Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Forest Products Laboratory | Research Paper FPL–RP–716 | May 2023

Life-Cycle Assessment of Hardwood Lumber Production in the Southeastern United States

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Abstract

Because of environmental awareness and regulations and the advent of environmental preferential purchasing, documenting the environmental profiles of building products using life-cycle assessment (LCA) has become a widespread emergent global trend. This study conducted a cradle-to-gate LCA of hardwood lumber production in the southeastern United States. System boundaries in this study included the following production stage information modules: raw material extraction (A1), resource and material transportation (A2), and hardwood lumber manufacturing (A3). Module A1 included forest management activities. The declared unit was 1 m^3 of hardwood lumber packaged and ready for shipment. Surveys were used to collect primary hardwood lumber production data. This LCA study followed the standards of the International Organization for Standardization and the wood products product category rules. The tool for the reduction and assessment of chemical and other environmental impacts (TRACI), CML baseline, and cumulative energy demand were used to conduct a life-cycle impact assessment. The weighted average oven-dried density of southeastern hardwood lumber was 576 kg/m^3. Results showed that about 209 kg CO_2eq were released in the production of 1 m^3 of hardwood lumber (all information modules combined), with the A3 module accounting for 71%, followed by A1 (15%) and then A2 (14%). Raw material extraction (A1), resource and material transportation (A2), and hardwood lumber manufacturing (A3) consumed about 9%, 7%, and 84%, respectively, of total cradle-to-gate primary energy. About 59% of the total primary energy used in the production of hardwood lumber (A1–A3) came from nonrenewable, mostly fossil, resources. One cubic meter of southeastern hardwood lumber stores 1,055 kg CO_2eq, which is about four times more than the embodied carbon released from all three modules of the production of this lumber (209 kg CO_2eq).

Keywords: LCA; life-cycle assessment; life-cycle inventory; wood; biogenic carbon; environmental impacts; ISO; PCR; product category rules

May 2023

Heidari, M. David; Salazar, James; Bergman, Richard D.; Hubbard, Steven S.; Bowe, Scott A. 2023. Life-Cycle Assessment of Hardwood Lumber Production in the Southeastern United States. Research Paper FPL-RP-716. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 35 p. https://doi.org/10.2737/FPL-RP-716.

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Executive Summary

Introduction

Hardwood lumber from wood species in the southeastern (SE) United States is used primarily for pallets, crossties, flooring, millwork, cabinets, and furniture. Total annual U.S. hardwood lumber production in 2005 and 2006 was 26.4 and 26.0 million m^3 (11.2 and 11.0 billion board feet (BF)), respectively (billion = 10^9).

Most hardwood lumber is consumed domestically. Domestic hardwood lumber production occurs mostly in the eastern United States and is split roughly in half between the SE and the northeastern and north central (NE/NC) United States. Rough green hardwood lumber is used in pallets and crossties whereas most of the hardwood planed dried lumber (PDL) is converted into building products for new construction and repair and remodeling of existing buildings. There are nearly 800 hardwood lumber producers in the United States with most producing less than 1 million BF. Similar to the NE/NC region, the SE region has about 90 large-size facilities that can or do produce about 60% percent of the regions annual production (estimated). About 30% of these facilities each produce or are capable of producing between 60 and 120 thousand m^3 (25 and 50 million BF) annually. Sawmills report their production based on rough green lumber. In 2019, the total annual production of sawn hardwood lumber in the United States was roughly 18 million m^3 (7.6 billion BF), which was a decrease from the 19.6 million m^3 (8.3 billion BF) produced in 2017.

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 hardwood lumber production in the SE United States. To develop a life-cycle inventory (LCI) and perform an LCA study, the authors collected primary data from hardwood lumber production facilities in the SE region of the United States. Using those inventory data, the LCA was conducted for hardwood lumber for SE United States according to the product category rules (PCR) for North American structural and architectural wood products. Comparative assertions were not the intended goal of this study.

Methodology

To conduct the LCA, this study followed the International Organization for Standardization (ISO) 14040 and 14044 standards. System boundaries delineated stages of the life cycle from the extraction of raw materials through product manufacturing. In this study, the declared unit was 1 m^3 of planed kiln-dry hardwood lumber. An industry standard production unit (such as thousand board feet (MBF)) was converted to a metric production unit (1 m^3) of lumber. The authors collected primary mill data through a survey questionnaire emailed to hardwood lumber manufacturing facilities in the SE region of the United States. This survey collected all raw material and energy 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, 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 (from Long Trail Sustainability, Huntington, Vermont, USA), which conforms with internationally accepted standards. The study used a mass allocation approach to assign the environmental impacts to 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.

Life-Cycle Inventory

Cradle-to-gate LCI flows for manufacturing hardwood lumber were presented by three information modules: raw material extraction (A1), resource and material transportation (A2), and hardwood lumber manufacturing (A3), which included the unit processes of log yard, sawing, drying, planing, and energy generation (i.e., boiler). The unit process modeling approach was followed for conducting the LCA. Of all the modules, lumber manufacturing was the most energy-intensive process, followed by raw material extraction and then transportation.

Life-Cycle Impact Assessment

Several impact categories were examined as recommended by Underwriters Laboratories Environment (ULE) PCR for North American structural and architectural wood products. The following seven impacts were assessed: global warming (GW (kg CO_2eq)), acidification (kg SO_2eq), eutrophication (kg Neq), ozone depletion (kg chlorofluorocarbons-11-eq), photochemical smog (kg NO_xeq), abiotic depletion potential for fossil resources (ADP fossil (MJ)), and fossil fuel depletion (MJ surplus). The LCIA also provided additional information such as the use of primary energy resources; energy consumption from nonrenewable, renewable (wind, hydro, solar, and geothermal), and nuclear fuels; renewable and nonrenewable resource consumption; water use; and indicators describing waste.

Key Findings

Among all modules assessed in this cradle-to-gate LCA, the hardwood lumber manufacturing module (A3) contributed the most to the total environmental impacts of hardwood lumber produced in the SE United States. The cradle-to-gate LCIA results (Table 1) showed that 209 kgCO_2eq were released per 1 m^3 PDL. From cradle to gate, total energy use was 5,575 MJ/m^3 PDL. Of this, 2,263 MJ/m^3 PDL was renewable and 3,312 MJ/m^3 PDL was nonrenewable. The nonrenewable energy was derived from fossil fuels and used to operate sawmill machinery, operate transportation machinery, generate electricity, and fuel a portion of the kiln-drying. Nonrenewable fuels represented 59% of the total energy use. Energy from biomass went exclusively to kiln-drying. The bulk of fresh-water use took place in the manufacturing module. Mills reported the use of sprinkler systems in the log yard but only reported water usage for the whole facility (41.8 L/m^3 hardwood PDL).

Sensitivity Analysis

A sensitivity analysis was completed per ISO 14040 to model the effects of changing the raw material transport distance and consumption of energy including electricity, natural gas, diesel, and biomass for hardwood lumber production. Overall, the variations in the environmental impacts from a 20% increase or decrease in electricity, heat, or fuel used to produce hardwood lumber were small (0% to 19%).

Conclusions

This study conducted a rigorous cradle-to-gate LCA for planed kiln-dry hardwood lumber production in the SE United States. The primary objective was to create LCI data and impact assessment results for planed kiln-dry hardwood lumber that could be used to develop an environmental product declaration (EPD) in accordance with ULE PCR. In addition to the impact assessment results, the LCI flows were also provided. The LCI flows provide the resource use inventory elements and waste flows as required by the PCR to be included in the EPD. This cradle-to-gate LCA included the necessary scope to develop a "business-to-business" EPD in accordance with ULE PCR.

Acknowledgments

We gratefully acknowledge those companies and their employees that participated in the surveys to obtain production data. Special appreciation is given to Linda Jovanovich, Executive Vice President of the Hardwood Manufacturers Association, for her assistance with promoting the study and solicitation of mill participation. The authors also thank Hongmei Gu and Poonam Khatri, USDA Forest Service, Forest Products Laboratory, and David Nicholls, USDA Forest Service, Pacific Northwest Research Station, for their thoughtful reviews of this report. This project was financially supported by a joint venture agreement between the USDA Forest Service, Forest Products Laboratory, and the U.S. Endowment for Forestry & Communities, Inc., Endowment Green Building Partnership—Phase 1, no. 18-JV-11111137-021. Any opinions, findings, conclusions, or recommendations expressed in this article do not necessarily reflect the views of the contributing entities.

Introduction

Because of environmental awareness and regulations and the advent of environmental preferential purchasing (EPP), documenting the environmental profiles of building products using life-cycle assessment (LCA) has become a widespread emergent global trend. Moreover, LCA studies are inevitable for various product certifications including green building certifications (Bergman and Taylor 2011, Ibáñez-Forés and others 2016). Scientific documentation such as environmental product declarations (EPDs) shows verified data on the environmental performance of products and services to stakeholders including builders and architects, consumers, regulating agencies, and policymakers (International Organization for Standardization (ISO) 14025 (ISO 2006a)). LCA study not only provides the necessary environmental performance of

Table 1—Life-cycle impact assessment for 1 m³ of hardwood lumber, cradle-to-gate, mass allocation

	Units	Total
Impact category		
Global warming potential – TRACI 2.1	kg CO_2eq	209
Global warming potential – w/ biogenic CO_2	kg CO_2eq	209
Depletion potential of the stratospheric ozone layer	kg CFC-11eq	9.12E–06
Acidification potential of soil and water sources	kg SO_2eq	1.26
Eutrophication potential	kg Neq	0.72
Formation potential of tropospheric ozone	kg O_3eq	28.36
Abiotic depletion potential for fossil resources	MJ, NCV[a]	2,646
Fossil fuel depletion	MJ surplus	311
Primary energy consumption[b]		
Nonrenewable, fossil	MJ	2,831
Nonrenewable, nuclear	MJ	481
Renewable, biomass	MJ	2,166
Renewable, wind, solar, geothermal	MJ	5.11
Renewable, hydro	MJ	92
Total	MJ	5,575

[a]NCV, net calorific value.
[b]Values based on lower heating values.

the product but also identifies the environmental hot spots for continuous improvements in the manufacturing of products and services provided (ISO 14040 (ISO 2006b) and ISO 21930 (ISO 2017)). Periodic update of EPDs (every five years) is mandatory for products that fall under the scope of the various certifications and thus require new or updated LCA data (ISO 2017, ULE 2019). This LCA is part of a larger project to update the life-cycle inventories for major wood products produced in the United States on a five-year cycle. For this LCA, hardwood lumber manufacturing data were collected for the 2018 production year from sawmills operating in the southeastern (SE) region of the United States.

A gate-to-gate life-cycle inventory (LCI) of hardwood lumber production in the SE region had previously been conducted for the production year of 2010 by Bergman and Bowe (2008a, 2010, 2012). Details on survey mechanisms and the LCI were given in Bergman and Bowe (2008a, 2010). In the current study, updated manufacturing inventory data were collected to conduct a life-cycle impact assessment (LCIA) using the North American impact method (the tool for the reduction and assessment of chemical and other environmental impacts (TRACI 2.1)) (Bare 2011). This work provides information necessary for subsequent EPDs. As such, this report follows the requirements outlined in the product category rules (PCR) for North American structural and architectural wood products (ULE 2019) and the American Center for Life Cycle Assessment (ACLCA 2019). This report builds on previous studies (Bergman and Bowe 2010, 2012; Puettmann and others 2010) and reports LCIA results for mass allocation to produce 1.0 m³ of planed kiln-dry hardwood lumber.

Abbreviations

BF	board feet
BOD	biological oxygen demand
CED	cumulative energy demand
CFC	chlorofluorocarbon
CH	Switzerland
CLR	cubic lumber recovery
CML	Centrum voor Millikunde Leiden
CORRIM	Consortium for Research on Renewable Industrial Materials
EPD	environmental product declaration
EPP	environmental preferential purchasing
GLO	global
GWP	global warming potential
HAP	hazardous air pollutant
HDPE	high-density polyethylene
IA	impact assessment
ISO	International Organization for Standardization
LCA	life-cycle assessment
LCI	life-cycle inventory

LCIA	life-cycle impact assessment
LRF	lumber recovery factor
MBF	thousand board feet
MC	moisture content
MMBF	million board feet
NCV	net calorific value
NE-NC	northeastern–north central
NREL	National Renewable Energy Laboratory
OD	oven-dry
PCR	product category rules
PDL	planed dried lumber
RNA	region North America
SE	southeastern
SERC	SERC Reliability Corporation
tkm	metric tonnes in kilometers
TRACI	tool for the reduction and assessment of chemical and other environmental impacts
U	unit process
ULE	Underwriters Laboratories Environment
US-EI	United States Ecoinvent
VOC	volatile organic compound

Glossary of Terms

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

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

Declared unit: Quantity of a wood building product for use as a reference unit (can be mass or volume) in reporting aspects of environmental information needed in information modules.

Dry kiln schedule: A set of parameters including temperature, humidity, and total drying time that have been developed for commercial lumber products and that kiln operators use to determine how a charge of wood will be dried.

Edging: Making a cut along the sides of boards using a saw to straighten and smooth rough green lumber or bowed boards.

Functional unit: Expresses the function of the studied product in quantitative terms and serves as the 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.

Hog fuel: A combination of wood residues, including bark.

Kiln-drying: Drying wood in a heated chamber where air circulation, relative humidity, and temperature are controlled so that the moisture content of wood can be decreased to a target value without causing any drying defects.

Life-cycle assessment (LCA): Method for the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle (ISO 14040).

Life-cycle impact assessment (LCIA): The phase of an LCA study during which the significance of potential environmental impacts of a product system based on the life-cycle inventory results are evaluated (ISO 14040).

Life-cycle inventory (LCI): The phase of data collection and calculation to quantify inputs and outputs (i.e., materials and energy) associated with a studied product system (ISO 14040).

Lumber recovery factor: The nominal board feet of lumber recovered per cubic foot of log input to a sawmill.

Overrun: The amount by which actual lumber recovery exceeds a log scale estimate.

Product category rules (PCR): Set of specific rules, requirements, and guidelines for the development of type III environmental product 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).

Trimming: Making cuts on the end of boards using a drop-down saw to finish the lumber.

Units

Conversion table

English unit	Conversion factor	SI unit
board foot (rough green lumber)	2.359737×10^{-3}	cubic meter (m^3) (nominal)
board foot (planed dried lumber)[a]	1.62×10^{-3}	cubic meter (m^3) (nominal)
British thermal unit (Btu)	1.055056×10^{-3}	megajoule (MJ)
cubic foot (ft^3)	2.831685×10^{-2}	cubic meter (m^3)
foot (ft)	3.048×10^{-1}	meter (m)
gallon (gal)	3.785412	liter (L)
inch (in.)	2.54×10^{1}	millimeter (mm)
mile (mi)	1.609347	kilometer (km)
pound, mass (lb)	4.535924×10^{-1}	kilogram (kg)
ton (2,000 lb)	9.071847×10^{-1}	metric ton (t)
$T_{°F}$	$T_{°C} = (T_{°F} - 32)/1.8$	$T_{°C}$

[a]For 2 by 6, conversion factor varies by lumber size.

Methods

Goal

The goals of this study were twofold: (1) calculate the cradle-to-gate life-cycle impacts associated with the manufacturing of hardwood lumber in the SE United States, and (2) provide a platform for EPDs by collecting data consistent with the methodology and guidelines of the Consortium for Research on Renewable Industrial Materials (CORRIM), ISO protocols (ISO 2006b,c), and PCR for North American structural and architectural wood products (ULE 2019).

Scope

The scope of this study was cradle to gate. Impacts of input materials, fuels, and electricity, as well as associated emissions and waste, from forest establishment, management, and harvesting through hardwood lumber produced and packaged at the sawmill gate were considered. Hardwood forest resource data for this system boundary was obtained from the US LCI database (DATASMART 2018). This report did not make substitute product comparisons, consider use by consumers, or examine end-of-life scenarios.

Intended Audience

The intended audience for this report includes hardwood consumers, hardwood lumber manufacturers, LCA practitioners, Hardwood Manufacturers Association, and American Hardwood Export Council. The data from this report were used to develop upstream wood LCAs such as those for wood pallets (Alanya-Rosenbaum and Bergman 2020; Alanya-Rosenbaum and others 2021, 2022a), wood flooring (Heidari and others 2023a, 2023b), and urban hardwood lumber (Alanya-Rosenbaum and others 2022b).

Comparative Assertions

This report excludes product use and end-of-life stages necessary for claims or assertions comparing substitute products. Future studies with a goal of product alternative comparisons can address this issue by expanding the LCA boundary to include use and end-of-life phases consistent with ISO 14040 and 14044 (ISO 2006b, 2006c) guidelines and principles and compliant with the PCR.

Scope of Considered System

Functional and Declared Units

In accordance with the Underwriters Laboratories Environment (ULE) PCR, the declared unit of this study was one cubic meter (1.0 m^3) of packaged planed kiln-dry hardwood lumber produced in the SE United States. If the function and reference scenario for the whole life cycle of a wood building product is not stated, the declared unit is used (ULE 2019). Collected data were entered into a commercial spreadsheet, and weight averages were calculated based on the contribution of individual sawmills to total production for a given criterion. All inputs and emissions data were then harmonized relative to 1.0 m^3 (the declared unit) of packaged planed kiln-dry hardwood lumber.

System Boundary

The system boundary for the declared unit is shown in Figure 1. The system boundary began with the planting, growth, and harvest of trees in the SE United States, as well as purchased rough green hardwood lumber from outside suppliers, and ended with planed kiln-dry hardwood lumber packaged to leave the sawmill gate. The production stage of hardwood lumber included three information modules. These were (A1) raw material extraction (including forest management and resource harvesting), (A2) resource and material transportation (to the mill), and (A3) hardwood lumber manufacturing (ISO 2017).

Raw material extraction (A1) included forest initiation (site preparation for planting), forest management (periodic thinnings), and the harvesting of timber (tree felling, log bucking, and transportation of logs to decks). U.S. hardwood forests tend to be mostly natural-grown and thus have minimal inputs compared with plantation-grown softwood forests (Oneil and others 2010). Equipment used in the resource extraction module included chain saws, mechanized harvesters, and skidders. These machines rely primarily on diesel fuel and lesser amounts of gasoline. Manufacturing, maintenance, and repair of equipment and infrastructure were excluded from the system. The system included the impacts associated with the manufacture of rough green lumber produced by outside firms and purchased by the sawmills in this study.

Transportation of logs from the forest and transportation of purchased rough green lumber from outside suppliers to the mill (A2) was captured. Purchased rough green lumber was included to maintain the integrity of mass and energy balances for both the individual sawmills and the overall system. Diesel tractor-trailers including logging trucks were used for the transportation.

Hardwood lumber manufacturing (A3) was modeled as a series of unit processes, including log yard, sawing, kiln-drying, planing (including packaging the final product for distribution), and energy use and generation with an industrial boiler. Outputs from the system included 1.0 m^3 of kiln-dry planed hardwood lumber packaged ready for shipping and emissions to air, land, and water. Coproducts produced in the unit processes were not tracked beyond the system boundary. This consideration ensured that coproducts such as green bark and green chips, which exit the system boundary prior to kiln-drying, do not carry the burdens associated with that drying.

Parameters considered for the system boundary in this study are summarized in Table 2.

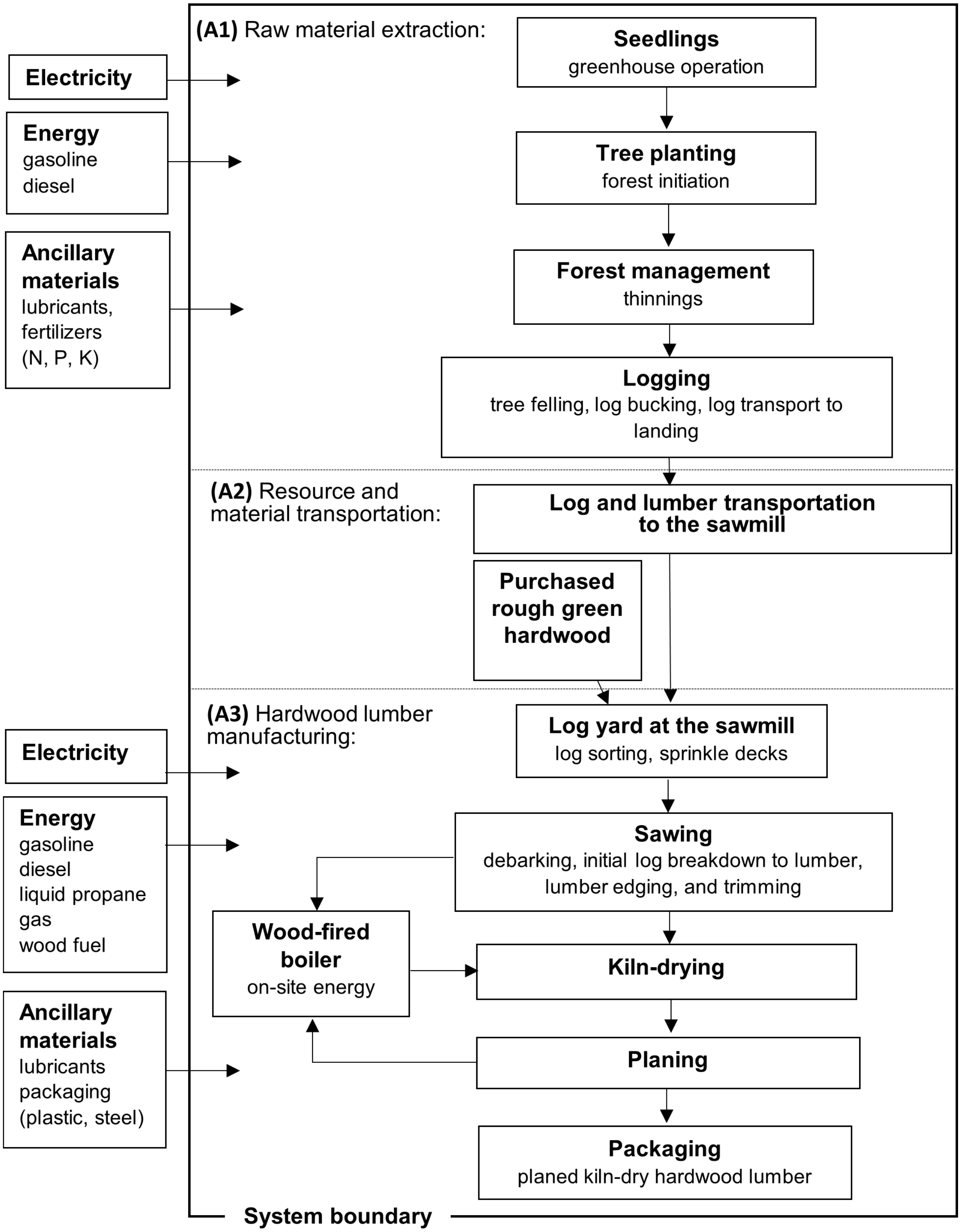

Figure 1—System boundary for the cradle-to-gate production of planed kiln-dry hardwood lumber in the southeastern region of the United States.

Table 2—System boundary inclusions and exclusions for the cradle-to-gate life-cycle analysis of southeastern U.S. hardwood lumber production

Included	Excluded
• All resources, raw materials, fuels, and energy for hardwood lumber production used in forestry operations, harvesting, and hardwood lumber manufacturing • Transportation of materials throughout the three information modules (cradle-to-gate) • Packaging	• Fixed capital equipment and facilities (infrastructure) • Transportation of employees • Construction, maintenance, use, and end-of-life treatment

Allocation Rules

Because coproducts are generated during the production process, it was necessary to allocate the inputs and outputs using a standardized approach. In compliance with allocation rules in the PCR, this report presents results based on mass allocations (ULE 2019).

Cut-Off Rules

According to the ULE PCR, if the mass–energy of a flow was less than 1% of the cumulative mass–energy of the model flow, it may be excluded. This assumes the environmental impacts of the flow were not significant. The analysis for planed kiln-dry hardwood lumber in this study included all energy and mass flows in the primary data collected. No cut-offs were used in the impact assessment.

Data Collection

In 2018, a survey questionnaire was mailed to sawmills in the SE region to collect data consistent with the methodology and guidelines of ISO protocols (ISO 2006b,c) and PCR for North American structural and architectural wood products (ULE 2019). A survey was constructed by updating the previous version used by Bergman and Bowe (2010). Appendix 1 shows the survey that was used. Sawmills located in the SE United States (Fig. 2) were identified by the Hardwood Manufacturers Association. Copies of the survey were emailed, and the sawmills were invited to participate in the study.

Figure 2—Shaded area shows the southeastern region for hardwood lumber production in the United States.

Survey questions were designed for the collection of detailed production data from each mill. The authors did not know who received the survey. Four mills responded, providing input and output data for the assessment. Although the number of mills surveys received may have been small ($n = 4$) compared with a typical survey, the level of detail and amount of primary mill data for an LCA study were very high (Appendix 1). Each mill contributed a substantial amount of time completing the questionnaire and follow-up questions (Appendix 2), ranging from 6 to 24 hours with an average of 15 hours. Obviously, greater response rate would have probably provided a more accurate assessment of the industry. However, the number of production facilities does meet the minimum requirements of three for developing an EPD per ULE PCR. For quality control, the authors also compared the results to the previous hardwood lumber studies. This resulted in secondary data that was used to supplement the primary data collected in the survey of the lumber manufacturing mills. Also, the hardwood resource model and other secondary process data were taken from DATASMART (2018) and are described in the section “A1—Raw Material Extraction” under the main heading “Life-Cycle Inventory Analysis”, and a wood-fired boiler LCI was provided by Puettmann and Milota (2017).

Calculation Rules

Mills reported the volume of incoming logs in thousands of board feet (MBF), which was then converted to cubic meters. Also, the moisture content (MC) of each log was recorded and the wood species mix used at each mill was obtained. Densities for each species were calculated by averaging specific gravities for the reported MC as found in Alden (1995) and Glass and Zelinka (2021).

If mills did not report a given value in the survey, follow-up checks were made with the mill respondent to clarify whether the value was zero or not known. Survey results for each unit process were further converted to a production basis using the base unit of 1.0 m^3 of planed dried lumber (PDL).

The material flow was given in oven-dried weight per 1.0 m^3 of PDL. Data from the mill questionnaires were weight-averaged through the following equation, as has been done in previous CORRIM reports (e.g., Milota 2015). Missing data were not averaged as zeros.

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\overline{P}_{\text{weighted}}$ is the weighted average of the values reported by the mills, P_i is the reported mill value, and x_i is the fraction of the mill’s value to total production for that specific value. In this way, values from larger mills had more weight than their smaller counterparts. The overall result is an industry average that maintains individual mill confidentiality. SimaPro, version 9.1.0.8 (PRé Consultants 2021) was used as the LCA modeling tool to track all materials and report the LCIA results.

Description of Industry

Categories of Products and Coproducts

The primary product from SE sawmills is hardwood lumber. For this analysis, we considered sawn hardwood the same as hardwood lumber. Additional coproducts are made in the breakdown of logs into lumber and in the lumber planing process. Coproducts could be used internally to the mill or sold externally and include green bark (for boiler fuel and landscaping mulch), green chips and sawdust (for boiler fuel and sold), dry sawdust (for boiler fuel, animal bedding, and value added furnish for composite products), and dry shavings (for boiler fuel and sold). Hog fuel for boilers is also produced. Hog fuel in this study included bark and was defined as a combination of wood residues from multiple processing centers.

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

There are nearly 800 hardwood lumber producers in the United States with most producing less than 2,360 m^3 (1 million BF) annually. Producers in the western and northeast/northcentral (NE/NC) United States were not considered in this study. Most U.S. hardwood lumber production is split between the NE/NC and the SE regions because of the physical location of the hardwood resources found there. Similar to the NE/NC region, the SE region has about 90 large facilities that do or can produce about 60% of the region's annual production (estimated). About 30% of these facilities each produce or are capable of producing between 60 and 120 thousand m^3 (25 and 50 million BF) annually (Luppold 2017, Hubbard and others 2020). Sawmills report their production based on rough green lumber. In 2019, the total annual production of sawn hardwood lumber in the United States was roughly 18 million m^3 (7.6 billion BF) (billion = 10^9), which was a decrease from 19.6 million m^3 (8.3 billion BF) produced in 2017 (HMR 2020, Howard and Liang 2019). The four sawmills surveyed produced 152 thousand m^3 (64.3 million BF) rough green lumber in 2017. The data collected in this study represented roughly 2% of the total regional production for the SE region in 2017.

Location of Markets and Typical Transportation Methods

Hardwood lumber produced in the SE region of the United States is sold both domestically and in global markets for use in value-added products including hardwood flooring, wooden pallets, furniture, railroad ties, molding, and millwork. Grading rules for hardwood lumber are governed by the National Hardwood Lumber Grading Association (NHLA) to ensure consistency and help establish pricing metrics.

Transportation of hardwood lumber in the United States is primarily conducted by over-the-road trucking and is supplemented by rail. To reach global markets, lumber is typically sent bi-modally (combination of truck and rail) to domestic shipping ports where it is then loaded onto ships for transoceanic transport to foreign seaports.

Mill Types, Age, Efficiencies, and Geographical Distribution

Most sawmills in the SE region (Fig. 2) have been in operation for many years. The sawmills in this study were located in North Carolina (1 mill), Georgia (1 mill), Tennessee (1 mill), and Alabama (1 mill), which represents the studied geographic area well. As a result of the 2007 economic downturn in the U.S. economy, many mills were unable to remain viable and were either closed or consolidated. Some sawmills have turned to process improvement methodologies or additional investments in technology to remain competitive. Most of this new technology has occurred in the sawing process with optimization systems. In addition, upgrades to dry kilns have increased during the past decade (Bergman 2021). However, the majority of sawmills have remained relatively unchanged since 2007 in terms of their processes and equipment used in production. The findings in this study for sawmill infrastructure were consistent with those of Milota (2015) and Bergman and Bowe (2010).

Conversion Efficiencies

A lumber recovery factor (LRF) is obtained by determining the volume of lumber produced per volume of log inputs. The breakdown of logs into rough green lumber during sawing in this study had a weighted average LRF of 7.56 BF of rough green lumber per cubic foot of logs (0.630 m^3/m^3). In the SE region of the United States, 2.60 m^3 of logs are sawn, dried, and planed to a final product of 1.0 m^3 of PDL. The resulting total volume conversion for incoming logs to final lumber product is therefore 38.4%. This is consistent with a previous LCI study for this region by Bergman and Bowe (2010). Shrinkage of approximately 14% during the drying process accounts for the difference between total volume and total mass conversion (Bergman and Bowe 2010, Bergman 2021).

A mass balance for this study is shown in Table 3 for the tracking of materials flow through the unit processes identified. The mass balance revealed that 1,353 kg oven-dry (OD) basis of incoming logs produced 1.0 m^3 of hardwood PDL. The sawing unit process produced 676.91 OD kg of rough green lumber destined to the drying process. There was no change in mass after kiln-drying (because all the mass value reported here has been converted to OD mass), but planing decreased the final product mass to 576 OD kg per 1.0 m^3 PDL and generated

Table 3—Mass balance for material flows across the five unit processes

	Mass (OD kg/m^3 planed dried lumber)								
	Log yard		Sawing		Boiler	Drying		Planing	
Material (OD)	In	Out	In	Out	In	In	Out	In	Out
Logs (wood and bark)	1,353	1,353	1,353						
Rough green lumber, manufactured				677		677			
Green coproducts, sold				547					
Green coproducts, fuel				129	129				
Rough oven-dry lumber, produced							677	677	
Planed dried lumber, produced									576
Dry coproducts, sold									101
Dry coproducts, fuel									0.00
Total	1,353	1,353	1,353	1,353	129	677	677	677	677

101 OD kg of shavings as coproduct. The conversion of incoming logs to 1.0 m^3 of PDL is shown in Table 4.

Typical Emission Control Measures by Mill Process

Control of emissions (or pollutants) in the log yard was limited to sprinkler and misting systems, which were also used for dust (particulate matter) control of vehicles used on dirt roads. Water use was mainly for sprinkling logs, boiler make-up water, and dust control of the mill yards during the dry season. Bag houses, cyclones, or both were used to control emissions in the sawing process, particularly at the chop saw and edging operations. No emission control devices were used at the kilns. The planar process used cyclones or bag houses. Control of emissions from the boiler was achieved with electrostatic precipitators.

General Types of Wastes and Emissions

The three types of on-site emissions considered in this study were to air, water, and land. The most commonly reported air emissions included hazardous air pollutants (HAPs), dust, volatile organic compounds (VOCs), and dry particulate matter. Kilns and boilers contributed most of the nitrogen oxides and sulfur dioxide emissions. Mills did not report emissions to water in this study.

Table 4—Conversion of incoming logs to 1.0 m^3 of planed dried lumber

	Wood volume[a]	
	(m^3 per 1.0 m^3)	Conversion (actual m^3/nominal) (MBF)
Raw wood material		
Incoming green log	2.60	—
Rough green lumber	1.30	2.44
Rough dried lumber	1.16	2.13
Final product		
Planed dried lumber	1.00	1.68

[a]All values provided in actual dimensions.

Sawmills reported some refuse going to landfills, such as ash from the wood boilers, general refuse, and small amounts of plastic and steel strapping and plastic wrapping along with stickers. In many instances, boiler ash gets re-used when it is applied to fields in agricultural applications. Other metals, oils, and plastics are sent to recycling streams.

Description of Product

Dimensions

Unlike structural lumber, hardwood lumber outside of wood pallets and railroad ties is valued largely for its aesthetic characteristics in finished products such as furniture and flooring. As such, hardwood lumber is usually manufactured, bought, and sold in random lengths and widths. In the United States, hardwood lumber is referred to by its thickness in graduations of inches. Common lumber reporting is 4/4 (1 in. thick), 6/4 (1.5 in. thick), 8/4 (2.0 in. thick), and so on with large variation around the inch values depending on roughness and MC of the board. Because hardwood lumber is manufactured for its highest possible grade, widths and lengths are variable. A representative length of 8 ft is a fair assumption. Packages for distribution are bundled in units of board feet, the unit of commerce for lumber. One board foot of lumber is a piece of wood that is 1 in. by 12 in. by 12 in. (nominal).

The standard for planing 4/4 (1 in. thick) dry lumber is 0.8125 in. A portion of some lumber is skip-planed from 1 in. to 0.9375 in. To maximize the grade (and therefore value) of rough dry lumber, precision end-trimming is not performed at the sawmill. In the United States, as with softwood lumber, hardwood lumber volumes are reported in units of board foot (BF). In this study, the conversions of 2.44, 2.13, and 1.68 MBF/m^3 for rough green, rough dry, and PDL, respectively, were used (Bergman and Bowe 2008b, 2010).

Wood Species

Many wood species are used for hardwood lumber production in the SE United States. For this study, close to

90% were oaks and poplar. Table 5 shows the percentage contribution of each species to the total of all species used. Wood densities and specific gravities were calculated for the incoming hardwood logs by weighting averages based on species distribution percentages reported by sawmill respondents and the specific gravity of each species. *Hardwoods of North America* (Alden 1995) provides wood densities by species. It is common for several species to fall within the classification of one species group. For example, the Red Oak species group contains nine species, including red oak (*Quercus rubra*), and the Ash group (*Fraxinus* spp.) contains three species. For instances where a species fell into a broader species group, the average density of that group was calculated. For example, a weighted average green specific gravity, OD specific gravity, and 8% MC specific gravity were 0.52, 0.59, and 0.55, respectively. Interestingly, the hardwood lumber industry considers bald cypress (*Taxodium distichum*) a hardwood, although it is a softwood species.

Moisture Content

Moisture content is an important consideration because it is the basis from which wood densities and efficiencies (wood as fuel) can be calculated. A weighted average of 70% (dry basis) initial green MC was observed in this study. Hardwood lumber was kiln-dried to a final MC of 8% on a dry basis. For this report, the following equations were used to calculate MC and to aid in wood density calculations:

Percentage MC on a dry basis:

$$\text{Percentage MC (dry basis)} = \left(\text{weight of water in wood/weight of oven-dry wood}\right) \times 100$$

Percentage MC on a wet basis:

$$\text{Percentage MC (wet basis)} = \left(\text{weight of water in wood/weight of wet wood}\right) \times 100$$

OD weight:

$$\text{Weight oven-dry} = \text{green weight} \times \left(1 - \text{MC\% wet basis}\right)$$

Flow Diagram of Production Process

Process flows show the sequential steps used for a manufacturer to produce their product offerings. Flow diagrams are useful tools in resource accounting and process improvement methodologies. A process flow diagram for hardwood PDL is shown in Figure 3.

Life-Cycle Inventory Analysis

This section describes the LCI results for the unit process flows to produce 1.0 m^3 of planed kiln-dry hardwood lumber. The LCI was based on material flow and production data for 2017. There were no gaps in data. The analysis examines the inputs, outputs, and emissions to air, land, and water for the three information modules (A1–A3) discussed in the following sections.

A1—Raw Material Extraction

Harvested sawlogs are the primary raw material input to produce hardwood lumber. Production of merchantable sawtimber begins with forest stand initiation, followed by forest thinning, and ends with harvesting. Although fertilization of forested sites is mentioned in other studies, it is not common practice outside of supplemental seedling production in greenhouses for the region under consideration here. The hardwood resource model used to extend the system boundary for this study considers forest establishment, management, and site preparation practices. Once hardwood forests are established, they typically undergo periodic commercial thinning to promote vigor in the higher quality trees. Both thinning operations and final harvesting of timber use felling and hauling equipment, including chainsaws, mechanized harvesters, skidders, and log trucks. Fuels and lubricants to operate this equipment were included in the forest resource LCI. For the purposes of this study, the primary product from the forest resource LCI was a log ready for transport to the sawmill. Forest residuals are left on the forest site and decomposed by

Table 5—Species composition and calculated wood specific gravities for hardwood lumber production in the southeastern United States (kiln-dried specific gravity at 8% moisture content (MC))

Common name	Scientific name	Percentage of total volume surveyed	Green specific gravity	Oven-dried specific gravity	12% MC specific gravity	Kiln-dried specific gravity
Red oak (mix)	*Quercus* spp.	39.9	0.57	0.68	0.65	0.66
White oak (mix)	*Quercus* spp.	20.5	0.60	0.72	0.67	0.69
Hard maple (mix)	*Acer* spp.	1.2	0.54	0.65	0.60	0.62
Sweetgum	*Liquidambar styraciflua*	1.2	0.46	0.53	0.52	0.52
Hickory	*Carya* spp.	1.0	0.64	0.78	0.72	0.71
Sycamore–beech	*Fagus* spp.	1.2	0.51	0.61	0.57	0.58
Poplar (mix)	*Populus* spp.	26.6	0.40	0.43	0.42	0.42
Bald cypress	*Taxodium distichum*	1.0	0.42	0.48	0.46	0.47
Ash (mix)	*Fraxinus* spp.	3.3	0.51	0.59	0.55	0.56
Black cherry	*Prunus serotina*	1.9	0.47	0.53	0.50	0.56
Miscellaneous	—	2.1	0.40	0.43	0.42	0.42
Weighted average	—	100	0.519	0.607	0.577	0.588

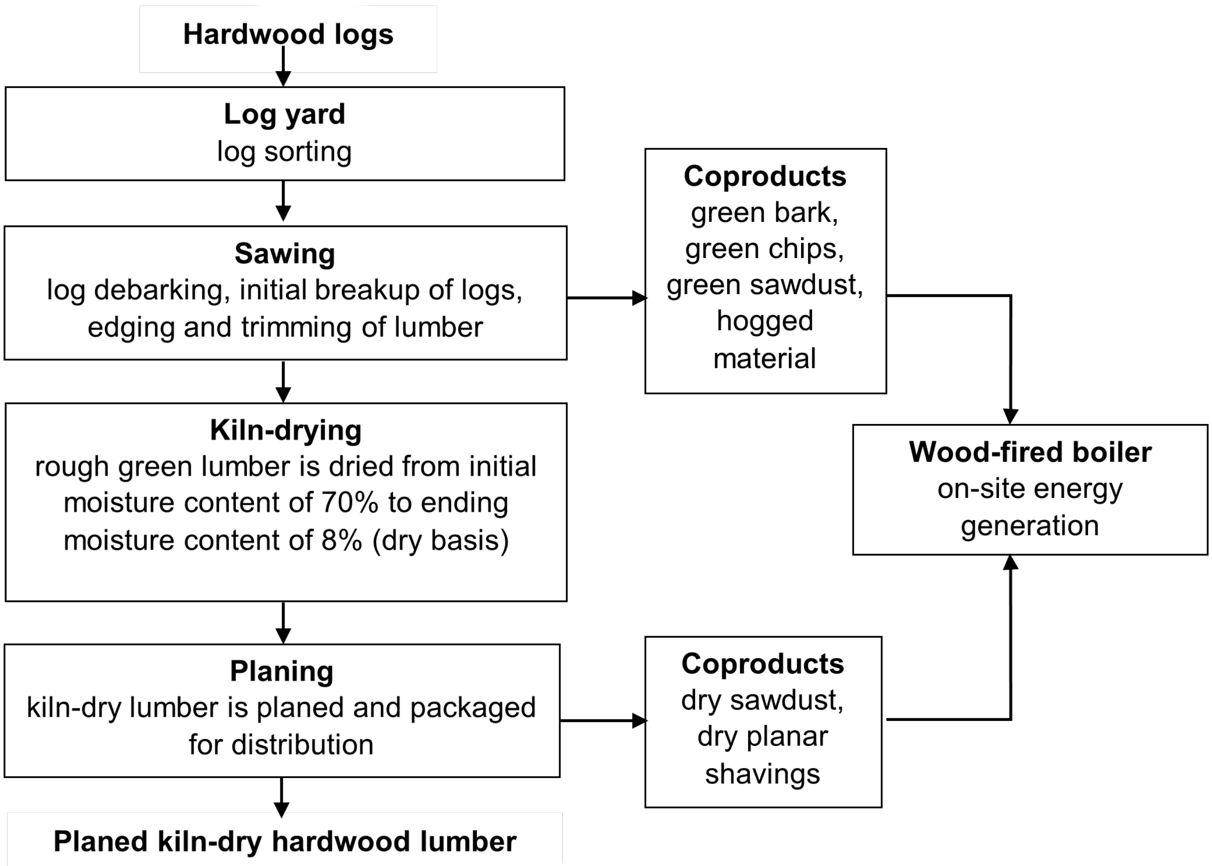

Figure 3—Process flow diagram for the production of planed kiln-dry hardwood lumber.

natural processes and are not considered in the system boundary of this study.

The SE hardwood forest resource LCI data were developed from various data sources (Oneil and others 2010; ASMI 2012; Bergman 2015a, 2015b). For SE hardwood forests, reforestation occurs using natural regeneration that did not require inputs from human-related activities (i.e., the technosphere) for seedlings, site preparation, planting, and precommercial thinning. Weighted average allocation to different processes considers inherent differences in energy usage by different kinds of logging equipment and site productivity.

The mills reported that they purchased varying amounts of rough green lumber to supplement their own hardwood lumber production. The weighted average amount of purchased rough green lumber was 0.021 m^3 (31.25 OD kg) per 1.0 m^3 of hardwood PDL, a slight portion. For the surveyed mills, this lumber undergoes value-adding on site in the kiln-drying and planing processes. To account for the burdens associated with this mill input, the system boundary includes the manufacturing of the purchased lumber. The process to produce rough green lumber by mills in the study was used as the proxy for supplier production. A detailed accounting of the process is described in the sawing section.

A2—Resource and Material Transportation

Logs from forest landings (average distance of travel 139 km) and purchased rough green lumber from outside suppliers are transported by truck. Lumber producing mills in this study take possession of these raw materials upon delivery to their production facility. Transportation was modeled as an input to the log yard unit process.

A3—Hardwood Lumber Manufacturing

The study considered five unit processes in the production of hardwood PDL. They are log yard, sawing, drying, planing, and energy generation with an industrial wood-fired boiler. Each process is detailed next. For liquid petroleum gas (LPG), a boiler proxy with the same emission profile as industrial equipment was used.

Log Yard

The log yard unit process starts with receivership of hardwood logs and purchased rough green lumber trucked to the sawmill. Delivered logs are sorted, graded, and stored on site. A concern with hardwood use is sapstain (bluestain fungi) in logs and lumber. To control this, logs are often exposed to sprinkling systems or end-coated with a wax sealant to deprive the fungi of the oxygen they need to thrive. Equipment used in the log yard includes large forklifts. Primary fuels are diesel and lesser amounts of gasoline to operate this equipment. The output of the log yard process is logs ready for sawing. Inputs and outputs for the log yard unit process appear in Table 6.

Sawing

The sawing unit process breaks logs down into rough green lumber. The most common hardwood lumber dimensions are 1.0 in. (25.4 mm) thick, 8 ft (2.44 m) long, and various widths. Sawing uses the most electrical consumption among all the unit processes. Rough green lumber is edged and trimmed to achieve optimal lumber grades, scaled, and stickered for kiln-drying. A portion of the rough green lumber produced is sold in that form, and the manufacturing burdens associated with further processing was omitted in those instances. Equipment used in the sawing process includes debarkers, metal detectors, headrigs (headsaws), resaws, edgers, trim saws, optimized scanners, stackers, sorters, conveyors, and forktrucks (forklifts). Stationary saws, stackers, and sorters depend on electricity for their operation whereas forktrucks use diesel or natural gas. The outputs associated with the sawing process included rough green lumber ready for sale or kiln-drying, green bark, green chips, green sawdust, and green hogged material (edgings and trimmings). Table 7 lists the inputs and outputs for the sawing process.

Drying

The drying unit process begins with stacked and stickered rough green lumber. Stickers are wood spacers placed between lumber to allow air flow and heat to pass uniformly over the wet lumber. Drying methods are dependent on species, lumber grades, and lumber thickness. Although air-drying of green lumber can represent large decreases in energy use, most hardwood-using mills do not practice this because of staining and other value-degrading consequences such as checks and cracks from the uncontrolled nature of air-drying.

Kiln-drying of hardwood lumber is primarily a batch process. Lumber charges (the total amount of wood batched for drying) are loaded into commercial kilns and dried from an initial MC of typically about 70% (OD basis) to a final MC of 8% (OD). Kilns are physical structures typically 16 to 40 m long. One or both sides of the kiln open for loading lumber charges and are then closed during drying times of 4 to 30 days per charge depending on the drying schedule for a given hardwood species and lumber thickness (Boone and others 1988). Drying is accomplished when heated air is circulated through the kiln by fans and passes over the stickered lumber. Steam-fed heating coils release energy to heat the air up to a desired temperature according to kiln-drying schedules. Controlling the humidity in the kiln is a key consideration in drying and is accomplished by opening vents in the kiln to release moisture-laden warm air while bringing in fresh ambient air (Denig and others 2000, Bergman 2021). A charge of stacked and stickered green lumber entering the kiln is generally between 2.5 and 3 m wide. The kiln can accommodate stacking the lumber to a height of 5 m. The primary equipment used is a forklift for loading and unloading the kilns. Energy used is diesel and gasoline for forklifts; electricity for kiln controls, motors, and lighting; and natural gas and wood fuel in industrial boilers for process heat. Energy for a kiln operation is derived from fossil fuels and industrial wood-fired boilers described in the following section. Kiln-drying produced the bulk of VOCs that were produced on-site during the combustion of fossil and wood fuels. The output of the kiln-drying process is rough kiln-dry lumber ready for planing. The inputs and outputs for the drying unit process are shown in Table 8.

Wood-Fired Boiler

On-site energy production is captured in the boiler unit process. Sawmills use wood residues in the form of green and dry sawdust, green chips, green and dry hogged fuel, and green bark as inputs to industrial wood-fired boilers. Respondents in our study reported that no fraction of dry planar shavings were used for fuel. Sawmills in this study did not purchase wood for their boilers but instead relied 100% on the wood fuel sources from within their manufacturing operations. Wood combusted in the boiler process and its associated emissions were tracked for this study (Table 9). Thermal energy produced by the boiler was used in the kiln-drying process by generating steam for indirectly heated kilns. The total heat energy used in the kiln-drying process was 2,860 MJ (heat from CORRIM wood boiler = 2,700 MJ/m^3 rough dry lumber and natural gas 160 MJ/m^3 rough dry lumber) per cubic meter of rough dry hardwood lumber. This study made use of a wood-fired boiler process developed by Puettmann and Milota (2017).

Planing

The final stage of product manufacturing in this study was the planing unit process. The process begins with stickered, rough kiln-dried lumber, which is then unstacked, unstickered, and fed through planers. Planers consist of varying configurations of rotating knives that shave the wood to uniform thicknesses and remove sawing blemishes. Although the standard for planing is 0.8125 in. (20.6 mm) for 1.0 inch (4/4) hardwood lumber, a portion of the lumber is only skip planed, generally from 1 to 0.9375 in. (25.4 to 23.8 mm). After planing, the surfaced lumber is packaged using steel or plastic bands and in some cases plastic wrapping and corner protectors. Not only is fuel used to run the planer machinery, it is also used in the conveyers and forklifts that transported the material. Primary fuels are electricity, diesel, and LPG. Wood dust is controlled using baghouses, cyclones, or a combination of the two. A small portion of the dry sawdust is sent to on-site wood-fired

Table 6—Inputs and outputs of the log yard unit process for production of 1 m^3 of roundwood hardwood sawlogs in the southeastern (SE) United States (US)

Inputs and outputs	Value	Unit	Allocation (%)
Products			
Roundwood sawlogs, hardwood, green, at log yard, SE US	1.00	m^3	100
Materials and fuels			
Roundwood, hardwood, average, at forest road, NE-NC/RNA	1.00	m^3	—
Transport, combination truck, diesel powered, NREL/US U[a]	116	tkm[b]	—
Diesel, combusted in industrial equipment, NREL/US U	0.613	L	—
Gasoline, combusted in equipment, NREL/US U	0.005	L	—
Liquefied petroleum gas, combusted in industrial boiler, US (proxy)	0.460	L	—

[a]Reflects transportation of the bark and log, which comes in together.
[b]tkm, tonne kilometer, includes the mass of bark and timber.

Table 7—Inputs and outputs for the sawing unit process for production of 1 m^3 of rough green hardwood lumber in the southeastern (SE) United States (US)

Inputs and outputs	Value	Unit	Allocation (%)
Products			
Sawn lumber, hardwood, rough, green, SE US	1.00	m^3	50.05
Bark, hardwood, green, sold, SE US	66.1	OD kg	6.36
Green coproducts, fuel, SE US[a]	98.8	OD kg	9.50
Green coproducts, sold, SE US[b]	354	OD kg	34.09
Materials and fuels			
Roundwood sawlogs, hardwood, green, at log yard, SE US	2.00	m^3	—
Diesel, combusted in industrial equipment NREL/US U	0.613	L	—
Gasoline, combusted in equipment NREL/US U	0.005	L	—
Liquefied petroleum gas, combusted in industrial boiler/US (proxy)	0.459	L	—
Water, well, in ground, US-EI 2.2	22.0	L	—
Water, recycled	19.8	L	—
Process-specific burdens, sanitary landfill/CH U, US-EI 2.2	44.3	kg	—
Materials for recycling[c]	23.6	kg	—
Electricity and heat			
Electricity, low voltage (SERC)| market for cut-off, U	61.8	kWh	—

[a]Green coproducts, fuel, are wood residues including sawdust and hogged material that is generated by the sawing process and used internally for fuel.
[b]Green coproducts, sold, are wood residues including sawdust and hogged material that is generated by the sawing process and sold to outside customers.
[c]Metals, oils, and plastics.

Table 8—Inputs and outputs for the drying unit process of 1 m^3 of rough dry hardwood lumber in the southeastern (SE) United States (US)

Inputs and outputs	Value	Unit	Allocation (%)
Products			
Sawn lumber, hardwood, rough, dry, SE US	1.00	m^3	100
Materials and fuels			
Sawn lumber, hardwood, rough, green, SE US	1.12	m^3	—
Diesel, combusted in industrial equipment NREL/US U	0.69	L	—
Gasoline, combusted in equipment NREL/US U	0.01	L	—
Liquefied petroleum gas, combusted in industrial boiler/US (proxy)	0.52	L	—
Electricity and heat			
Electricity, low voltage (SERC)| market for cut-off, U	30.9	kWh	—
Heat from CORRIM wood-fired boiler	2,700	MJ	—
Natural gas, combusted in industrial boiler NREL/US U	4.01	m^3	—
Emissions to air			
Volatile organic compounds (VOCs)	0.04	kg	—

Table 9—Inputs and outputs for the wood-fired boiler process per 1.0 oven-dried (OD) kg wood fuel

Inputs and outputs	Value	Unit	Allocation (%)
Products			
Heat from CORRIM wood-fired boiler	20.9	MJ	100
CORRIM wood ash, at boiler, at mill	0.02	kg	—
Resources			
Water, process, surface	0.31	kg	—
Water, process, well	0.24	kg	—
Water, process, surface	0.79	kg	—
Water, process, well	0.24	kg	—
Materials and fuels			
Green coproducts, hardwood, fuel, SE US	0.97	OD kg	—
Dry coproducts, hardwood, fuel, SE US	0.03	OD kg	—
Diesel, loaders and haulers	8.05E–04	L	—
Gasoline, loaders and haulers	3.95E–05	L	—
Propane, loaders and haulers	1.21E–05	L	—
Engine oil, in engines of loaders and haulers	5.00E–06	kg	—
Engine oil, stationary equipment	1.90E–05	kg	—
Hydraulic fluid for loaders and haulers	7.00E–06	kg	—
Hydraulic oil for stationary equipment	4.50E–05	kg	—
Transmission fluid, loaders and haulers	4.00E–07	kg	—
Ethylene glycol, at plant	1.07E–06	kg	—
Solvent, at plant/US	5.00E–08	kg	—
Solvent, at plant/US	6.70E–07	kg	—
Water treatment, at plant/US	1.26E–04	kg	—
Boiler streamline treatment	3.67E–06	kg	—
Oils, mobile equipment	2.00E–06	kg	—
Oils, stationary equipment	1.00E–05	L	—
Urea, as N, at regional storehouse	3.15E–03	kg	—
Disposal, ash, to unspecified landfill	7.59E–03	kg	—
Disposal, solid waste, unspecified, to unspecified landfill, RNA	7.26E–06	kg	—
Metal, to recycling, RNA	3.96E–08	kg	—

Table 9—Inputs and outputs for the wood-fired boiler process per 1.0 oven-dried (OD) kg wood fuel—continued

Inputs and outputs	Value	Unit	Allocation (%)
Electricity and heat			
Electricity, at grid, US	8.20E–02	kWh	—
Natural gas, combusted in industrial boiler/US	1.38E–03	m^3	—
Emissions to air			
Acetaldehyde	1.05E–06	kg	—
Acrolein	8.07E–07	kg	—
Benzene	1.69E–07	kg	—
Carbon monoxide, biogenic	3.23E–03	kg	—
Carbon dioxide, biogenic	1.76E+00	kg	—
Wood (dust)	5.62E–04	kg	—
Formaldehyde	1.26E–05	kg	—
HAPs	6.27E–06	kg	—
Hydrogen chloride	1.17E–06	kg	—
Lead	1.75E–07	kg	—
Mercury	1.83E–09	kg	—
Methane, biogenic	2.23E–05	kg	—
Methanol	7.95E–06	kg	—
Nitrogen oxides	1.10E–03	kg	—
Particulates, <10 um	4.71E–04	kg	—
Particulates, <2.5 um	1.39E–04	kg	—
Phenol	6.21E–07	kg	—
Propanal	5.14E–08	kg	—
Sulfur dioxide	7.71E–05	kg	—
Volatile organic compounds (VOCs)	8.76E–04	kg	—
Dinitrogen monoxide	2.93E–06	kg	—
Naphthalene	5.77E–08	kg	—
Other organic	2.11E–07	kg	—
Emissions to water			
Suspended solids, unspecified	8.35E–07	kg	—
Biological oxygen demand (BOD_5)	2.10E–06	kg	—

boilers and combusted to produce on-site energy. The output of the planing unit process is packaged, planed kiln-dry hardwood lumber sorted by grade and type and ready for distribution to customers. Coproducts include sawdust and planar shavings. The inputs and outputs for the planing process are shown in Table 10. Packaging materials are listed in Table 11.

Secondary Data Sources

Secondary data sources for raw material inputs, ancillary materials and packaging, transportation of materials and resources, fuels and energy for manufacturing, water sources, and waste streams used in this LCA are shown in Table 12.

Life-Cycle Impact Assessment

This study used the TRACI method to determine environmental impacts (Bare 2011) associated with the production of 1.0 m^3 hardwood PDL in the SE region of the United States. For conformance with the PCR, target impact indicators are summarized in Table 13. The units associated with the impact indicator values are not comparable with others, and as such, should not be packaged together. Fuels are categorized as renewable or nonrenewable. Renewable fuels include biomass, geothermal, solar, wind, and hydro, whereas nonrenewable fuels are fossil and nuclear forms.

Results of the cradle-to-gate environmental performance of SE hardwood PDL for the reporting indicators in Table 13 are reported in Table 14. LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Table 10—Inputs and outputs for the planing unit process

Inputs and outputs	Value	Unit	Allocation (%)
Products			
Sawn lumber, hardwood, planed, dry, SE US	1.00	m^3	850
Dry coproducts, hardwood, sold, SE US[a]	101	kg	15.0
Materials and fuels			
Sawn lumber, hardwood, rough, dry, SE US	1.16	m^3	—
Diesel, combusted in industrial equipment NREL/US U	0.80	L	—
Gasoline, combusted in equipment NREL/US U	0.01	L	—
Liquefied petroleum gas, combusted in industrial boiler/US (proxy)	0.60	L	—
Electricity and heat			
Electricity, low voltage (SERC)| market for cut-off, U	21.36	kWh	—

[a]Dry coproducts, sold, are on an oven-dry basis; sold are wood residues including sawdust, planar shavings, and hogged material that are generated by the planing process and sold to outside customers.

Table 11—Total amount of packaging materials reported in the sawmill survey for the production year 2017 per 1 m^3 of planed dry lumber

Material[a]	Value	Unit
Steel strapping	7.69	kg/m^3
Plastic strapping	2.48	kg/m^3
End paint	1.41	L/m^3
Cardboard corner protectors	0.03	kg/m^3

[a]More details in Table 12.

Results of the LCIA are shown in absolute values for A1-raw material extraction (including forest management activities), A2-resource and material transportation, and A3-hardwood lumber manufacturing in Table 14. Some specific categories included in Table 14 are energy use, material resource consumption, and generated waste indicators. Total energy use from cradle to gate was 5,575 MJ/m^3. Of this, 2,263 MJ/m^3 was renewable and 3,312 MJ/m^3 was nonrenewable. The nonrenewable energy was derived from fossil fuels and used to operate sawmill machinery, operate transportation machinery, generate electricity, and fuel a portion of the kiln-drying. Nonrenewable fuels represented 59% of the total energy use. Energy from biomass went exclusively to kiln-drying. The bulk of fresh-water use took place in the A3 module (manufacturing). Mills reported the use of sprinkler systems in the log yard but only reported water usage for the whole facility (41.8 L/m^3 PDL).

Interpretation

Life-cycle interpretation is defined by ISO as the phase of an LCA where findings from an LCI, LCIA, or both are brought together within the defined goal and scope of the project for the purpose of drawing conclusions and offering recommendations. Based on the results of the LCI in this report, significant issues are reported for the production of hardwood PDL. In addition, we consider checks on the completeness, sensitivity, and consistency of the LCI results and follow with conclusions, limitations, and recommendations.

Identification of Significant Issues

The LCI results were used to identify significant issues inherent in the manufacture of hardwood PDL in the SE region of the United States. For the interpretation phase of this report, a contribution analysis examined the A1, A2, and A3 information modules. In this way, significant impacts from a unit process or substances of particular interest can be examined.

Life-Cycle Phase Contribution Analysis

Contributions from each module (A1–A3) for each impact indicator are shown in Table 15. For global warming impact (CO_2 equivalent emissions), 15% of the emissions were from raw material extraction (A1), 14% from resource and material transportation (A2), and 71% from hardwood lumber manufacturing (A3). Hardwood lumber manufacturing (A3) had the highest impact for global warming potential (GWP), depletion potential of the stratospheric ozone layer, acidification potential of soil and water sources, eutrophication potential, abiotic depletion potential for fossil resources, and fossil fuel depletion.

Renewable fuels use was highest for hardwood lumber manufacturing (A3). This reflects the use of wood residues for combustion in the boiler unit process. Renewable fuels had the greatest proportion of energy consumption. For nonrenewable fossil fuels, 74% was contributed by A3, whereas A1 contributed 15% (Table 15). About 12% of total nonrenewable fuels were used by A2. Biomass energy was primarily used in kiln-drying lumber (A3). The cradle-to-gate total biomass energy was 0.01% (A1), 0.01% (A2), and 99.98% (A3).

Tables 16 and 17 report the cradle-to-gate energy use contribution analysis results by fuel type and information modules of A1 raw material extraction, A2 resource and material transportation, and A3 hardwood lumber

Table 12—Material inputs, secondary data sources, geography, years, and data quality for life-cycle assessment of hardwood lumber production in the southeastern United States

Inputs	LCI data source	Geography	Year	Data quality assessment
		A1: raw material extraction		
Wood resource	Database: USLCI (U.S. Life Cycle Inventory) Database. (DATASMART 2018). Accessed October 7, 2022: https://www.lcacommons.gov/nrel/search Process: roundwood, hardwood, average, at forest road, NE-NC/RNA	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: resource and material transportation		
Trucking	Database: US EI 2.2 (DATASMART 2018) Process: transport, combination truck, diesel powered NREL/US U	North America	2018	Technology: very good; process models average North American technology Time: fair; data are less than 15 years old Geography: very good; data are representative of North American trucking
		A3: hardwood lumber manufacturing		
Electricity	Database: Ecoinvent 3.4 (Wernet and others 2016) Process: electricity, low voltage (SERC)| market for cut-off, U	North America, region specific egrid	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 2018) 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 2018) 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: using the published report/model from 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: good; some data are less than 10 years old 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 2018) 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 2018) 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 2018) 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
Steel strapping	World Steel Association (2011) Worldsteel LCI database https://www.worldsteel.org/steel-5 by-topic/life-cycle-thinking/lca-lciform.html world steel data for finished cold rolled coil	Global	2018	Technology: very good; process models average North American technology Time: very good; data are less than 5 years old Geography: good; data are representative of global conditions

Table 12—Material inputs, secondary data sources, geography, years, and data quality for life-cycle assessment of hardwood lumber production in the southeastern United States—continued

Inputs	LCI data source	Geography	Year	Data quality assessment
Plastic strapping	Database: US EI 2.2 (DATASMART 2018) 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 2018) Process: proxy oil and grease, at plant 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 processes
Plastic wrapping	Database: US EI 2.2 (DATASMART 2018) 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
End paint	Database: Ecoinvent 3.4 (Wernet and others 2016) Process: market for chemical, organic GLO	Global	2018	Technology: very good; process models average North American technology Time: very good; data are less than 5 years old Geography: good; data are representative of global conditions

manufacturing, respectively. For nonrenewable fossil fuel energy, 70.0% was used in A3, 16.7% in A1, and 13.3% in A2.

Within the raw material extraction (A1) module, 98.4% of the total energy was derived from nonrenewable fuels (Table 17). Biomass energy was used primarily in kiln-drying the hardwood lumber (A3) and was 99.99% of the total energy for that module (Table 16). These results are consistent with previous hardwood lumber studies (Comstock 1975; Denig and others 2000; Bergman and Bowe 2008a, 2012; Hubbard and others 2020). Considering the cradle-to-gate total energy for producing SE hardwood lumber, including fuels for heat, equipment, and electricity, 49.9% comes from nonrenewable fossil fuels, 8.5% from nuclear, 39.8% from renewable biomass fuel, 0.1% from wind, solar, and geothermal, and 1.7% from hydro (Table 17).

Uncertainty Analysis

Uncertainty in the results can arise from variation between different data sources (survey respondents and participating sawmills). For this study, uncertainty was addressed by conducting different scenarios for log transport distances and the use of electricity, natural gas, and woody biomass fuel. The resultant values when each of these parameters are decreased or increased by 20% from the baseline results are shown in Tables 18 and 19. In Table 18, an increase of 20% in the distance to transport logs from the forest to the sawmill gate resulted in an increase of 6 kg CO_2eq from the baseline amount of 209 kg CO_2eq for the impact indicator GWP. Conversely, decreasing the log transport distance by 20% created a 6-kg-CO_2eq decrease in the GWP indicator. For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of electricity used decreased the surplus to 301 MJ compared with the baseline amount of 311 MJ, a difference of 10 MJ.

In Table 19, an increase of 20% in natural gas consumption resulted in an increase of 2 kg CO_2eq from the baseline amount of 209 kg CO_2eq for the impact indicator GWP. Conversely, decreasing natural gas consumption by 20% decreased the GWP indicator by 2 kg CO_2eq. For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of woody biomass used decreased the surplus to 307 MJ compared with the baseline amount of 311 MJ, a difference of 4 MJ.

A change of ±20% in the distance trucks traveled to deliver logs from the forest to the sawmill gate resulted in a ±3% deviation from the baseline amount of CO_2eq for the impact indicator GWP (Table 20). For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of electricity used led to a 3% decrease in the surplus from the baseline amount. The greatest change (±16%) was observed for eutrophication potential when electricity was increased or decreased by 20% from the original baseline amount. Changes in eutrophication are mainly affected by changes in nitrogen oxide flows used in the process of electricity production.

Using the same principle, Table 21 shows that a 20% increase in natural gas usage compared with the baseline amount resulted in a 1% increase in the baseline value for GWP. Similarly, the addition of 20% more woody biomass for fuel increased the GWP impact indicator 1% compared with the baseline.

Table 13—Selected impact indicators, reporting categories, and assessment methods

Reporting category per tables E1-E5 in ISO 21930:2017	Indicator name	Abbreviation	Unit	Impact assessment method
Core mandatory impact indicators	Global warming potential, with biogenic	GWP	kg CO_2e	TRACI 2.1
Core mandatory impact indicators	Global warming potential, fossil	GWP	kg CO_2e	CML-IA (baseline)
Core mandatory impact indicators	Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	TRACI 2.1
Core mandatory impact indicators	Acidification potential of soil and water sources	AP	kg SO_2e	TRACI 2.1
Core mandatory impact indicators	Eutrophication potential	EP	kg PO_4e	TRACI 2.1
Core mandatory impact indicators	Formation potential of tropospheric ozone	SFP	kg O_3e	TRACI 2.1
Core mandatory impact indicators	Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	CML-IA (baseline)
Core mandatory impact indicators	Fossil fuel depletion	FFD	MJ surplus	TRACI 2.1
Use of primary resources	Renewable primary energy carrier used as energy	RPRE	MJ, NCV	CED
Use of primary resources	Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	CED
Use of primary resources	Renewable primary energy carrier used as material	NRPRM	MJ, NCV	CED
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	m^3	—
Indicators describing waste	Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	—
Indicators describing waste	Components for reuse	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	—

Limitations

The LCA developed here was dependent on weight-averaged primary industry data from the defined region of interest. Similarly, upstream data was used to extend the system boundary from a gate-to-gate LCI to a more complete cradle-to-gate LCI. Variation, which is inherent to manufacturing processes, production efficiencies, fuel types, and the equipment used, is a consideration for users of this report. Not all of the environmental impacts associated with the production stage of this project can be established. Only impacts in categories with known LCA-based methodologies can be examined and reported on. This report does not include environmental impacts on human health, habitat destruction, or land use changes. Because of the

Table 14—Environmental impacts of 1.0 m³ of planed kiln-dry hardwood lumber in the southeastern United States, mass allocation, cradle to gate

Impact indicator	Abbreviation	Unit	A1	A2	A3	Total
Core mandatory						
Global warming potential, fossil	GWP	kg CO_2e	31.8	28.6	148	209
Global warming potential, with biogenic	GWP	kg CO_2e	–2,448	28.6	2,628	209
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	1.93E–07	4.78E–08	8.88E–06	9.12E–06
Acidification potential of soil and water sources	AP	kg SO_2e	0.397	0.158	0.710	1.265
Eutrophication potential	EP	kg Ne	0.028	0.012	0.680	0.721
Formation potential of tropospheric ozone	SFP	kg O_3e	12.74	4.53	11.10	28.4
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	453	358	1,835	2,646
Fossil fuel depletion	FFD	MJ surplus	68.0	53.8	190	311
Primary resources						
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	0.984	0.770	2261	2,263
Renewable primary energy carrier used as material	RPRM	MJ, NCV	12,028	0.000	0.000	12,028
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	487	386	2,439	3,312
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	0.00	0.00	0.00	0.000
Secondary material, fuel, and recovered energy						
Secondary material	SM	kg	0.00	0.00	0.00	0.00
Renewable secondary fuel	RSF	MJ, NCV	0.00	0.00	0.00	0.00
Nonrenewable secondary fuel	NRSF	MJ, NCV	0.00	0.00	0.00	0.00
Recovered energy	RE	MJ, NCV	0.00	0.00	0.00	0.00
Mandatory inventory parameters						
Consumption of freshwater resources	FW	L	4.16	2.80	547	554
Waste						
Hazardous waste disposed	HWD	kg	0.00	0.00	0.00	0.00
Nonhazardous waste disposed	NHWD	kg	0.00	0.00	0.00	0.00
High-level radioactive waste, conditioned, to final repository	HLRW	m^3	3.61E–09	2.82E–09	2.69E–07	2.76E–07
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	1.74E–08	1.36E–08	2.23E–06	2.26E–06
Components for reuse	CRU	kg	0.00	0.00	0.00	0.00
Materials for recycling	MR	kg	0.00	0.00	0.00	0.00
Materials for energy recovery	MER	kg	0.00	0.00	0.00	0.00
Recovered energy exported from the product system	EE	MJ, NCV	0.00	0.00	0.00	0.00

stated goal and scope of this project, comparisons to substitute products are not appropriate. As noted previously, this LCA was built on four sawmills from various states in the region. Although this met the requirements for developing an EPD, this was fewer than the 12 sawmills providing survey data in the previous study (Bergman and Bowe 2010, 2012). Therefore, the LCA presented here makes no assertions that the product under investigation is superior to other alternative products.

Treatment of Biogenic Carbon

Biogenic carbon is defined as materials originating from biological sources such as plants, trees, and soil and is present in biobased materials such as wood. The treatment of biogenic carbon in this study follows the requirements of the reference PCR and conforms to the guidelines for the treatment of biogenic carbon set forth in ISO 21930. Per ISO 21930, biogenic carbon enters the product system (removal) as primary or secondary material. Carbon removal in this context is taken as a negative emission. Biogenic carbon then leaves a system (emission) as product,

Table 15—Cradle-to-gate southeastern U.S. hardwood lumber life-cycle inventory analysis contribution results for A1-raw material extraction, A2-resource and material transportation, and A3-hardwood lumber manufacturing

Indicator name	Abbreviation	Unit	A1 (%)	A2 (%)	A3 (%)	Total (%)
Global warming potential	GWP	kg CO_2e	15	14	71	100
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	2	1	97	100
Acidification potential of soil and water sources	AP	kg SO_2e	31	13	56	100
Eutrophication potential	EP	kg Ne	4	2	94	100
Formation potential of tropospheric ozone	SFP	kg O_3e	45	16	39	100
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	17	14	69	100
Fossil fuel depletion	FFD	MJ surplus	22	17	61	100
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	0	0	100	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	15	12	74	100
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	—	—	—	—
Secondary material	SM	kg	—	—	—	—
Renewable secondary fuel	RSF	MJ, NCV	—	—	—	—
Nonrenewable secondary fuel	NRSF	MJ, NCV	—	—	—	—
Recovered energy	RE	MJ, NCV	—	—	—	—
Consumption of freshwater resources	FW	m^3	0.8	0.5	98.7	100
Hazardous waste disposed	HWD	kg	—	—	—	—
Nonhazardous waste disposed	NHWD	kg	—	—	—	—
High-level radioactive waste, conditioned, to final repository	HLRW	m^3	1.3	1.0	97.7	100
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	0.8	0.6	98.6	100
Components for reuse	CRU	kg	—	—	—	—
Materials for recycling	MR	kg	—	—	—	—
Materials for energy recovery	MER	kg	—	—	—	—
Recovered energy exported from the product system	EE	MJ, NCV	—	—	—	—

Table 16—Cradle-to-gate southeastern U.S. hardwood lumber life-cycle inventory analysis energy use contribution results by fuel type for A1-raw material extraction, A2-resource and material transportation, and A3-hardwood lumber manufacturing

Fuel type	Unit	Total (%)	A1 (%)	A2 (%)	A3 (%)
Nonrenewable, fossil	MJ	100	16.76	13.26	69.98
Nonrenewable, nuclear	MJ	100	1.44	1.13	97.43
Nonrenewable, biomass	MJ	100	0.13	0.01	99.87
Renewable, biomass	MJ	100	0.01	0.01	99.99
Renewable, wind, solar, geothermal	MJ	100	4.67	3.54	91.79
Renewable, water	MJ	100	0.64	0.50	98.86

Table 17—Cradle-to-gate southeastern U.S. hardwood lumber life-cycle inventory analysis energy use contribution results by A1-raw material extraction, A2-resource and material transportation, and A3-hardwood lumber manufacturing

Energy use	Unit	Total (%)	A1 (%)	A2 (%)	A3 (%)
Nonrenewable, fossil	MJ	49.91	98.35	98.37	41.20
Nonrenewable, nuclear	MJ	8.48	1.44	1.42	9.75
Nonrenewable, biomass	MJ	0.00	0.00	0.00	0.00
Renewable, biomass	MJ	39.83	0.03	0.04	46.98
Renewable, wind, solar, geothermal	MJ	0.09	0.05	0.05	0.10
Renewable, water	MJ	1.69	0.13	0.13	1.97
Total	%	100.00	100.00	100.00	100.00

Table 18—Deviations in the results for a 20% increase or decrease from the baseline amount for log transportation distances and electricity use

Core mandatory indicator	Abbreviation	Unit	Baseline results	Log transport distance –20%	Log transport distance +20%	Electricity –20%	Electricity +20%
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	209	203	215	195	222
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	9.12E–06	9.11E–06	9.13E–06	7.95E–06	1.03E–05
Acidification potential of soil and water sources	AP	kg SO_2e	1.27	1.23	1.31	1.23	1.30
Eutrophication potential	EP	kg Ne	0.721	0.718	0.723	0.607	0.834
Formation potential of tropospheric ozone	SFP	kg O_3e	28.4	2.75E+01	2.93E+01	2.81E+01	2.87E+01
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	2,646	2,574	2,717	2,502	2,790
Fossil fuel depletion	FFD	MJ surplus	311	301	322	301	321
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	2,263	2,263	2,263	2,258	2,267
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	3,312	3,235	3,389	3,082	3,542

Table 19—Deviations in the results for a 20% increase or decrease from the baseline amount for natural gas and woody biomass use as fuel

Core mandatory indicator	Abbreviation	Unit	Baseline results	Natural gas –20%	Natural gas +20%	Biomass –20%	Biomass +20%
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	209	207	211	206	212
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	9.12E–06	9.12E–06	9.12E–06	8.87E–06	9.37E–06
Acidification potential of soil and water sources	AP	kg SO_2e	1.26	1.25	1.28	1.23	1.30
Eutrophication potential	EP	kg Ne	0.721	0.721	0.721	0.710	0.731
Formation potential of tropospheric ozone	SFP	kg O_3e	2.84E+01	2.83E+01	2.84E+01	2.75E+01	2.92E+01
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	2,646	2,616	2,676	2,609	2,682
Fossil fuel depletion	FFD	MJ surplus	311	306	316	307	315
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	2,263	2,263	2,263	1,831	2,694
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	3,312	3,279	33,345	3,258	3,366

Table 20—Sensitivity analysis results for 20% increase or decrease to baseline results for log transport distance and electricity

Core mandatory indicator	Abbreviation	Unit	Baseline results	Log transport distance		Electricity	
				–20%	+20%	–20%	+20%
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	209	–2.74%	2.74%	–6.49%	6.49%
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	9.12E–06	–0.10%	0.10%	–12.84%	12.84%
Acidification potential of soil and water sources	AP	kg SO_2e	1.26	–2.50%	2.50%	–2.88%	2.88%
Eutrophication potential	EP	kg Ne	0.72	–0.34%	0.34%	–15.76%	15.76%
Formation potential of tropospheric ozone	SFP	kg O_3e	28.4	–3.20%	3.20%	–1.04%	1.04%
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	2,646	–2.71%	2.71%	–5.44%	5.44%
Fossil fuel depletion	FFD	MJ surplus	311	–3.46%	3.46%	–2.79%	2.79%
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	2,263	–0.01%	0.01%	–0.19%	0.19%
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	3,312	–2.33%	2.33%	–6.94%	6.94%

Table 21—Sensitivity analysis results for 20% increase or decrease to baseline results for natural gas and woody biomass use as fuel

Core mandatory indicator	Abbreviation	Unit	Baseline results	Natural gas		Biomass	
				–20%	+20%	–20%	+20%
Global warming potential – TRACI 2.1	GWP_{TRACI}	kg CO_2e	209	–0.91%	0.91%	–1.36%	1.36%
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	9.12E–06	0.00%	0.00%	–2.72%	2.72%
Acidification potential of soil and water sources	AP	kg SO_2e	1.26	–1.29%	1.29%	–2.50%	2.50%
Eutrophication potential	EP	kg Ne	0.72	–0.01%	0.01%	–1.46%	1.46%
Formation potential of tropospheric ozone	SFP	kg O_3e	28.4	–0.14%	0.14%	–3.10%	3.10%
Abiotic depletion potential for fossil resources	ADP fossil	MJ, NCV	2,646	–1.13%	1.13%	–1.37%	1.37%
Fossil fuel depletion	FFD	MJ surplus	311	–1.60%	1.60%	–1.48%	1.48%
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	2,263	0.00%	0.00%	–19.08%	19.08%
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	3,312	–1.00%	1.00%	–1.63%	1.63%

coproduct, or directly to the atmosphere when combusted. Mass flows for biogenic carbon in this study are listed in the LCI and have units of kilograms CO_2. Biogenic carbon indicators appear in Table 22.

Biogenic carbon entering the product system is characterized in the impact assessment with a factor of –1 kg CO_2 equivalent. Combustion of biomass fuel for the boiler during the production stage creates biogenic carbon emissions (CO_2). Per ISO 21930, biogenic carbon exiting the product system as CO_2 emissions has a factor of +1 kg CO_2 equivalent. Therefore, all wood material that contains biogenic carbon must be expressed with a factor of +1 kg CO_2 equivalent when it leaves the system boundary. TRACI is specified as the default method for GWP in ULE PCR. This method, however, does not account for removals or emissions of biogenic CO_2. Therefore, the GWP relative to biogenic carbon was calculated manually and is reported with and without the biogenic CO_2 component for transparency. Results for GWP and biogenic CO_2 are as follows:

- 2,480 kg CO_2eq (A1) were removed in the production of 1.0 m^3 of hardwood PDL, which corresponded to wood in log form entering the system boundary.
- 1 m^3 of hardwood PDL stored 288 kg of carbon or 1.056 kg CO_2eq (576 OD kg/m^3 × 0.5 kg C/1.0 OD kg wood × 44 ÷ 12 = 1,056 kg CO_2eq) which is shown in modules C3/C4.
- Coproducts produced during lumber production accounted for 1,188 kg CO_2eq (A3) for a total "emission" in wood product leaving the system boundary of +1,056 kg CO_2eq.
- In hardwood lumber manufacturing (A3), combusted wood fuel emitted 236 kg CO_2eq.
- Packaging resulted in –1 kg CO_2eq removal and +1 kg CO_2eq emission.

In summary, total removal was –2,480 kg CO_2eq and total "emissions" were 1,424 (1,189 + 236 – 1) kg CO_2eq from cradle to gate (A1–A3) (Table 22). In accordance with ISO 21930, emission from packaging (BCEK) was reported in A5. Emission from the main product was recorded in modules C3/C4. The system boundary for this LCA only included modules A1, A2, and A3.

Discussion

This LCA updates a previous study by Bergman and Bowe (2010). The 2010 study was not required to be in conformance with a PCR (completion of LCIA and other non-LCIA indicators) as this study was, and therefore some direct comparisons are not possible. Table 23 provides a comparison of the volume conversions found for 2005 to 2006 production in the 2010 study to those of this study. The results show comparable conversions for the two. A strong temptation when viewing LCA data is to make comparisons between the product studied and substitute or alternative products. Because the defined boundary here did not include end-of-life scenarios or consider human impacts, it would not be appropriate to do so solely based on our results. If product comparisons are a key consideration, future studies could accomplish this by extending the system boundary presented here. Wood-based products do have positive attributes. In the broadest sense, forests that provide the timber for hardwood lumber sequester (or capture) carbon during their growth. Carbon is then fixed (stored) within that lumber until it is disposed of or combusted for fuel. This provides the basis for the argument that wood is "carbon neutral" when coming from a sustainable forest resource, as U.S. lumber does. Energy consumption is a key consideration for LCA. Table 24 provides a comparison of energy consumption results between the 2010 and 2023 findings. The expanded use of wood-fired boilers and more efficient sawing practices may account for the observed differences. Sawmills in this study used 187 MJ/m^3 less electrical energy than sawmills in 2010. Similarly, a difference of 1,945 MJ/m^3 was found between the earlier study and this one for thermal energy. Mills have opportunities to decrease their fuel use further; however, there are important trade-offs to consider. One avenue to accomplish this would be decreasing MC of the wood below the industry average 70% (dry basis) found in our survey prior to kiln-drying. Care is needed here, however. Current air-drying methods are not practical for many hardwoods, especially those where the color of the wood is important. Poor air-drying techniques can lead to staining of lumber and logs by sapstain fungi. Additional defects such as cracks and checks can also arise when the drying conditions are inconsistent and not controlled. Nevertheless, the bulk of energy use at the sawmill is currently attributed to kiln-drying lumber. The sawmill industry continues to adopt wood-fueled boilers into their operations. The potential benefits of this are twofold. First, boilers dependent on

Table 22—Biogenic carbon inventory indicators

Additional inventory parameters	Abbreviation	Unit	Total	A1	A2	A3	A5	C3/C4
Biogenic carbon removal from product	BCRP	kg CO_2	–2,479.64	–2,480	—	—	—	—
Biogenic carbon emission from product	BCEP	kg CO_2	2,243.95	—	—	1,189	—	1,056
Biogenic carbon removal from packaging	BCRK	kg CO_2	–0.95	—	—	–1	—	—
Biogenic carbon emission from packaging	BCEK	kg CO_2	0.95	—	—	—	1	—
Biogenic carbon emission from combustion of waste from renewable sources used in production	BCEW	kg CO_2	235.69	—	—	236	—	—

Table 23—Volume conversion comparison of incoming logs to 1.0 m^3 of planed dried lumber for 2010 and 2023 hardwood lumber production studies

	Wood volume (m^3 per 1.0 m^3) 2010[a]	Wood volume (m^3 per 1.0 m^3) 2023
Raw wood material		
Incoming green log	2.44	2.60
Rough green lumber	1.45	1.30
Rough dried lumber	1.27	1.16
Final product		
Planed dried lumber	1.00	1.00

[a]Hardwood lumber life-cycle inventory by Bergman and Bowe (2010) reports 2005–2006 production statistics.

Table 24—Comparison of overall energy consumption for hardwood lumber in 2010[a] and 2023 life-cycle analysis studies

	Electrical energy (MJ per m^3)	Thermal energy (MJ per m^3)
Hardwood lumber 2010	598	4,678
Hardwood lumber 2023	411	2,733

[a]2010 data from Bergman and Bowe (2010, 2012).

wood fuel to operate provide an outlet for mill residues such as sawdust, bark, chips, and shavings. Second, the energy generated on-site necessarily decreases the mill's dependence on alternate nonrenewable fossil fuels, which in turn saves money and, as seen in this study, lowers emissions, particularly to air. Another consideration would be upgrades to aging equipment including kiln-drying systems (Bergman 2021). Mills are concerned with staying profitable, but feasibility studies to determine payback periods on kiln upgrades should be considered. In the same vein, computer-aided sawing provided by scanning and optimizing technology and decreased saw kerfs could both decrease errors introduced by manual sawing and increase mill efficiency. Because scanning and optimizing technology has improved in the past decade, mills may do well to see how these systems could benefit their specific manufacturing processes. This analysis did not capture data on the adoption of these technologies, but future studies would benefit from doing so.

Conclusions and Recommendations

This study conducted a rigorous cradle-to-gate LCA for hardwood PDL production in the SE United States. The primary objective was to create LCI data and impact assessment results for hardwood PDL that could be used to develop EPDs in accordance with ULE PCR. In addition to the impact assessment results, the LCI flows were also provided. The LCI flows provide the resource use inventory elements and waste flows as required by the PCR to be included in the EPD. This cradle-to-gate LCA included the necessary scope to develop a "business-to-business" EPD in accordance with ULE PCR.

To go from cradle-to-gate, the study was dependent on using previous LCI for the hardwood forest resource developed from many sources. Primary data for the hardwood manufacturing LCI were collected via a survey questionnaire mailed to hardwood lumber producers in the region of interest. Results of the survey are assumed to be representative of the region, and responses provided an opportunity to weight-average data for raw materials use, energy sources and consumption, and in some cases, emissions to air, land, and water. In the LCI, hardwood lumber manufacturing (A3) emissions were higher than those from raw material extraction (A1) . Most impacts of note in the hardwood lumber manufacturing process were associated with the drying of that lumber from an initial MC of 70% (dry basis) to a final MC of 8% (OD basis). Airborne emissions are most prevalent at the boiler and kilns. Boiler operations used electrostatic precipitators for emission control. Not surprisingly, the use of electrical energy is highest in the sawmill for the operation of sawing equipment. Advances in optimizing equipment may help lower this burden in the future. In terms of total energy consumed, hardwood lumber manufacturing (A3) was the largest of the modules examined, largely due to the drying that occurs in that module. Hardwood lumber producers are able to off-set some purchased energy requirements by combusting wood residues that result from their production processes. Additional energy savings could be realized if more effective methods of air-drying could be realized without the threat of stain and other defects. Although the overall environmental impacts may seem relatively small compared with other resource-dependent products, it was not appropriate in this study to make direct product comparisons or environmental performance claims. By following the protocols set forth in the PCR, the data presented here can help inform future EPDs.

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Appendix 1—Survey for Southeastern Hardwood Lumber Production

Hardwood Lumber Life Cycle Analysis Project

Thank you for working on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be a good marketing tool for the U.S. hardwood industry. A growing demand for building projects that use environmentally friendly and energy-efficient materials has spurred a green building movement in the construction industry.

The final report will describe a cradle-to-gate analysis of hardwood lumber production. Our focus is on overall mill information because this data is vital for precise and accurate results. Details are important, so I encourage you to call with specific questions. We realize you may not have all the information requested but please provide a response for each item indicated. If you do not have an answer for a particular item, please put in a dash (-) so we know you evaluated the question.

Questions are focused on annual production, energy use and generation, material inputs, and environmental emissions **for the reporting year 2017**. **Strict confidentiality** will be maintained for all companies that supply data for this project. Please complete the following questionnaire by **August 1, 2018**.

Questions should be directed to:

Steve Hubbard
2802 Interlaken Pass
Madison, Wisconsin, 53719
Email: hfsllc@zoho.com
Phone: 608-445-1477

Please fill in the following: (All responses are confidential)

Company Name: ______________________________

Mill Address: ______________________________

Contact Person: ______________________________

Position/Title: ______________________________

Telephone: ____________________ Email of Contact Person: __________________

Please fill in the following:

Reporting Year: 2017	Starting Month:	Ending Month:

General mill information (Check all that apply):

Mill type (Check all that apply; indicate what your primary production is):

- ❑ Green lumber mill
- ❑ Dry lumber mill
- ❑ Cant / tie mill
- ❑ Pallet mill
- ❑ Other (specify)____________________

Log storage:

(Wet) or **(dry) (circle one)**

Average log diameter _______________ inches

Average log length _________________ inches

Rough green lumber production for reporting year___________ thousand board feet (MBF)

Average lumber dimension _________ (Please provide estimate if able)

Percent of annual lumber production that is kiln dried on site _______ % (Starting %MC _____ / Ending %MC _____)

Total log/lumber inputs (Annual production)

Logs: ⟶ ***What type of log scaling is used?***____________________

Volume of incoming logs ________________ thousand BF (MBF)

Volume of logs that are sorted and sold ________________ thousand BF (MBF)

Volume of logs processed at the sawmill (on-site) ________________ thousand BF (MBF)

Rough Green Lumber:

Volume of green lumber produced (on-site/your mill) ________________thousand BF (MBF)

Volume of green lumber purchased from outside firms______________ thousand BF (MBF)

Volume of green lumber sold _________________thousand BF (MBF)

Volume of green lumber from pre-dryers _________________thousand BF (MBF)

Volume of green lumber that is kiln-dried on-site _________________thousand BF (MBF)

Rough Dry Lumber:

Volume of rough dry lumber produced at your sawmill_____________ thousand BF (MBF)

Volume of rough dry lumber purchased from outside firms _________ thousand BF (MBF)

Volume of rough dry lumber sold to outside firms ______________ thousand BF (MBF)

Volume of rough dry lumber that goes to your planer ______________ thousand BF (MBF)

Planed Dry Lumber:

Volume of dry planed lumber produced _________________ thousand BF (MBF)

Volume of dry planed lumber purchased _________________ thousand BF (MBF)

Volume of dry planed lumber sold _________________ thousand BF (MBF)

Volume of dry planed lumber used internally (on-site) ______________ thousand BF (MBF)

Please complete the following table for the breakdown of individual tree species and approximate sizes processed by your mill (by species) or the average log diameter. If a species used is less than 2% of the total, use the category labeled "Other".

Species	% of Total Log Input into Sawmill	Average Log Diameter (in)
Total	**100%**	

Total transportation fuel use on-site

Fuel Type	Units
On-road diesel	Gallons
Off-road diesel	Gallons
Fuel Oil #6	Gallons
Propane	Gallons
Gasoline	Gallons
Other(s)	

Consider/include all sources of energy such as fuels for yard equipment, forklifts, and carriers

Total (non-transportation) fuel use

Wood:

On-site wood used for boiler fuel ________________MBF ________% MC tons

Wood purchased for boiler fuel ________________MBF ________% MC tons

Fossil Fuel:

Natural Gas ____________________________ thousand cubic feet (ft^3)

Fuel oil #1 (kerosene) ____________________________ gallons

Fuel oil #2 (heating oil) ____________________________ gallons

Fuel oil #6 ____________________________ gallons

Propane ____________________________ gallons

Electricity for entire facility ____________________________ kilowatt-hours (kWh)

Other ____________________________

Water use

Ground water ______________ gallons or ft^3 _________%recycled

Surface water ______________ gallons or ft^3 _________%recycled

Wood co-product/by-product output

For each co-product and by-product, please indicate the total production (last column) for the reporting period along with material sold (shipped) to other users, used internally (either as fuel or other uses), landfilled, or inventoried for future use. Select whatever category best fits your mill's situation. If zero, enter a dash (-). Please state units if other than tons like cubic yards.

Co-products and By-Products	Moisture Content (wet basis)	Sold (Shipped)	Used Internally (as fuel)	Used Internally (other uses)	Landfilled	Inventory	Total
	(%)	tons	tons	tons	tons	tons	tons
Chips, green							
Sawdust, green							
Bark, green							
Edging strips, green							
Sawdust, dry							
Shavings, dry							
Hogged material							
Other							

Total log transportation by trucks

Logging trucks:

_____________ Number of trips per year

_____________ Total hauling distance

_____________ % of trucks that travel one-way _____________ % of trucks empty on backhaul

_____________ Average round-trip (miles)

_____________ % of trucking that is contracted

Total log transportation by rail

Trains:

_____________ Number of trips per year

_____________ Total hauling distance (miles)

Cogeneration production output at your sawmill (If your facility has this):

Electricity (kW or MW)	Process heat (BTU/hr)	Fuel type	% used or sold off site	
			Electricity	**Process heat**

Annual air emissions: (Attach stack test if available)

Emission Type	Total Quantity	Whole sawmill	Boiler/Co-gen	Units
Dust				Pounds
Total Particulate Matter				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
Lead				Pounds
Ozone (O3)				Pounds
Nitrogen dioxide				Pounds
Others (please list all known):				Pounds

Annual water effluent: (Provide water discharge test if available)

Type	Total Quantity	Percent of total by process (percentage or volume)					Units
		Log Yard	Sawing	Drying	Planing	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

Ancillary materials used (for the reporting year; if unknown please enter a dash (-))

Type	Total Quantity	Units
Hydraulic Fluid		Gallons
Motor Oils		Gallons
Greases		Pounds
Gasoline		Gallons
Steel strapping		Pounds
Plastic strapping		Pounds
Paint		Gallons
Corrugated cardboard		Pounds
Replacement stickers		Pounds
Antifreeze		Gallons
Antistain treatment		Gallons
Corner Protectors		Pounds
Paper Lumber Wrapping		Pounds
Plastic Lumber Wrapping		Pounds
Other		
Other		
Other		

Annual industrial solid waste (material requiring disposal outside of mill)

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

If your facility has emission control devices, please complete the table below. Please list ALL devices. If your facility has more than one of the same device please indicate the total number for that type of device.

1) **For air emissions include devices such as cyclones, bag houses, and electric static precipitators (ESPs)**
2) **For water emissions, explain how runoff or other water discharges from the boiler and mill are controlled (i.e. settling pond, city sewer, septic; annual basis).**

Type of Emission Control Device (cyclone, bag house, esp, etc.)	How Many?	Equipment Controlled	Type of Emissions Controlled (gas, liquid, solid)	Electrical Usage For Device kWh (annual basis)

This concludes the questionnaire!

- **Thank you for your dedicated time and thorough input!**
- **Place this questionnaire and any attachments into the envelope provided, seal, and put into the mail. The postage and return address are already provided on the envelope.**
- **The responses you have provided will be kept in strict confidentiality. Only industry averaged data will be used or made available and results of this study will not identify participating mills unless an individual mill wishes to be acknowledged publicly for their efforts with this project.**

If you have questions regarding this questionnaire or the project please contact:

Steve Hubbard

Phone (608) 445-1477 ● Email: hfsllc@zoho.com

Appendix 2—Follow-Up Questionaire

Hardwood Production Life Cycle Assessment Follow Up Questions

These follow up questions are needed to complete the Life Cycle model we are developing. Your help is greatly appreciated! Please indicate your responses in the spaces provided. If a question is not applicable to your mill, please write N/A in the space provided.

KILN DRYING

Amount of energy that is used per year to operate kilns at your mill _________ Units______

Total kiln drying capacity at your mill ____________MBF

Total number of kilns at your mill __________

EMMISION CONTROLS (Baghouses, Cyclones, Dust Collectors, etc.)

Total amount of electricity used for emission control devices at your mill _________kWh/year

BOILER USE

Boiler #1

___________________(MMBTU/hr.)

__________________(lbs. steam/hr.)

Boiler #1 Horsepower _________(BHP)

Boiler #1 Model/Make ___________

Boiler # 1 Fuel Type ______ for wood fuel please indicate % Moisture Content______

Boiler #2

___________________(MMBTU/hr.)

___________________(lbs. steam/hr.)

Boiler #1 Horsepower ____________(BHP)

Boiler #1 Model/Make ____________

Boiler # 1 Fuel Type ____________ if applicable (e.g. wood) % Moisture Content ____

TRANSPORTATION

Lumber trucks travel _____________ (miles a year)

Average amount that *lumber* trucks travel one way _____________ (miles)