produce 1 m^3 of RG, PG, and PD lumber, respectively. All input values were weighted by each sawmill's respective share on total annual consumption. With weighted averages, sawmill energy inputs are considered to represent 2016 lumber production in California. Data for extraction and use of ancillary materials such as motor oil, hydraulic fluid, paint, and packaging in the sawmills were taken from the redwood lumber LCA study conducted in California (Sahoo and Bergman 2020, Sahoo et al. 2021). A mass allocation approach was used to assign the LCI data and environmental impacts to final lumber product and coproducts, which is consistent with the North American building product category rules (UL Environment 2019, 2022).

A substantial part of residues produced in the sawmill operations was used for on-site generation of heat and electricity, especially in the sawmills that reported PD lumber as their main product. An LCI of wood-fired boiler developed by the Consortium for Research on Renewable Industrial Materials (CORRIM) was used for the on-site energy generation (Puettmann and Milota 2017). The downstream impacts of residues that were sold and left the system boundary for manufacturing of other products like mulch, wood composites, and paper were not included in this analysis. In this study, to account for the phenomenon of wood shrinkage during drying, the specific gravities of the studied mixed wood species were considered 0.38 and 0.41 for green and dry lumber, respectively, which corresponded to 380 and 410 oven-dry density kg/m^3, respectively (Miles and Smith 2009, Bergman 2021). The mass allocation factor, shown in parentheses in Table 4 for PD lumber, was lower than for both PG and RG lumber because both wood shrinkage during drying (i.e., increased specific gravity) and wood removed during planing lowered the final dimensions of PD lumber compared with the other two lumber types (Hubbard et al. 2020, Bergman 2021), but tended to be higher by mass for coproducts such as sawdust and other residues for the same reasons. Last, the biogenic carbon was addressed with 0/0 approach, assuming roundwood was sourced from sustainably managed forests. In this approach, the release of CO_2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO_2 during the biomass growth (ISO 21930 2017, Tellnes et al. 2017, Giacomello et al. 2024).

Life-cycle impact assessment.—This study aimed to identify the most significant environmental input–output flows (i.e., hot spots) in lumber manufacturing on the basis of LCIA results. In the LCIA phase, the LCI flows were converted into environmental impacts using US Environmental Protection Agency's Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.1 impact assessment method (Bare 2014) available in SimaPro 9.4 software (PRe Consultants 2021). Different environmental impact categories cannot be directly compared or added because of different measuring units. This study focused on the following six impact categories of the TRACI method: global warming (kg CO_2 eq), ozone depletion (kg trichlorofluoromethane [CFC-11] eq), photochemical smog formation (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), and fossil fuel depletion (MJ surplus). A sensitivity analysis was conducted for two key input parameters in lumber manufacturing: sawlog transportation distance and on-site electricity consumption. A 20 percent change in transportation

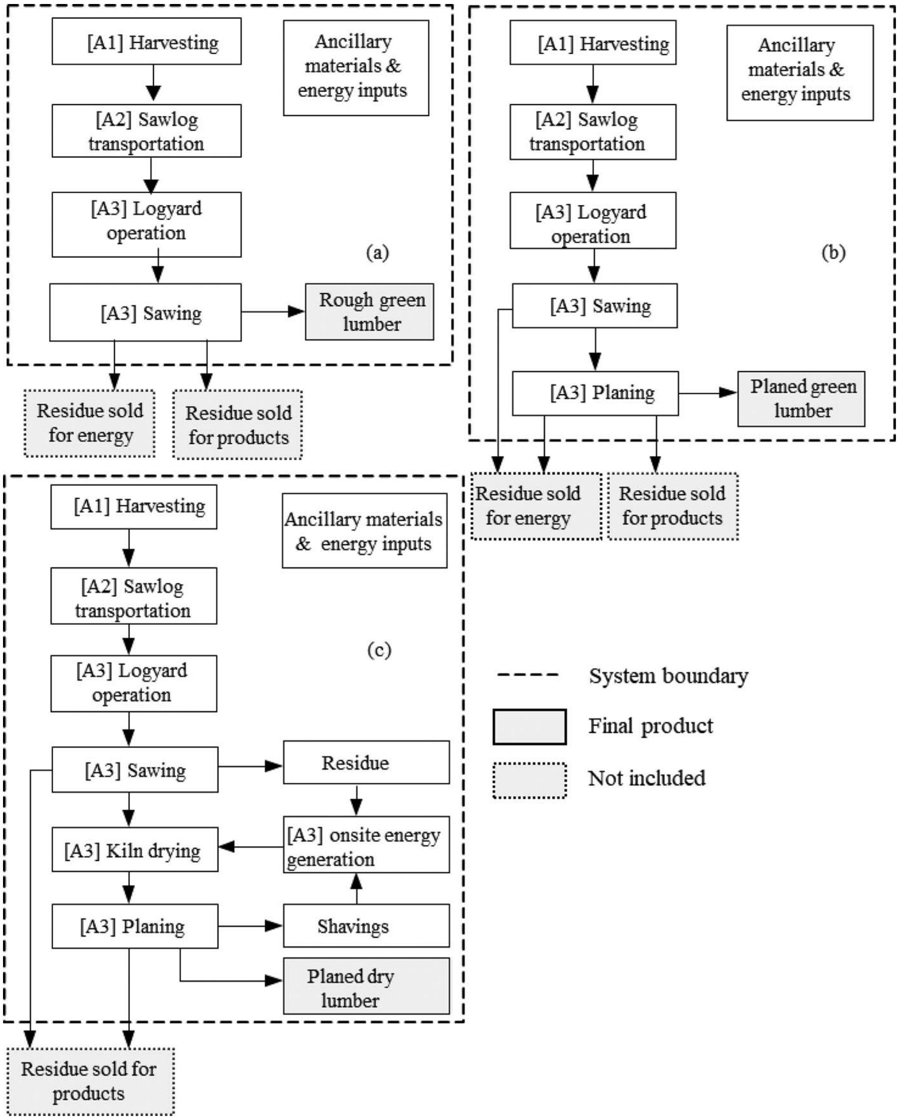

Figure 2.—System boundary for cradle-to-gate life-cycle assessment of three types of lumber products manufactured in California sawmills: (a) rough-green lumber, (b) planed-green lumber, (c) planed-dry lumber.

distance and grid electricity consumption in lumber manufacturing was examined for its impact on environmental impacts due to these two inputs. For the sawmills having on-site electricity generation, change in grid electricity amount was compensated by an increase or decrease in on-site electricity generation.

Results and Discussion

Sawmills' performance and energy analysis

During 2016, the California sawmills produced slightly more than 2,000,000 MBF of lumber. Across the 16 sawmills surveyed, an average 1.79 MBF lumber output per MBF Scribner input of sawlogs was estimated. The sawmills varied in their annual output, with G1 sawmills (>100,000 MBF lumber output) producing 65 percent of the lumber and the remaining supplied by G2 sawmills (<100,000 MBF lumber output). The performance of sawmills was evaluated by estimating their lumber overrun (LO) and energy consumption. The average LO of California sawmills was 1.79 (range 1.25 to 2.81) MBF lumber output per MBF Scribner input of sawlogs (Fig. 3a). This was consistent with the previously reported average values for LO in California sawmills (Buchholz et al. 2021). G2 sawmills producing a larger percentage of RG and PG lumber have a higher LO of 1.92 compared with the G1 sawmills producing PD lumber, which have a 1.63 LO (Fig. 3b). During sawmill operations, large quantities of residues are produced (bark, sawdust, chips, etc.) that can be used to fuel boilers or to make other engineered wood products (Blatner et al. 2012). Percent share of residues produced with each lumber type are indicated in Table 4. Our analysis indicated that >99 percent of residues generated in sawmill operations in California were either used internally or sold for energy or other products, with only a small amount remaining unused and assumed to be sent to landfill.

Table 5 displays a summary of total 2016 energy consumption, weighted average, and the lowest and the highest reported values for different fuels. By aggregating the survey data by weighted average production of sawmills, a state-level and sector-level evaluation that is useful for policymakers is provided while keeping the original mill-level

Table 4.—Process inputs and outputs to produce 1 m^3 of types of lumber in California.

LCI flows[a]	Unit	RG lumber (four sawmills)	PG lumber (four sawmills)	PD lumber (eight sawmills)
Material and energy inputs				
Sawlogs	m^3	1.82	2.16	2.31
Transportation	tkm	70.9	84.3	97.4
Diesel	L	1.22	2.49	3.88
Gasoline	L	0.12	0.023	0.061
Natural gas, heating	m^3	0.017	0.00001	2.76
Propane	L	0.027	0.0045	0.054
Diesel, heating	L	0.01	0.893	0.139
Electricity, cogeneration	kWh	—	80.6	116
Electricity, grid	kWh	37.75	31.3	21.4
Electricity, natural gas	kWh	—	0.0001	0.573
Product outputs				
Lumber[b]	m^3	1 (55%)	1 (46%)	1 (43.2%)
Sawdust	kg	61.18 (9%)	76.58 (9%)	91.92 (9.7%)
Shavings	kg	6.13 (1%)	81.93 (10%)	72.35 (7.6%)
Bark	kg	92.45 (13%)	120.60 (15%)	141.60 (14.9%)
Other residues	kg	151.24 (22%)	162.07 (20%)	232.94 (24.6%)

[a] LCI = life-cycle inventory; RG = rough green; PG = planed green; PD = planed dry.

[b] Oven dry (OD) density of 1 m^3 lumber: 380 OD kg for RG and PG lumber, and 410 OD kg for PD lumber. Values in parentheses are mass allocation percentages estimated for lumber and coproducts from raw sawlogs.

data confidential. The annual energy consumption (per MBF lumber) of surveyed sawmills was found to be substantially higher or lower than the reported values in other studies (Loeffler et al. 2016a, 2016b; Puettmann 2020a; Sahoo et al. 2021). Average electricity consumed per cubic meter of lumber was 109 kWh in the present study compared with 43.27 kWh consumed in production of redwood lumber in Sahoo et al. (2021). A study on 11 sawmills from Montana reported an electricity consumption of 276 kWh/m^3 of lumber (Loeffler et al. 2016b). The electricity consumption in California sawmills was much lower than those of Montana sawmills. Since these studies were either regional, North American average (Puettmann 2020a), from wood species-specific sawmills (Sahoo et al. 2021), or sawmills in other states (Loeffler et al. 2016a, 2016b), it was not possible to draw conclusions by directly comparing on-site energy consumption of sawmills with other analyses. The rate and source of electricity consumed per cubic meter depended on the type of lumber produced in the sawmills. Thus, keeping track of the electricity consumption rates and source would make a benchmarking metric for comparing the energy performance of sawmills.

Electricity consumption at the respondent sawmills was a substantial input and thus evaluated by the source of electricity generation. The energy profile of sawmills was primarily influenced by electricity and heat generated from burning woody biomass on-site. Although the 16 California sawmills consumed nearly 194 kWh per MBF of lumber output (Fig. 4), nearly 85 percent came from electricity generated on-site (renewable) and 15 percent from off-site grid electricity. The on-site electricity was generated via cogeneration of heat and power mostly by burning sawmill residues and a small amount of fossil fuels (natural gas). The energy analysis grid electricity was tracked to find the providers and their distribution of fuel sources (Table 6). In addition, nearly 54 percent of the grid electricity was further categorized as coming from renewable sources. Therefore, the on-site generation of energy was found to be a significant factor in the sawmills' energy profile. The average electricity consumption per MBF was 215 and 153 kWh in

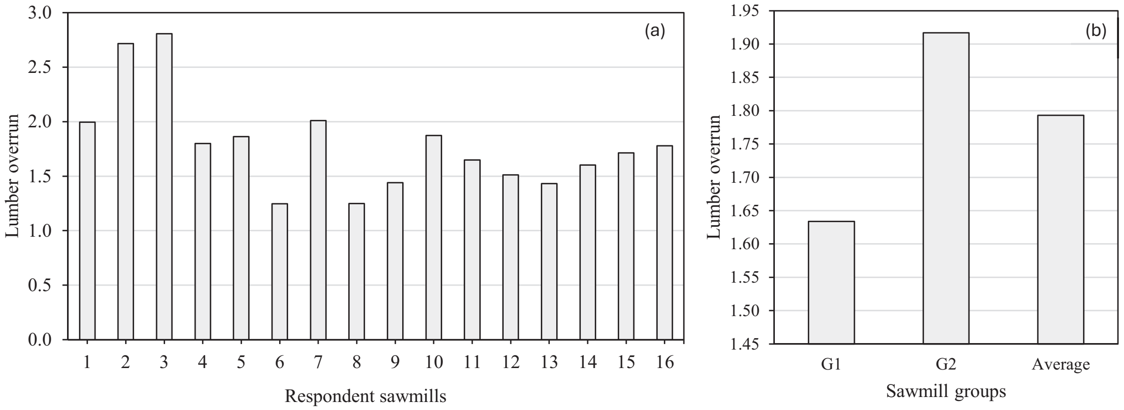

Figure 3.—(a) Lumber overrun of respondent California sawmills in 2016. (b) Lumber overrun by sawmill groups by annual production: G1 group of sawmills producing >100,000 thousand board feet (MBF) lumber output and G2 group of sawmills producing <100,000 MBF lumber output.

Table 5.—Annual energy consumption on-site at 16 Californian sawmills, by fuel type.

Energy inputs	Total energy consumption (16 sawmills)	Annual energy consumption per sawmill[a]	Energy consumption per thousand board feet (MBF) lumber output[a]	Lowest reported value (per MBF)	Highest reported value (per MBF)
Diesel (L)	10,122,339	834,000	5.55	2.15 ($n = 16$)	9.82
Gasoline (L)	205,314	10,490	0.07	0.14	0.88
Propane (L)	121,804	6,290	0.04	0.01	0.92
Natural gas for heat (m^3)	171,123	6,502	0.04	0.01	1.95
Propane for heat (L)	5,318	249	0.02	0.06[b]	0.06[2]
Diesel for heat (L)	262,732	30,363	0.20	0.0004	1.22
Residue for heat (tonne)	343,216	31,029	0.21	0.22	0.35
Electricity generated on-site (kWh)	260,061,409	24,694,075	164.27	24.33	262.87
Electricity from grid (kWh)	88,723,518	4,527,029	30.12	3.03	208.66

[a] Weighted average.

[b] One reported value.

G1 and G2 sawmills, respectively, which could be associated with more energy-intensive operations in G1 sawmills.

In addition to electricity, diesel fuel used in various sawmill operations was another source of energy consumption. The use of diesel fuel across all sawmills varied from 2.15 to 9.82 L and the weighted average was 5.55 L per MBF lumber output. Figure 5 shows the diesel consumption profile of sawmills. The G1 sawmills, which produce mostly PD lumber, consume more diesel, electricity, and heat per MBF output because of the additional sawmill operations like planing and heat generation from a boiler compared with G2 sawmills. Half of the 16 sawmills had on-site heat and power generation facilities where wood residues were the main fuel (Fig. 4).

LCA results

Table 7 presents the cradle-to-gate LCA results for manufacturing 1 m^3 of softwood lumber products for the six TRACI impact categories. In all impact categories, the potential impacts per cubic meter were highest for PD lumber, followed by PG and RG lumber types. This was likely due to the additional energy use and related emissions from drying and planing operations during PD lumber manufacturing as indicated in Figure 2. Across all impact categories, PG and PD lumber manufacturing had 18 to 73 percent and 34 to 99 percent higher cradle-to-gate impacts, respectively, when compared with the same volume of RG lumber. In PG and PD lumber, global warming and ozone depletion impact categories showed smallest and largest percent difference, respectively. Figure 6 shows a breakdown of impact potential by individual modules. The percent share of A3 manufacturing module was highest (79%) in ozone depletion and lowest (19%) in smog and eutrophication impacts. This was followed by A1 resource extraction module accounting for 21 to 69 percent and transportation module sharing up to 21 percent of the total impacts (Fig. 6). The contribution of individual sawmill (manufacturing) unit operation (e.g., sawing, drying, planing) on overall impacts could not be determined as the LCI data for lumber manufacturing was at facility level instead of specific to each sawmill unit operation.

Global warming impacts.—In LCAs, global warming (GW) refers to the warming that can occur as a result of GHG emissions arising from the life cycle of the product being produced. It is one of the most assessed environmental impact categories in wood products research (González-García et al. 2011, Bergman et al. 2014, Ganguly et al. 2020, Khatri et al. 2023). The cradle-to-gate GW impacts of RG, PG, and PD lumber were 36, 42.3, and 48.4 kg CO_2 eq/m^3, respectively (*Table 7*). Higher GW impacts of PD and PG lumber can likely be attributed to additional sawmill operations of drying and planing during manufacturing (*Fig. 2*). These results were within the range of GW impacts estimated for three redwood lumber types varying from 22 to 65 kg CO_2 eq/m^3 (Sahoo et al. 2021). Another LCA study covering PD lumber production in three

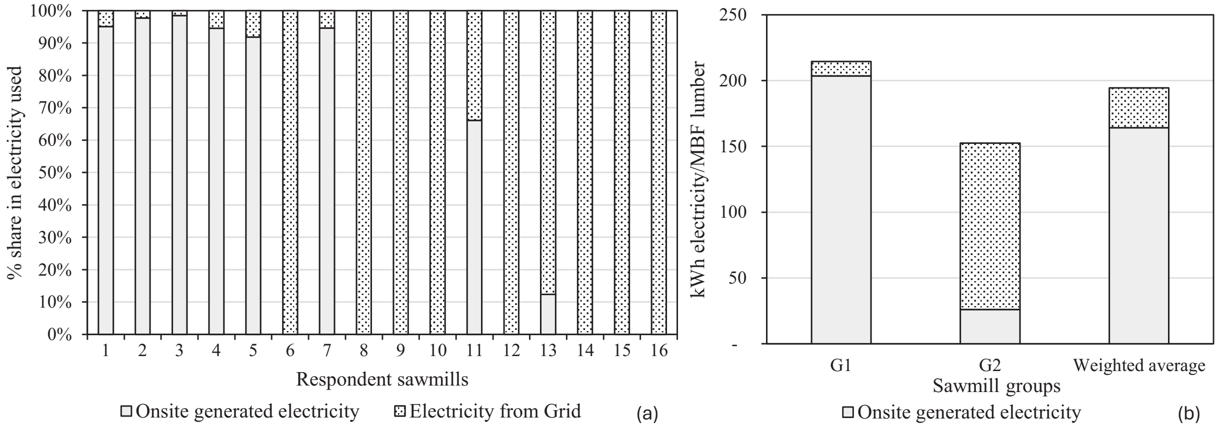

Figure 4.—(a) Electricity consumption profile of the 16 respondent sawmills and (b) sawmill groups per annual thousand board feet (MBF) lumber output (i.e., G1: >100,000; G2: <100,000).

Table 6.—Percent distribution of fuel sources used in grid electricity generation by electricity providers for the 16 California sawmills in 2016.

Fuel source	Average	Minimum	Maximum
Biomass and waste	1.3	0	4
Geothermal	4.8	0	7
Solar	10.5	0	19
Hydroelectric	32.5	6	100
Wind	4.5	0	10
Natural gas	14.5	0	22
Nuclear	7.5	0	24
Contract sources[a]	24.5	0	43
% Share of renewable and nonrenewable electricity			
Renewable	53.5	34	100
Nonrenewable	46.5	0	66

[a] Assuming all "contract" electricity was produced from nonrenewable fossil fuels.

Pacific Coast states reported 61 kg CO_2 eq/m^3 GW impact (Puettmann 2020a). The GW impacts of PG and PD lumber were 18 and 34 percent higher when compared with RG lumber, respectively. However, when comparing the informational modules, A1 and A3 showed higher and almost equal shares of total GW impact as compared with A2 (*Fig. 6a*). The contribution of each module to total GW impacts was influenced by mass allocation factors of three lumber types (*Table 4*). For example, the percent shares of A3 module GW impacts of RG and PG lumber were slightly less than PD lumber even though the PD lumber manufacturing had more energy-intensive operations. This was because sawmills producing RG and PG lumber had higher consumption of purchased electricity, which had higher GW impacts than on-site-generated electricity. The carbon intensity of on-site electricity was lower because of woody biomass used as a feedstock. As the source of biomass was harvested roundwood that would regrow in sustainably managed forest and is a part of carbon stock accounting in land use, land-use change and forestry, the CO_2 emissions from burning biomass were not considered when calculating GW impacts (IPCC 2022). Thus, the on-site-generated electricity had lower GW impacts than electricity purchased from a grid, which is considered to have the fuel mix of the California grid. Also, because mass loss occurred in planing of lumber and loss of volume due to shrinkage during drying, the allocation factor for PD lumber was smaller compared with RG and PG lumber (*Table 4*), which resulted in a relatively small difference in the share of A3 module GW impacts for RG, PG, and PD lumber.

Ozone depletion.—Ozone depletion refers to thinning of the stratospheric ozone layer that occurs when ozone-depleting substances containing gaseous chlorine or bromine are released (Bare 2014). These substances are often linked with use of refrigerants; solvents measured as mass of equivalent CFC-11 released per declared unit (kg CFC-11 eq/m^3). Of the three lumber types, PD lumber showed the highest ozone depletion impact (*Table 7*). Among the three modules, a major share of the impacts was coming from the A3 (lumber manufacturing, *Fig. 6b*) contributing 67 to 79 percent in total impacts. This high contribution of the A3 module was primarily due to the production and use of fossil fuels and auxiliary materials like antifreeze (ethylene glycol) and waxes for end-coating the logs and lumber. LCI data on these inputs were obtained from a LCA of redwood lumber manufacturing in California (Sahoo et al. 2021). These inputs show as a small quantity in absolute values, but they have high potential for ozone depletion and hence indicate need for future improvements.

Photochemical smog formation.—Photochemical smog is a secondary pollutant formed when nitrogen oxides (NO_x) and volatile organic compounds (VOCs) react to sunlight, which results in increased ground-level ozone concentration. It is commonly expressed in ozone equivalents (kg O_3 eq). Smog formation due to lumber manufacturing was associated with emissions of NO_x, VOCs, and hydrocarbons. Fuel uses and solvents, having potential to emit smog emissions, were noted to be main contributors. The cradle-to-gate smog formation potential impacts were 8.95, 14.6, and 17.5 kg O_3 eq/m^3 of RG, PG, and PD lumber, respectively (*Table 7*). The total impacts were 63 and 96 percent higher in PG and PD lumber manufacturing, respectively, when compared with those per cubic meter of RG lumber. Fuel-based emissions from A1 and A2 modules contributed 45 to 69 percent and 8 to 12 percent of the total impacts, respectively. The use of ancillary inputs like motor oil, hydraulic fluid, and solvents for cleaning equipment were identified as sources of smog emissions in PD and PG lumber manufacturing.

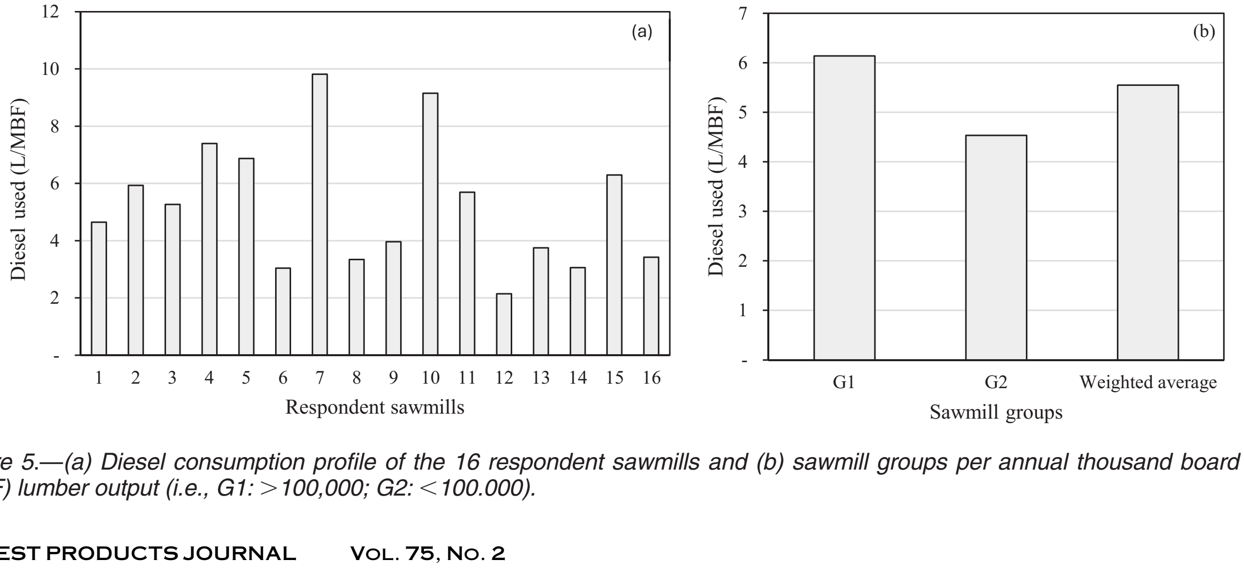

Figure 5.—(a) Diesel consumption profile of the 16 respondent sawmills and (b) sawmill groups per annual thousand board feet (MBF) lumber output (i.e., G1: >100,000; G2: <100.000).

Table 7.—Cradle-to-gate environmental impact assessment results per cubic meter for California softwood lumber.

Impact category	Unit	Rough-green lumber	Planed-green lumber	Planed-dry lumber
Global warming	kg CO_2 eq	3.60×10^1	4.23×10^1	4.84×10^1
Ozone depletion	kg CFC-11[a] eq	1.75×10^{-7}	3.02×10^{-7}	3.47×10^{-7}
Smog formation	kg O_3 eq	8.95	1.46×10^1	1.75×10^1
Acidification	kg SO_2 eq	3.41×10^{-1}	5.06×10^{-1}	6.13×10^{-1}
Eutrophication	kg N eq	1.95×10^{-2}	2.98×10^{-2}	3.53×10^{-2}
Fossil fuel depletion	MJ surplus	6.01×10^1	7.67×10^1	9.44×10^1

[a] CFC-11 = trichlorofluoromethane.

Acidification.—In LCAs, the acidification impact category describes the potential contribution of studied product systems to acid rain and is reported in sulfur dioxide equivalents (kg SO_2 eq). Acidification impacts can be attributed to SO_2 and NO_x emissions from burning fossil fuels, which would potentially deposit as acid rain. In this study, the cradle-to-gate acidification impacts of RG, PG, and PD lumber products were 0.34, 0.51, and 0.61 SO_2 eq/m^3, respectively (Table 7). Use of liquid fossil fuels in raw material extraction activities (A1) contributed to 41 to 56 percent of the total acidification impacts of each lumber type (Fig. 6d). During lumber manufacturing operations, most of the NO_x and SO_2 emissions came primarily from the combustion of fossil fuels on-site and from transportation fuels (e.g.,

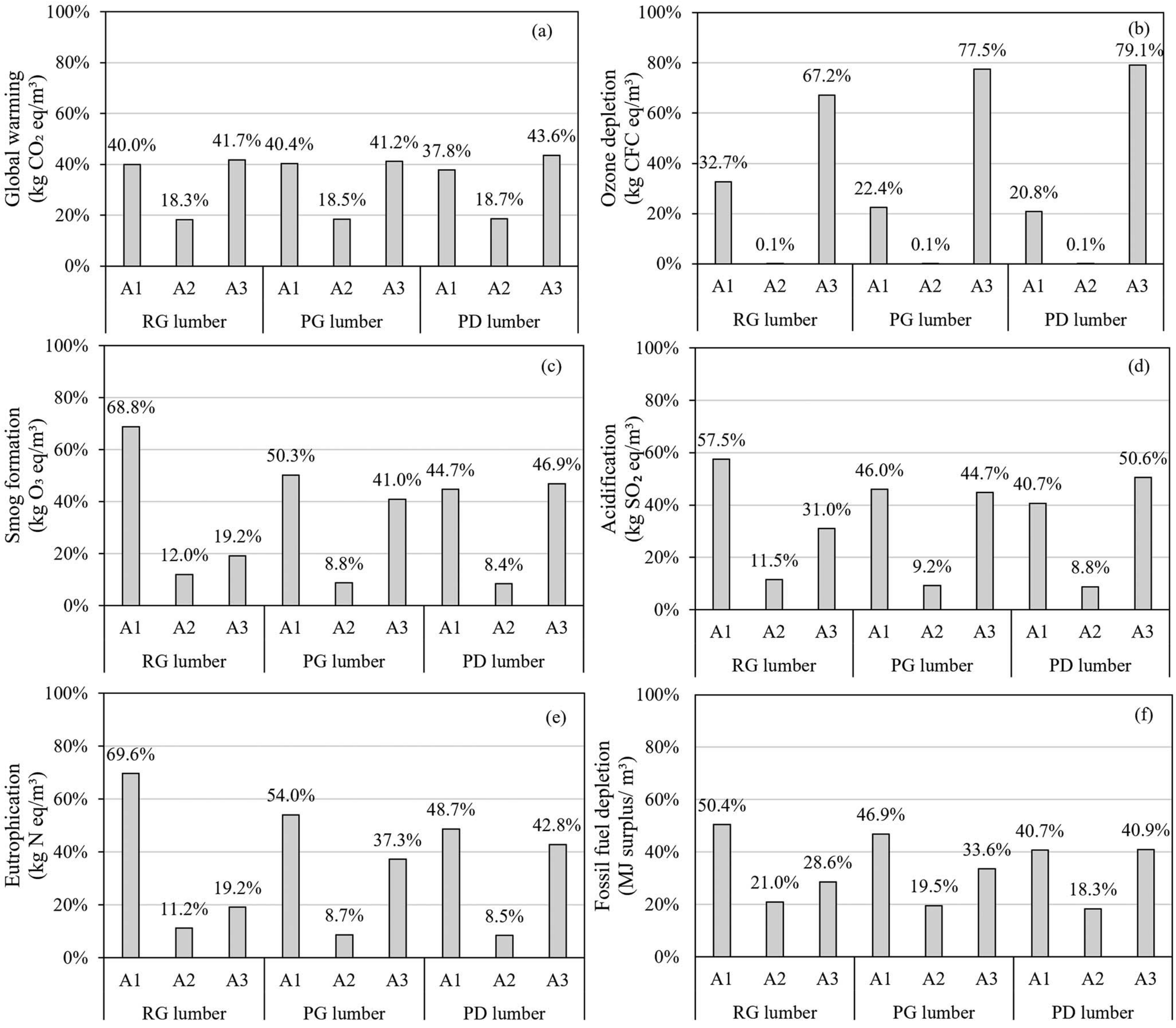

Figure 6.—Contribution analysis of individual life-cycle modules to total estimated cradle-to-gate environmental impacts per cubic meter of California softwood lumber manufacturing: forest management and harvesting operations (A1), raw material transportation (A2), and lumber manufacturing (A3). CFC = chlorofluorocarbon.

diesel). As we expected, both A1 and A3 modules together caused >85 percent of the acidification impacts.

Eutrophication.—Eutrophication is the buildup of excess nutrients (nitrogen and phosphorus) in water bodies, reducing the oxygen levels in water and accelerating the growth of weeds and algal biomass. Eutrophication is reported in nitrogen equivalents (kg N eq). The common cause of eutrophication is emissions such as NO$_x$, NH$_3$, different phosphates, and production of agrochemicals. Among the lumber types, PG and PD lumber manufacturing showed a higher impact share than RG lumber manufacturing. The cradle-to-gate eutrophication impacts were 0.019, 0.029, and 0.035 kg N eq./m^3 for RG, PG, and PD lumber, respectively (*Table 7*). In the total eutrophication impacts of each lumber type, *Figure 6e* shows the percent share of each life module. Among the three modules included in the analysis, the A1 module was the largest contributor, ranging from 49 to 68 percent (*Figure 6*). The emissions from lumber manufacturing in sawmills (A3) contributed 19 to 43 percent of the total eutrophication impacts.

Fossil fuel depletion.—As an indicator of energy use, fossil fuel depletion is measured in megajoule surplus. The surplus of megajoules indicates an additional amount of energy that would be required in the future for the extraction of a unit of fossil fuel that was used for the product system being studied, which for this analysis is lumber production (Bare 2014, Arvidsson et al. 2021). Thus, more fossil fuel consumption for a given system results in higher megajoule surplus values. Cradle-to-gate manufacturing of the three lumber products was reported as 60.1, 76.7, and 94.4 MJ surplus/m^3 of RG, PG, and PD lumber, respectively (*Table 7*). Across all three lumber types, A3 module had highest share of 41 percent in PD lumber manufacturing, followed by 34 and 28 percent in PG and RG lumber, respectively. The A1 module had the highest percent share in RG lumber (*Figure 6f*). A2 modules contributed 18 to 24 percent of the total impacts.

Sensitivity analysis

Figures 7a and 7b show the results of sensitivity analysis conducted for two key input parameters in lumber manufacturing:

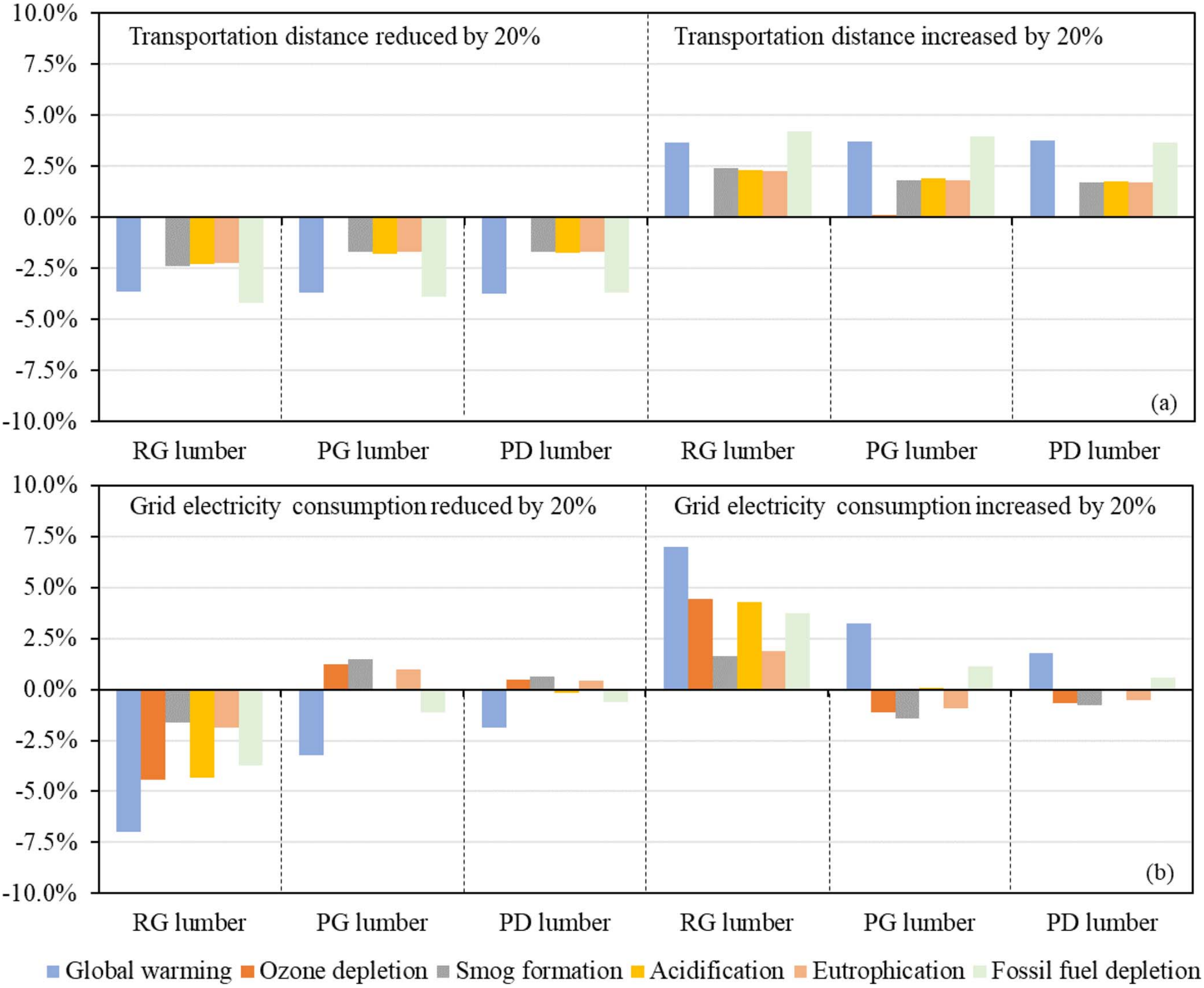

Figure 7.—Sensitivity results of change in two input parameters: (a) transportation distance increased and decreased by half and (b) grid electricity consumption in sawmills increased and decreased by 20 percent; the on-site-generated electricity was adjusted to match the total electricity consumption.

sawlog transportation distance and on-site electricity consumption. Among all impact categories, GW and fossil fuel depletion were affected by the change in transportation distance. Among the lumber types, results were relatively less sensitive for PD lumber. It can be interpreted that distance to lumber manufacturing sawmills could be increased further. There is less than 1 to 4 percent environmental impact if distance to lumber manufacturing sawmills is increased by 20 percent. Change in grid electricity consumption showed relatively high influence on life-cycle environmental impacts of RG, unlike PG and PD lumber, which use only grid electricity and do not produce on-site renewable energy. Sawmills having on-site energy generation showed less sensitivity to change in grid electricity consumption. Overall, the sawmills producing PD lumber as the main product were found relatively less sensitive to change in both inputs. This also indicates that PD lumber manufacturing sawmills with large production were more flexible to change in travel distance and electricity consumption.

Limitations

The energy analysis in this study was performed on the basis of the on-site fuel and energy use data collected from the 16 California sawmills for year 2016. Because the survey questions were designed and executed for an industry-level energy analysis, but not at the unit process level, it was difficult to differentiate the energy consumptions of different sawmill unit processes, as is typically done in other LCAs (Bergman and Bowe 2012, Puettmann 2020b, Sahoo et al. 2021, Heidari et al. 2023). However, we were able to expand that analysis to a cradle-to-gate LCA by using LCI data from other similar efforts as outlined in the goal and scope definition. The primary data collected in the survey proved useful for this overall effort to include a LCA in tandem with our analysis of sawmills' on-site energy consumption. Although the primary survey data collected on fuel and energy usage of 16 sawmills supported high data quality for LCI preparation, we had to rely on secondary or published information concerning auxiliary materials utilized by the sawmills, which presented limitations to complete the LCI. Additionally, more detailed information about on-site energy consumption as well as auxiliary materials could assist sawmills in improving their efficiency.

Conclusions

In this study we conducted an analysis of energy consumption by California sawmills in 2016 and assessed the life-cycle environmental impacts of three categories of softwood lumber products—RG, PG, and PD. The energy analysis was based on a survey designed to characterize types and quantities of all energy sources consumed by sawmills on-site. The surveyed sawmills represented 88 percent of the total lumber production in California in 2016. The energy profile of sawmills showed that electricity and heat were the most common energy sources, followed by diesel fuel. Around 85 percent of the average annual electricity consumption of sawmills was generated on-site by renewable coproducts (mill residues), a substantial carbon benefit, and the remaining 15 percent was met from electricity providers, which was generated with just over 50 percent from renewable sources, another carbon benefit. The energy analysis concluded that on-site energy generation had a significant effect on the sawmills' performance, which is consistent with prior studies (Puettmann et al. 2010, Oneil and Puettmann 2017). Although future energy analysis efforts could benefit from separating information on sawmill operations, the collected data provided sufficient representation of LCI data on lumber manufacturing for a cradle-to-gate LCA.

Sawmills were grouped by the three main lumber types, and mass allocation was applied to distribute the LCI and environmental impacts between lumber and coproducts such as sawdust, shavings, and bark. Secondary data from published LCA studies in California were used to develop a cradle-to-gate LCI per cubic meter of RG, PG, and PD lumber. The LCIA results showed that lumber production (A3) followed by resource extraction (A1) were major contributors in most of the impact categories. Sources of the environmental impacts were energy-related activities such as cogeneration to produce on-site heat and electricity, burning fossil fuels in equipment, and transportation. Overall, this study helped in generating a state-level assessment of energy and environmental impacts of sawmills. Both energy analysis and LCA results showed that the sawmills could be encouraged further on having combined heat and power generation on-site. Logging residues can supply additional feedstock. More such studies at individual sawmills would be needed to make necessary improvements in energy and resource efficiency of the forest products industry for future sustainable development of the California timber industry.

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