# A Life Cycle Assessment of Hardwood Lumber Production in the Northeast and North Central United States

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## Abbreviations

| | |
|---|---|
| BF | Board Feet |
| CLR | Cubic Lumber Recovery |
| EPDs | Environmental Product Declarations |
| GWP | Global Warming Potential |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LRF | Lumber Recovery Factor |
| $m^3$ | Cubic meter |
| MBF | Thousand Board Feet |
| MMBF | Million Board Feet |
| OD kg | Oven-Dry Weight of Wood in Kilograms |
| PCR | Product Category Rules |
| tkm | Metric Tonne – Kilometers |

## 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 product at a factory gate.

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

**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 from multiple processing centers.

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

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

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

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

**Lumber recovery factor:** The volume of lumber produced measured in the standard measurement of board feet to cubic feet of logs processed.

**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 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).

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## Background

This life cycle assessment is part of a larger project to update the life cycle inventories for major wood products produced in the United States (U.S.) on a five-year cycle. Hardwood lumber manufacturing data were collected for the 2017 production year from sawmills operating in the northeast and north central regions (NE/NC) of the U.S.

A life cycle inventory (LCI) of hardwood lumber production in this region was conducted for the production year 2005 (Bergman and Bowe 2008a). The updated LCI data collected for this study were used to conduct a life cycle impact assessment (LCIA) using the North American impact method, TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare 2011). This work provides information necessary for subsequent environmental product declarations (EPDs). As such, this report follows the requirements outlined in Product Category Rules (PCR) for North American Structural and Architectural Wood Products (ULE 2019) and American Center for Life Cycle Assessment (2019). The report builds on previous studies (Bergman and Bowe 2008b, Puettmann et al. 2010) and reports LCIA results for mass allocation to produce 1.0 $m^3$ of planed, kiln-dry, hardwood lumber.

# 1 Goal and Scope

The goal of this study was to document the energy and material inputs, outputs, and emissions associated with the manufacturing of hardwood lumber in the NE/NC U.S. In 2018, a survey questionnaire was mailed to sawmills in these regions to collect data consistent with the methodology and guidelines of the Consortium for Research on Renewable Industrial Materials (CORRIM), International Organization for Standardization (ISO) protocols (ISO 2006), and the PCR for North American Structural and Architectural Wood Products (ULE 2019).

The scope of this study is 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 are considered. Hardwood forest resource data for this system boundary was obtained from USLCI database (DATASMART 2019). This report does not make substitute product comparisons, consider use by consumers, or examine the end of life scenarios.

## 1.1 Goals and Objectives

### 1.1.1 Goals

The goals of this study were twofold: (1) document the energy and material inputs, outputs, and emissions associated with the manufacturing of hardwood lumber in the NE/NC U.S., and (2) provide a platform for Environmental Product Declarations (EPD's) by collecting data consistent with the methodology and guidelines of CORRIM, ISO protocols (ISO 2006), and PCR for North American Structural and Architectural Wood Products (ULE 2019).

### 1.1.2 Intended Audience

The intended audience for this report includes hardwood lumber manufacturers, LCA practitioners, The Hardwood Manufacturers Association, and The American Hardwood Export Council.

### 1.1.3 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 of this study to include end of life phases consistent with the ISO 14040/44:2006 (ISO 2006) guidelines and principles and compliance with the PCR (ULE 2019).

## 1.2 Scope of Considered System

### 1.2.1 Functional and Declared Unit

In accordance with the ULE (2019) PCR, the declared unit of this study is one cubic meter (1.0 $m^3$) of packaged and planed kiln-dry hardwood lumber produced in the NE/NC U.S. Where 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). Because the analysis in this study does not follow the declared unit to installation in a building product, no service life is assigned. Collected data were entered into a commercial spreadsheet and weight averaged based on an individual sawmill's contribution for a given criterion to total production for that criterion. All inputs and emissions data were then harmonized relative to 1.0 $m^3$ (the declared unit) of packaged and planed kiln-dry hardwood lumber.

### 1.2.2 System Boundary

The system boundary for the declared unit is shown in Figure 1. The system boundary begins with the initiation, growth, and harvest of trees in the NE/NC U.S., as well as purchased rough green hardwood lumber from outside suppliers, and ends with planed, kiln-dry, hardwood lumber packaged to leave the sawmill gate. The production stage for hardwood lumber includes three modules. These are ($A_1$) resource extraction, ($A_2$) transportation of all materials and resources, and ($A_3$) hardwood lumber manufacturing.

Resource extraction ($A_1$) includes forest initiation (site preparation), forest management (periodic thinnings), and the harvesting of timber (tree felling, log bucking, and transportation of logs to decks). Equipment used in the resource extraction module includes chain saws, mechanized harvesters, and skidders. This equipment relies primarily on diesel fuel and lesser amounts of gasoline. The maintenance and repair of equipment as well as log road construction were not considered. Also included are the impacts associated with the manufacturing of rough green lumber that is produced by outside firms and purchased for value adding by sawmills in this study.

Transportation of logs from the forest and purchased rough green lumber from outside suppliers to the mill ($A_2$) was captured.

Hardwood lumber manufacturing, module ($A_3$), was modeled as a series of unit processes, log yard, sawing, kiln-drying, planing (including packaging the final product for distribution), and energy use and generation with an industrial boiler. Outputs to the system boundary include 1.0 $m^3$ of planed, kiln-dry, hardwood lumber packaged and ready for shipping as well as emissions to air, land, and water. Co-products produced in the unit processes are not tracked beyond the system boundary. This consideration ensured that co-products 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.

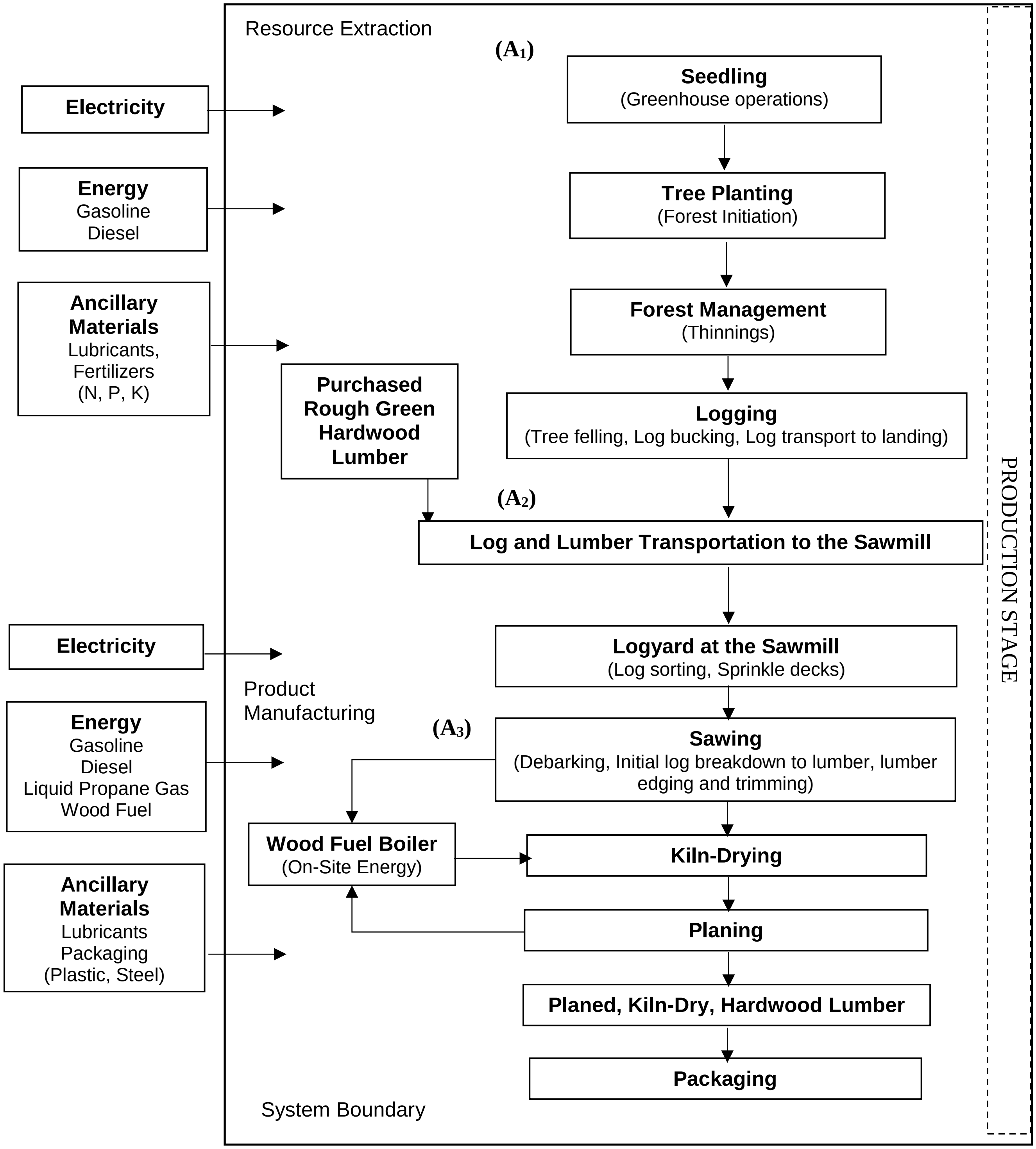


**Figure 1: System boundary for the cradle-to-gate production of hardwood lumber in the NE/NC region of the United States.**

Parameters considered for the system boundary in this study are summarized in Table 1.

**Table 1: Inclusions and exclusions for the system boundary of NE/NC hardwood lumber production**

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

### 1.2.3 Allocation Rules

Because co-products 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).

### 1.2.4 Cut-off Rules

According to the ULE (2019) PCR, if the mass/energy of a flow is less than 1% of the cumulative mass/energy of the model flow, it may be excluded. This assumes the environmental importance of the flow is not significant. The analysis for planed, kiln-dry, hardwood lumber in this study includes all energy and mass flows for the primary data. No cut-offs were used in the impact assessment.

### 1.2.5 Data Collection

A survey instrument was constructed by updating a previous version used by Bergman and Bowe (2008b). Sawmills located in the NE/NC U.S. (Figure 2) were identified by the Hardwood Manufacturers Association, were mailed hardcopies of the survey, and were invited to participate in the study.


**Figure 2: Northeast and north central hardwood lumber region in the United States.**

Survey questions were designed for the collection of detailed production data for each mill. The survey is included in Appendix 1. Six mills responded, providing input and output data for the assessment. This study utilized secondary data to supplement the primary data collected in the survey of the on-site lumber manufacturing production process. The hardwood resource model and other secondary process data was taken from DATASMART (2019) and is described in section 5.4 of this report. A wood boiler LCI was provided by Puettmann and Milota (2017).

### 1.2.6 Calculation Rules

Mills reported incoming logs in thousands of board feet (MBF), and the log moisture content (MC) was recorded. In addition, the species mix used at each mill was obtained. The log volumes were converted to cubic meters ($m^3$). Densities for each species were calculated by averaging specific gravities for the reported MC as found in *Hardwoods of North America* (Alden 1995).

Where 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 based on the production of 1.0 $m^3$ of planed dry lumber.

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

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

Where $\overline{P}$ 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 8.5+ (Pré Consultants 2017) was used as the LCA modeling tool to track all materials and report the LCIA results.

# 2 Description of Industry

## 2.1 Categories of Products and Co-products

The primary product from NE/NC sawmills is hardwood lumber. Additional co-products are made in the breakdown of logs into lumber and in the lumber planing process. Co-products included green bark (for landscaping mulch and boiler fuel), green chips (for boiler fuel and sold), dry sawdust (for animal bedding, boiler fuel, and value-added furnish for composite products), and dry shavings (sold and for boiler fuel). Hog fuel for boilers is also produced. Hog fuel in this study was defined as a combination of wood residues from multiple processing centers and includes bark.

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

There are nearly 800 hardwood lumber producers in the United States with most producing less than 1 million BF. Producers in the western and southeast/south central (SE/SC) U.S. are not considered in this study. Most U.S. hardwood lumber production is split between the NE/NC region and the SE/SC region because of the physical location of the hardwood resources found there. In 2017, the total annual production of hardwood lumber in the United States was 8.3 billion BF (Howard and Liang 2019). When the southern and western regions are removed, total hardwood lumber production for the northern regions was 4.8 billion BF in that same year. In the NE/NC region, there are 90 large-size facilities that can, or do, produce about 60% of the region's annual production (estimated), and about 30% of these facilities produce, or are capable of producing, between 25 and 50 million BF annually (Luppold 2017). The data collected in this study represents roughly 2% of the total regional production for the NE/NC region in the 2017 calendar year.

## 2.3 Location of Markets and Typical Transportation Methods

Hardwood lumber produced in the NE/NC region of the U.S. is sold both domestically and in global markets for furnish in value-added products including hardwood flooring, wooden pallets, furniture, railroad ties, moulding, 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 U.S. is primarily conducted by over the road trucking and 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.

## 2.4 Plant Types, Age, Efficiencies, and Geographical Distribution

Most sawmills in the NE/NC region (Figure 2) have been in operation for many years. Sawmills in this study were located in Indiana (2 mills), Wisconsin, Pennsylvania (2 mills), and Iowa. 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 made additional investments in technology to remain competitive. Where new technology has been employed, most occurs in the sawing process with optimization systems. In addition, upgrades to dry kilns have increased during the past decade. The majority of sawmills remain relatively unchanged 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 (2008b).

## 2.5 Conversion Efficiencies

A lumber recovery factor (LRF) is obtained by determining the BF of lumber produced per cubic feet of log inputs. The breakdown of logs into rough green lumber during sawing in this study had a weighted average LRF of 5.99 BF of rough green lumber per cubic foot of logs. In the NE/NC region of the U.S., 2.23 $m^3$ of logs are sawn, dried, and planed to a final product of 1.0 $m^3$ of planed dry lumber. The resulting total volume conversion for incoming logs to final lumber product is therefore 44.4%. This is consistent with a previous LCI study for this region by Bergman and Bowe (20008b) Shrinkage during the drying process accounts for the difference between total volume and total mass conversion (Bergman and Bowe 2008b).

A mass balance for this study is shown in Table 2 for the tracking of materials flow through the unit processes identified.

**Table 2: Mass balance for material flows across the five unit processes**

| Materials | Log yard (OD kg/m$^3$) | | Sawing (OD kg/m$^3$) | | Boiler (OD kg/m$^3$) | Drying (OD kg/m$^3$) | | Planing (OD kg/m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | In | Out | In | Out | In | In | Out | In | Out |
| Green logs | 1,164.54 | 1,164.54 | 1,164.54 | | | | | | |
| Green bark | | | | 130.98 | | | | | |
| Rough green lumber, manufactured | | | | 691.51 | | 691.51 | | | |
| Rough green lumber purchased* | | | | | | 22.49 | | | |
| Green co-products, fuel | | | | 173.55 | 173.55 | | | | |
| Green co-products, sold | | | | 168.50 | | | | | |
| Rough oven-dry lumber, produced | | | | | | | 714.00 | 714.00 | |
| Planed dry lumber, produced | | | | | | | | | 572.36 |
| Dry co-products, fuel | | | | | 6.10 | | | | 6.10 |
| Dry co-products, sold | | | | | | | | | 124.16 |
| Wood residue unaccounted for | | | | | | | | | 11.38 |
| **TOTAL** | 1,164.54 | 1,164.54 | 1,164.54 | 1,164.54 | 179.65 | 714.00 | 714.00 | 714.00 | 714.00 |

The mass balance reveals that 1,164.54 kg oven-dry (OD) basis of incoming logs produced 1.0 m$^3$ of planed dry hardwood lumber. The sawing unit process produced 691.5 OD kg of rough green lumber with an additional 22.49 OD kg of rough green lumber added from regional suppliers for a total of 714 OD kg destined to the drying process. There was no change in mass after kiln-drying, but planing reduced the final product mass to 572.36 OD kg per 1.0 m$^3$ planed dry lumber. The conversion of incoming logs to 1.0 m$^3$ of planed dry lumber is shown in Table 3.

**Table 3: Conversion of incoming logs to 1.0 m$^3$ of planed dry lumber**

| | Wood Volume (actual dimensions)[1] | |
|---|---|---|
| | (m$^3$ per 1.0 m$^3$ ) | Conversion (actual m$^3$/nominal) (MBF) |
| Raw Wood Material | | |
| Incoming green log | 2.23 | -- |
| Rough green lumber | 1.35 | 2.27 |
| Rough dried lumber | 1.25 | 2.10 |
| Final Product | | |
| Planed dried lumber | 1.00 | 1.68 |

[1] All values provided in actual dimensions

## 2.6 Typical Emission Control Measures by Plant Type

Control of emissions/pollutants in the log yard is limited to sprinkler and misting systems, which are also used to control sap-staining fungi. Bag houses or cyclones (or both) are used to control emissions in the sawing process, particularly at the chop saw and edging operations. No emission control devices are used at the kilns. The planar process uses cyclones or bag houses. Control of emissions from the boiler is achieved with electrostatic precipitators.

## 2.7 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 contribute most of the nitrogen oxides and sulfur dioxide emissions. Mills did not report emissions to water in this study. Roughly 6% of the water used at the mill gets recycled.

For waste going to the landfill, sawmills reported ash from the wood boilers and lesser materials, such as general refuse, in addition to 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 in agricultural applications to fields. Other metals, oils, and plastics are sent to recycling streams.

# 3 Description of Product

## 3.1 Dimensions

Unlike structural lumber, hardwood lumber 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. 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 moisture content 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 BF, the unit of commerce for lumber. One BF is a piece of wood 1 in. by 12 in. by 12 in. (nominal).

The standard for planing 4/4 (1-in. thick) dry lumber is 20.6 mm (0.8125 in.). A portion of some lumber is skip planed from 25.4 to 23.8 mm (1 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 U.S., hardwood lumber volumes are reported in units of BF, as with softwood lumber. In this study, the conversions of 2.27, 2.10, and 1.68 thousand BF/$m^3$ for rough green, rough dry, and planed dry lumber, respectively, were used (Bergman and Bowe 2008b; Bergman 2010).

## 3.2 Wood Species

Eleven tree species were utilized for hardwood lumber production in the NE/NC U.S. For each species, its percentage contribution to the total of all species used is shown in Table 4. 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 each species' specific density. The manual *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, red oak (*Quercus rubra*) has nine species listed within one species group while ash (*Fraxinus* spp.) has three. For instances where a species fell into a broader species group, the average density of that group was calculated. Weighted average green specific gravity, oven-dry specific gravity, and 8% MC specific gravity were 0.52, 0.61, and 0.572, respectively.

**Table 4**: **Species composition and calculated wood densities for hardwood lumber production in the NE/NC region of the United States.**

| Common Name | Scientific Name | Percentage of Total | Green Specific Gravity | OD Specific Gravity | KD Lumber Specific Gravity[1] |
|---|---|---|---|---|---|
| Red oak | *Quercus rubra* | 20 | 0.57 | 0.68 | 0.646 |
| White oak | *Quercus alba* | 25 | 0.60 | 0.72 | 0.673 |
| Hard maple | *Acer saccharinum* | 13 | 0.54 | 0.65 | 0.540 |
| Soft maple | *Acer saccharum* | 4 | 0.47 | 0.53 | 0.465 |
| Black walnut | *Juglans nigra* | 7 | 0.51 | 0.56 | 0.550 |
| Hickory | *Carya spp.* | 3 | 0.64 | -- | 0.720 |
| Basswood | *Tilia americana* | 3 | 0.32 | 0.4 | 0.370 |
| Poplar (mix) | *Populus spp.* | 5 | 0.40 | 0.43 | 0.420 |
| Birch (mix) | *Betula spp.* | 0.2 | 0.51 | 0.63 | 0.585 |
| Ash (mix) | *Fraxinus spp.* | 13 | 0.51 | 0.56 | 0.550 |
| Black cherry | *Prunus serotina* | 5 | 0.47 | 0.53 | 0.500 |
| Miscellaneous | -- | 3 | 0.53 | 0.57 | 0.550 |
| Weighted average | -- | -- | 0.52 | 0.61 | 0.572 |

**[1]At 8% Moisture Content**

## 3.3 Moisture Content

Moisture content is an important consideration since 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 moisture content was observed in this study. Hardwood lumber was kiln-dried to a final moisture content of 8% on a dry basis. For this report, the following equations were used to calculate moisture contents and to aid in wood density calculations:

**Equation 1: Percent moisture content on a dry basis**

$$\textbf{Percent Moisture Content}\ (\textbf{dry basis}) = \frac{\textbf{Weight of Water in Wood}}{\textbf{Weight of Oven Dry Wood}}\ \textbf{X 100}$$

**Equation 2: Percent moisture content on a wet basis**

$$\textbf{Percent Moisture Content}\ (\textbf{wet basis}) = \frac{\textbf{Weight of Water in Wood}}{\textbf{Weight of Wet Wood}}\ \textbf{X 100}$$

**Equation 3: Oven-dry weight**

$$\textbf{Weight Oven Dry} = \textbf{Green Weight X}\ (\mathbf{1} - \textbf{MC\% Wet Basis})$$

## 3.4 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 planed dry hardwood lumber is shown in Figure 3.

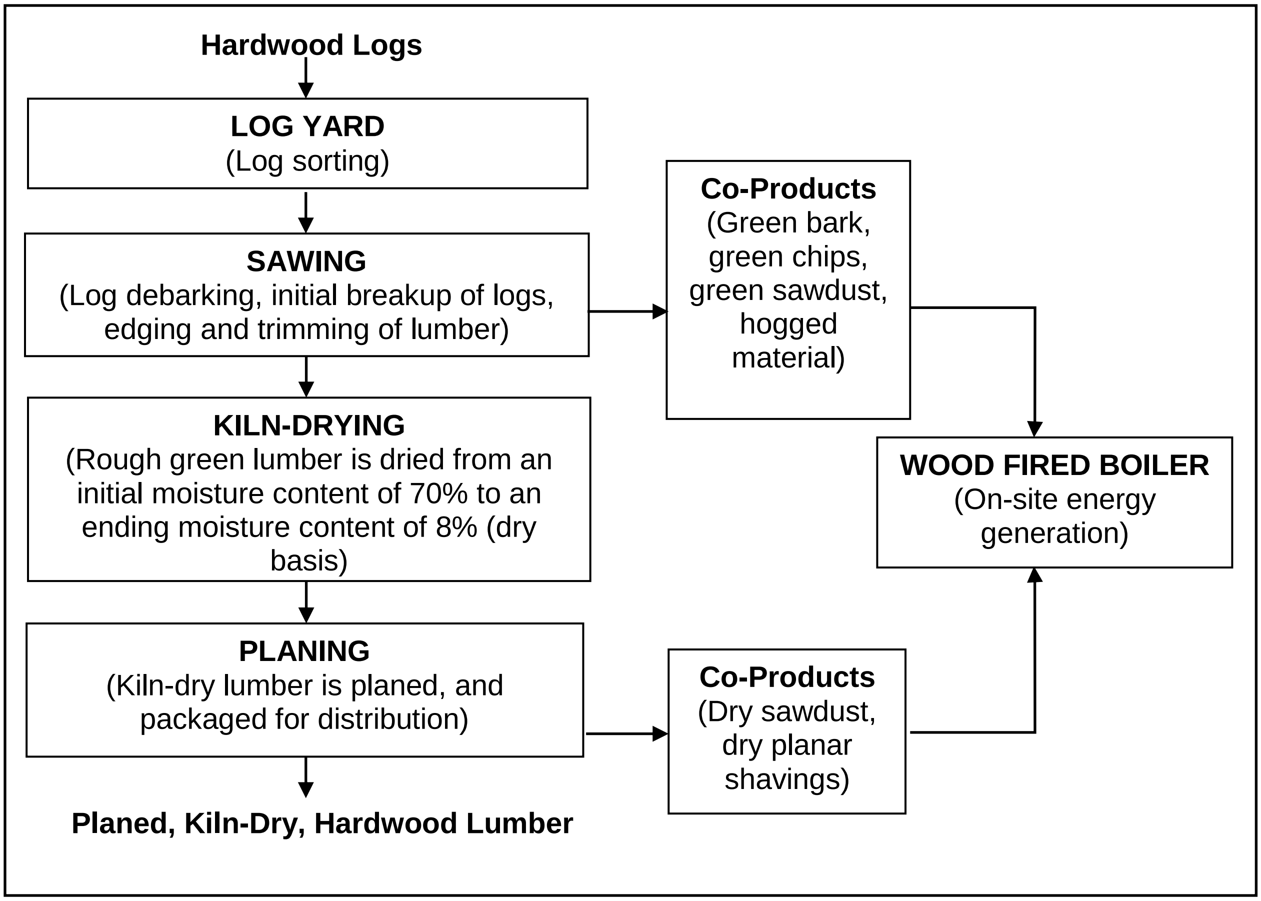


**Figure 3: Process flow diagram for the production of planed, kiln-dry hardwood lumber.**

# 4 Life Cycle Inventory Analysis

The LCI results for the unit process flows to produce 1.0 $m^3$ of planed, kiln-dry, hardwood lumber follow. The LCI was based on materials flow and production data for 2017. There were no gaps in data. The analysis presented here examines the inputs and emissions to air, land, and water for the three modules discussed in section 2.2.2.

## 4.1 $A_1$ – Resource 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 thinnings and finally 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. After hardwood forests are established, they typically undergo periodic commercial thinnings to promote vigor in higher quality trees. Both thinning operations and final harvesting of timber employ felling and hauling equipment including chainsaws, mechanized harvesters, skidders, and log trucks. Fuels and lubricants to operate this equipment are 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 natural processes and are not considered in the system boundary of this study.

NE/NC hardwood forest resource LCI data were developed from various data sources (Oneil et al. 2010; ASMI 2012; Bergman 2015a, 2015b). For NE/NC hardwood forests, reforestation occurs with natural regeneration, which does 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.

Mills in this study reported that they purchase varying amounts of rough green lumber to supplement their own hardwood lumber production. The weighted average amount of purchased rough green lumber was 0.03 $m^3$ (22.49 kg) per 1.0 $m^3$ of planed dry hardwood lumber, a slight portion. 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 section 5.4.

## 4.2 $A_2$ – Transport of Raw Materials from Extraction Sites

The transport of logs from forest landings and purchased rough green lumber from outside suppliers is done 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.

## 4.3 $A_3$ – Product Manufacturing

### 4.4.1 Unit Processes

The system boundary for this study considered five unit processes in the production of planed dry hardwood lumber. These were log yard, sawing, drying, planing, and energy generation with an industrial wood boiler. Each process is detailed next.

### 4.4.2 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 for hardwood-using mills 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 loaders and forwarders. 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 5.

**Table 5: Inputs and outputs of the log yard unit process for production of 1 $m^3$ of roundwood hardwood sawlogs in the NE/NC region**

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| **Products** | | | |
| Roundwood sawlogs, hardwood, green, at log yard, $m^3$, NE/NC US | 1.00 | $m^3$ | 100 |
| **Materials/fuels** | | | |
| Roundwood, hardwood, average, at forest road, NE-NC/RNA | 1.00 | $m^3$ | -- |
| Transport, combination truck, diesel-powered NREL/US U | 116.68 | tkm | -- |
| Transport, combination truck, diesel-powered NREL/US U* | 14.79 | tkm | -- |
| Diesel, combusted in industrial equipment NREL/US U | 1.22 | L | -- |
| Gasoline, combusted in equipment NREL/US U | 0.14 | L | -- |

*Reflects transportation of the bark that comes in on the log

#### 4.4.3 Sawing

The sawing unit process breaks logs down into rough green lumber. The most common hardwood lumber dimensions are 25.4-mm (1.0-in.) thick random width 2.44-m (8-ft) lengths. Sawing uses the most electrical consumption across all other 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 fork trucks (forklifts). Stationary saws, stackers, and sorters depend on electricity for their operation while fork trucks use diesel or liquid propane gas (LPG). The outputs associated with the sawing process include rough green lumber ready for sale or kiln-drying, green bark, green chips, green sawdust, and green hogged material (edgings and trimmings). Table 6 lists the inputs and outputs for the sawing process.

**Table 6: Inputs and outputs for the sawing unit process for the production of 1 m$^3$ of rough green hardwood lumber in the NE/NC region**

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| **Products** | | | |
| Sawn lumber, hardwood, rough, green, m$^3$, NENC-US | 1.00 | m$^3$ | 59.38 |
| Bark, hardwood, green, kg, NENC-US | 98.49 | kg | 11.25 |
| Green co-products, hardwood, fuel, kg, NENC-US | 130.50 | kg | 14.90 |
| Green co-products, hardwood, sold, kg, NENC-US | 126.71 | kg | 14.47 |
| **Materials/fuels** | | | |
| Roundwood at mill, kg, hardwood, NE/NC, USA, U | 1.68 | m$^3$ | -- |
| Gasoline, combusted in equipment NREL/US U | 0.58 | L | -- |
| Diesel, combusted in industrial equipment NREL/US U | 4.64 | L | -- |
| Water, well, in ground, US-EI 2.2 | 8.70 | L | -- |
| Process-specific burdens, sanitary landfill/CH U, US-EI 2.2 | 0.44 | kg | -- |
| **Electricity/heat** | | | |
| Electricity, low voltage {NPCC, US only}\| market for cut off, U | 67.02 | kWh | -- |

#### 4.4.4 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 energy reductions, 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 lumbers 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 moisture content ($MC_i$) of 70% (OD basis) to a final moisture content ($MC_f$) 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 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 et al. 2000). 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 forklifts for loading and unloading the kilns. Energy used is diesel, gasoline, and LPG for forklifts; electricity for kiln controls, motors, and lighting; and wood fuel in industrial boilers for process heat. Energy for kiln operation is derived from fossil fuels and industrial wood boilers as described in Section 5.4.6. Kiln-drying produces the bulk of volatile organic compounds (VOCs) 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 7.

**Table 7: Inputs and outputs for the drying unit process of 1 $m^3$ of rough dry hardwood lumber in the NE/NC region**

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| **Products** | | | |
| Sawn lumber, hardwood, rough, dry, $m^3$, NENC-US | 1.00 | $m^3$ | 100 |
| **Materials/fuels** | | | |
| Sawn lumber, hardwood, rough, green, $m^3$, NENC-US | 1.04 | $m^3$ | -- |
| Sawn lumber, purchased, hardwood, rough, green, $m^3$, NENC-US[1] | 0.03 | $m^3$ | -- |
| Gasoline, combusted in equipment NREL/US U | 0.12 | L | -- |
| Diesel, combusted in industrial equipment NREL/US U | 0.99 | L | -- |
| Liquefied petroleum gas combusted in industrial boiler NREL/US U | 0.05 | L | -- |
| **Electricity/heat** | | | |
| Electricity, low voltage {NPCC, US only}\| market for \| Cut-off, U | 26.16 | kWh | -- |
| Heat from CORRIM wood boiler | 3,754.60 | MJ | -- |
| Natural gas, combusted in industrial boiler NREL/US U | 22.3 | $m^3$ | |
| **Emissions to air** | | | |
| VOC, volatile organic compounds | 0.06 | kg | -- |

[1] Sawn lumber, purchased, hardwood, rough, green, $m^3$, NENC-US uses the lumber manufacturing process in this study as a proxy for supplier production.

### 4.4.5 Wood Boiler

On-site energy production is captured in the boiler unit process. Sawmills utilize 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 boilers. Respondents in our study reported that a small fraction of dry planar shavings (6.10 OD kg) are used for fuel. Sawmills in this study did not purchase wood for their boilers. Instead they 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 8). Thermal energy produced by the boiler generating steam is used in the kiln-drying process for indirect heated kilns. The total heat energy used in the kiln-drying process was 4,523.90 MJ/$m^3$ rough dry hardwood lumber (heat from CORRIM wood boiler = 3,754.6 MJ/$m^3$ rough dry lumber and natural gas 769.3 MJ/$m^3$ rough dry lumber). This study made use of a wood boiler process developed by Puettmann and Milota (2017).

**Table 8: Inputs and outputs for the wood boiler process per 1.0 OD kg wood fuel**

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| **Products** | | | |
| Heat from CORRIM wood boiler, MJ | 20.9 | MJ | 100 |
| CORRIM wood ash, at boiler, at mill, kg | 1.91E-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/fuels** | | | |
| Green co-products, hardwood, fuel, kg, NENC-US | 0.97 | kg | -- |
| Dry co-products, hardwood, fuel, kg, NENC-US | 0.03 | 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 | -- |
| **Electricity/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 | -- |
| **Emissions to air** | | | |
| 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 | -- |

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| 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 | -- |
| VOC, volatile organic compounds | 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 | -- |
| BOD5, biological oxygen demand | 2.10E-06 | kg | -- |

### 4.4.6 Planing

The final stage of product manufacturing in this study is the planing unit process. The process begins with stickered, rough kiln-dried lumber, which is then unstacked and unstickered and fed through planers. Planers consist of varying configurations of rotating knives that shave the wood to uniform thicknesses and remove sawing blemishes. While the standard for planing is 20.6 mm (0.8125 in.) for 1.0 in. (4/4) hardwood lumber, a portion of the lumber is only skip planed, generally from 25.4 to 23.8 mm (1 to 0.9375 in.). Once planed, the surfaced lumber is packaged using steel or plastic bands and, in some cases, plastic wrapping and corner protectors. In addition to the planer machinery, conveyers and forklifts are used to transport the material. Primary fuels are electricity, diesel, and LPG. Wood dust was controlled using baghouses, cyclones, or a combination of the two. A small portion of the dry sawdust was sent to on-site wood 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. Co-products included sawdust and planar shavings. The inputs and outputs for the planing process are in Table 9. Packaging materials are listed in Table 10.

**Table 9: Inputs and outputs for the planing unit process**

| Inputs and Outputs | Value | Units | Allocation (%) |
|---|---|---|---|
| **Products** | | | |
| Sawn lumber, hardwood, planed, dry, $m^3$, NENC-US | 1.00 | $m^3$ | 80.00 |
| Dry co-products, hardwood, fuel, kg, NENC-US* | 6.10 | kg | 0.85 |
| Dry co-products, hardwood, sold, kg, NENC-US** | 124.16 | kg | 19.15 |
| **Materials/fuels** | | | |
| Sawn lumber, hardwood, rough, dry, $m^3$, NENC-US | 1.25 | $m^3$ | -- |
| Natural gas, combusted in industrial boiler NREL/US | 0.068 | L | |
| Gasoline, combusted in equipment NREL/US U | 0.15 | L | -- |
| Diesel, combusted in industrial equipment NREL/US U | 1.24 | L | -- |
| **Electricity/heat** | | | |
| Electricity, low voltage {NPCC, US only}\| market for \| cut-off, U | 32.628 | kWh | -- |

* Dry co-products, for fuel are on an OD basis, fuel is wood residues including sawdust, planar shavings, and hogged material that is generated by the planing process and used internally for fuel.

**Dry co-products, sold are on an OD basis, sold are wood residues including sawdust, planar shavings, and hogged material that is generated by the planing process and sold to outside customers.

**Table 10: Total amount of packaging materials reported in sawmill survey for the production year 2017 per $m^3$ of planed dry lumber**

| Material | Value | Units |
|---|---|---|
| Steel strapping | 0.57 | $kg/m^3$ |
| Plastic strapping | 0.89 | $kg/m^3$ |
| Corner protectors[1] | 0.22 | $kg/m^3$ |
| Plastic lumber wrapping | 0.14 | $kg/m^3$ |
| Replacement stickers | 0.04 | $kg/m^3$ |
| Total | 1.86 | $kg/m^3$ |

**[1]Corner protectors data used as a proxy. Taken from 2017 Southeast hardwood lumber production survey.**

## 4.5 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 11.

**Table 11: Material inputs, secondary data sources, geography, year, and data quality**

| **A1: Raw Material Inputs** | | | | |
|---|---|---|---|---|
| **Inputs** | **LCI Data Source** | **Geography** | **Year** | **Data Quality Assessment** |
| **Wood resource** | Database: USLCI (U.S. Life Cycle Inventory) Database. (DATASMART 2018). Accessed June 4, 2019: https://www.lcacommons.gov/nrel/search<br>Process: Roundwood, hardwood, average, at forest road, NE-NC | North America - Region Specific | 2005 - 2019 | **Technology:** good; process models region-specific technology<br>**Time:** good; some data are less than 10 years old<br>**Geography:** very good; data are representative of regional production |
| **A2: Raw Material Transportation** | | | | |
| **Inputs** | **LCI Data Source** | **Geography** | **Year** | **Data Quality Assessment** |
| **Trucking** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Transport, combination truck, diesel powered NREL/US U | North America | 2018 | **Technology**: very good; process models average North American technology<br>**Time**: good; data are less than 10 years old<br>**Geography**: very good; data are representative of North American trucking |
| **A3: Manufacturing** | | | | |
| **Energy Inputs** | **LCI Data Source** | **Geography** | **Year** | **Data Quality Assessment** |
| **Electricity** | Database: Ecoinvent 3.4<br>Process: Electricity, low voltage {NPCC, US only}\| market for \| cut-off, U | North America - Region Specific egrid | 2018 | **Technology**: very good; process models average electricity technology specific to regional grids<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of regional electricity generation |
| **Gasoline** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Gasoline, combusted in equipment NREL/US U | North America | 2018 | **Technology**: very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American propane production and combustion |
| **Diesel** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Diesel, combusted in industrial equipment NREL/US U | North America | 2018 | **Technology**: very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American diesel production and combustion |

| | | | | |
|---|---|---|---|---|
| **Biomass combustion** | Database: CORRIM Data<br>Process: Wood Combusted, at boiler, at mill, kg, US | North America | 2015 | **Technology:** very good; process represents combustion of biomass in an industrial boiler<br>**Time:** very good; data are within two years<br>**Geography:** very good; data is representative of North American biomass combustion |
| **Ancillary Materials and Packaging** | | | | |
| **Hydraulic fluid and lubricants** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Lubricating oil, at plant/US-US-EI U | North America | 2018 | **Technology**: very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American processes |
| **Antifreeze** | Database: US EI 2.2 (DATASMART 2018)<br>Process: ethylene glycol, at plant/US - US-EI U | North America | 2018 | **Technology**: very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American processes |
| **Solvents** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Hexane, at plant/US- US-EI U | North America | 2018 | **Technology:** very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American production and combustion |
| **Steel strapping** | World Steel Association (2018) 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<br>**Time**: very good; data are less than 5 years old<br>**Geography**: good; data are representative of global conditions |
| **Plastic strapping** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Polyethylene, HDPE, granulate, at plant/US- US-EI U | North America | 2018 | **Technology:** very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American processes |
| **Greases and oils** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Proxy oil and grease, at plant NREL/US U | North America | 2018 | **Technology:** very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American processes |
| **Plastic wrapping** | Database: US EI 2.2 (DATASMART 2018)<br>Process: Polyethylene, HDPE, granulate, at plant/US- US-EI U | North America | 2018 | **Technology:** very good; process models average North American technology<br>**Time**: very good; data are less than 5 years old<br>**Geography**: very good; data are representative of North American processes |

# 5 Life Cycle Impact Assessment

This study used the TRACI method to determine environmental impacts (Bare 2011) associated with the production of 1.0 $m^3$ planed dry hardwood lumber in the NE/NC region of the United States. Target impact indicators, categories, and the characterization of them are summarized. The units associated with the impact indicator values are not comparable with others, and as such, should not be packaged together. The LCIA results here do not have predictive power on category endpoints, safety margins and risk, or outcomes if thresholds are exceeded (more on this is described before

Table 13). Fuels are categorized as "renewable" or "nonrenewable." Renewable fuels include biomass, geothermal, solar, wind, and hydro, and nonrenewable fuels are fossil and nuclear forms. For conformance with the PCR, the source and scope of each impact category are reported and appear in Table 12.

**Table 12: Characterization models, and impact categories**

| Reporting Category Per Tables E1-E5 in ISO 21930:2017 | Indicator Name | Abbreviation | Units |
|---|---|---|---|
| Core Mandatory Impact Indicators | Global warming potential, w/ biogenic | GWP | kg $CO_2e$ |
| Core Mandatory Impact Indicators | Global warming potential, fossil | GWP | kg $CO_2e$ |
| Core Mandatory Impact Indicators | Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e |
| Core Mandatory Impact Indicators | Acidification potential of soil and water sources | AP | kg $SO_2e$ |
| Core Mandatory Impact Indicators | Eutrophication potential | EP | kg $PO_4e$ |
| Core Mandatory Impact Indicators | Formation potential of tropospheric ozone | SFP | kg $O_3e$ |
| Core Mandatory Impact Indicators | Abiotic depletion potential (ADP fossil) for fossil resources | ADPf | MJ, NCV |
| Core Mandatory Impact Indicators | Fossil fuel depletion | FFD | MJ surplus |
| Use of Primary Resources | Renewable primary energy carrier used as energy | RPRE | MJ, NCV |
| Use of Primary Resources | Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV |
| Use of Primary Resources | Renewable primary energy carrier used as material | NRPRM | MJ, NCV |
| Secondary material, secondary fuel and recovered energy | Secondary material | SM | kg |
| Secondary material, secondary fuel and recovered energy | Renewable secondary fuel | RSF | MJ, NCV |
| Secondary material, secondary fuel and recovered energy | Nonrenewable secondary fuel | NRSF | MJ, NCV |
| Secondary material, secondary fuel and recovered energy | Recovered energy | RE | MJ, NCV |
| Mandatory Inventory Parameters | Consumption of freshwater resources | FW | $m^3$ |
| Indicators Describing Waste | Hazardous waste disposed | HWD | kg |
| Indicators Describing Waste | Nonhazardous waste disposed | NHWD | kg |
| Indicators Describing Waste | High-level radioactive waste, conditioned, to final repository | HLRW | kg or $m^3$ |
| Indicators Describing Waste | Intermediate- and low-level radioactive waste, conditioned, to final repository | ILLRW | kg or $m^3$ |
| Indicators Describing Waste | Components for re-use | CRU | kg |
| Indicators Describing Waste | Materials for recycling | MR | kg |
| Indicators Describing Waste | Materials for energy recovery | MER | kg |
| Indicators Describing Waste | Recovered energy exported from the product system | EE | MJ, NCV |
| Additional Inventory Parameters for Transparency | Biogenic carbon removal from product | BCRP | kg $CO_2e$ |
| Additional Inventory Parameters for Transparency | Biogenic carbon emission from product | BCEP | kg $CO_2e$ |
| Additional Inventory Parameters for Transparency | Biogenic carbon removal from packaging | BCRK | kg $CO_2e$ |
| Additional Inventory Parameters for Transparency | Biogenic carbon emission from packaging | BCEK | kg $CO_2e$ |

| | | | |
|---|---|---|---|
| Additional Inventory Parameters for Transparency | Biogenic carbon emission from combustion of waste from renewable sources used in production processes | BCEW | kg $CO_2$e |
| Additional Inventory Parameters for Transparency | Carbon emissions from combustion of waste from nonrenewable sources used in production processes | CWNR | kg $CO_2$e |

Table 13 reports the results of the cradle-to-gate environmental performance of NE/NC planed dry hardwood lumber for the reporting indicators in Table 12. LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, or safety margins or risks.

**Table 13: Environmental impacts of 1.0 m$^3$ of planed dry hardwood lumber in the NE/NC region based on mass allocation**

| | | Units | $A_1$ | $A_2$ | $A_3$ | Total |
|---|---|---|---|---|---|---|
| **Core Mandatory Impact Indicator** | | | | | | |
| Global warming potential, fossil | GWP | kg $CO_2e$ | 27.36 | 31.62 | 107.31 | 166.29 |
| Global warming potential, w/biogenic | GWP | kg CO2e | -2,107.64 | 31.62 | 2,242.31 | 166.29 |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.70E-07 | 5.57E-08 | 9.98E-06 | 1.02E-05 |
| Acidification potential of soil and water sources | AP | kg $SO_2e$ | 0.34 | 0.17 | 0.43 | 0.94 |
| Eutrophication potential | EP | kg Ne | 0.03 | 0.02 | 0.12 | 0.17 |
| Formation potential of tropospheric ozone | SFP | kg $O_3e$ | 10.99 | 5.04 | 10.29 | 26.32 |
| Abiotic depletion potential (ADP fossil) for fossil resources | ADPf | MJ, NCV | 388.95 | 395.63 | 1,522.49 | 2,307.07 |
| Fossil fuel depletion | FFD | MJ surplus | 58.39 | 59.40 | 238.59 | 356.38 |
| **Use of Primary Resources** | | | | | | |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 0.92 | 0.91 | 3874.59 | 3,876.42 |
| Renewable primary energy carrier used as material | RPRM | MJ, NCV | 11,962.32 | 0.00 | 0.00 | 11,962.32 |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 396.68 | 403.30 | 2,357.65 | 3,157.62 |
| Nonrenewable primary energy carrier used as material | NRPRM | MJ, NCV | 0.00 | 0.00 | 0.00 | 0.00 |
| **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 | 0.00 | 0.00 | 545.20 | 545.20 |
| **Indicators Describing Waste** | | | | | | |
| Hazardous waste disposed | HWD | kg | 0.00 | 0.00 | 0.00 | 0.00 |
| Nonhazardous waste disposed | NHWD | kg | 0.00 | 0.00 | 0.59 | 0.59 |
| High-level radioactive waste, conditioned, to final repository | HLRW | kg or m$^3$ | 3.153E-09 | 3.133E-09 | 8.764E-07 | 8.826E-07 |
| Intermediate- and low-level radioactive waste, conditioned, to final repository | ILLRW | kg or m$^3$ | 1.518E-08 | 1.509E-08 | 3.139E-06 | 3.169E-06 |
| Components for re-use | CRU | kg | 0.00 | 0.00 | 0.00 | 0.00 |
| Materials for recycling | MR | kg | 0.00 | 0.00 | 0.03 | 0.03 |
| 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 |

Results of the LCIA are shown in absolute values for $A_1$-Resource extraction, $A_2$-Transportation, and $A_3$-Hardwood lumber production. For global warming potential (GWP), 65% of the $CO_2$ equivalent emissions come from product manufacturing ($A_3$), whereas forestry operations ($A_1$) and transportation ($A_2$) contribute 16% and 19%, respectively, to GWP.

Table 13 provides energy use, material resource consumption, and generated waste indicators. Total energy use for the cradle-to-gate was 7,034 $MJ/m^3$. Of this, 3,876 $MJ/m^3$ is renewable and 3,158 $MJ/m^3$ is nonrenewable. The nonrenewable energy is derived from fossil fuels and used to operate sawmill machinery, transportation machinery, generate electricity, and fuel a portion of the kiln-drying. Nonrenewable fuels represented 45% of the total energy use. Energy from biomass goes exclusively to kiln-drying. The bulk of freshwater use is given to the $A_3$ life cycle stage. Mills reported the use of sprinkler systems in the logyard but only reported water usage for whole facility, 545.2 $L/m^3$.

# 6 Interpretation

Life cycle interpretation is defined by ISO (2006) as the phase of an LCA where findings from an LCI, LCIA, or both are brought together within the project's defined goal and scope 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 planed dry hardwood lumber. In addition, we consider checks on the completeness, sensitivity, and consistency of the LCI results and follow with conclusions, limitations, and recommendations.

## 6.1 Identification of the Significant Issues

To identify significant issues inherent in the manufacture of planed dry hardwood lumber in the NE/NC region of the U.S., the results of the LCI performed are used. For the interpretation phase of this report, a contribution analysis examined the life cycle stages of $A_1$, $A_2$, and $A_3$. In this way, significant impacts from a unit process or substances of particular interest can be examined.

## 6.2 Life Cycle Phase Contribution Analysis

Contributions from modules $A_1$-$A_3$ for the impact indicators are shown in

Table 14. For global warming impact, of the total $CO_2$ equivalent emissions, 16.5% are attributed to $A_1$-Resource extraction, 19.0% to $A_2$-Transportation, and 64.5% to $A_3$-Product manufacturing. Lumber production ($A_3$) carries the highest impact for global warming potential, 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 categories.

Renewable fuels use was highest for product manufacturing ($A_3$). 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, 74.7% is contributed by $A_3$, whereas $A_1$ contributes 12.6% (

Table 14). About 13% of the total nonrenewable fuels use can be contributed to $A_2$. Biomass energy is primarily used in drying lumber in kilns ($A_3$). The cradle-to-gate total biomass energy was 0% ($A_1$), 0% ($A_2$), and 100% ($A_3$).

**Table 14: Cradle-to-gate NE/NC hardwood lumber LCIA contribution analysis results for $A_1$-Resource extraction, $A_2$-Transportation, and $A_3$-Hardwood lumber production**

| Indicator Name | Abbreviation | Units | $A_1$ | $A_2$ | $A_3$ | Total |
|---|---|---|---|---|---|---|
| Global warming potential | GWP | kg $CO_2$e | 16.5% | 19.0% | 64.5% | 100% |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.7% | 0.5% | 97.8% | 100% |
| Acidification potential of soil and water sources | AP | kg $SO_2$e | 36.2% | 18.6% | 45.2% | 100% |
| Eutrophication potential | EP | kg Ne | 16.2% | 9.9% | 73.9% | 100% |
| Formation potential of tropospheric ozone | SFP | kg $O_3$e | 41.8% | 19.1% | 39.1% | 100% |
| Abiotic depletion potential (ADP fossil) for fossil resources | ADPf | MJ, NCV | 16.9% | 17.1% | 66.0% | 100% |
| Fossil fuel depletion | FFD | MJ surplus | 16.4% | 16.7% | 66.9% | 100% |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 0.0% | 0.0% | 100% | 100% |
| Renewable primary energy carrier used as material | RPRM | MJ, NCV | 100% | 0.0% | 0.0% | 100% |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 12.6% | 12.8% | 74.7% | 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 | $m^3$ | 0.0% | 0.0% | 100% | 100% |
| Hazardous waste disposed | HWD | kg | - | - | - | - |
| Nonhazardous waste disposed | NHWD | kg | - | - | 100% | 100% |
| High-level radioactive waste, conditioned, to final repository | HLRW | kg or $m^3$ | 0.4% | 0.4% | 99.3% | 100% |
| Intermediate- and low-level radioactive waste, conditioned, to final repository | ILLRW | kg or $m^3$ | 0.5% | 0.5% | 99.0% | 100% |
| Components for re-use | CRU | kg | - | - | - | - |
| Materials for recycling | MR | kg | - | - | 100% | 100% |
| Materials for energy recovery | MER | kg | - | - | - | - |
| Recovered energy exported from the product system | EE | MJ, NCV | - | - | - | - |

Table 15 and Table 16 report the cradle-to-gate energy use contribution analysis results by fuel type and modules for $A_1$-Resource extraction, $A_2$-Transportation, and $A_3$-Hardwood lumber production, respectively. For nonrenewable fossil fuel energy, 67.9% is used in $A_3$, whereas 15.9% and 16.2% are used in $A_1$ and $A_2$, respectively.

Within the resource extraction ($A_1$) life cycle stage, 98.3% of the total energy was derived from nonrenewable fuels (Table 16). Biomass energy was used primarily in drying the hardwood lumber in kilns ($A_3$) and was 60.5% of the total energy for that module. These results are consistent with previous hardwood lumber studies (Comstock 1975; Denig et al. 2000; Bergman and Bowe 2008a). Considering the cradle-to-gate total energy for producing NE/NC hardwood lumber, including fuels for process heat, equipment, and electricity, 26.7% comes from nonrenewable fossil fuels, 11.1% from nuclear, 60.5% from renewable biomass fuel, and 1.4% from hydro (Table 16).

**Table 15: Cradle-to-gate NE/NC hardwood lumber LCIA energy use contribution analysis results by fuel type for $A_1$-Resource extraction, $A_2$-Transportation, and $A_3$-Hardwood lumber production**

| | Unit | Total | $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|---|---|
| Nonrenewable, fossil | MJ | 100% | 15.94% | 16.21% | 67.84% |
| Nonrenewable, nuclear | MJ | 100% | 0.82% | 0.82% | 98.36% |
| Nonrenewable, biomass | MJ | 100% | 0.36% | 0.06% | 99.57% |
| Renewable, biomass | MJ | 100% | 0.00% | 0.00% | 99.99% |
| Renewable, wind, solar, geothermal | MJ | 100% | 1.37% | 1.31% | 97.31% |
| Renewable, water | MJ | 100% | 0.59% | 0.59% | 98.82% |

**Table 16: Cradle-to-gate NE/NC hardwood lumber LCIA energy use contribution analysis results by $A_1$-Resource extraction, $A_2$-Transportation, and $A_3$-Hardwood lumber production**

| | Unit | Total | $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|---|---|
| Nonrenewable, fossil | MJ | 34.85% | 98.31% | 98.35% | 26.69% |
| Nonrenewable, nuclear | MJ | 10.04% | 1.46% | 1.43% | 11.14% |
| Nonrenewable, biomass | MJ | 0.00% | 0.00% | 0.00% | 0.00% |
| Renewable, biomass | MJ | 53.64% | 0.05% | 0.05% | 60.53% |
| Renewable, wind, solar, geothermal | MJ | 0.22% | 0.05% | 0.05% | 0.24% |
| Renewable, water | MJ | 1.26% | 0.13% | 0.13% | 1.40% |
| | | 100.00% | 100.00% | 100.00% | 100.00% |

## 6.3 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 17 and 18. In Table 17, an increase of 20% in the distance to transport logs from the forest to the sawmill gate results in an increase of 6.3 kg $CO_2e$ from the baseline amount of 166.3 kg $CO_2e$ for the impact indicator GWP. Conversely, decreasing the log transport distance by 20% creates a reduction in the GWP indicator of 6.3 kg $CO_2e$. For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of electricity used reduced the MJ surplus to 342.4 MJ compared with the baseline amount of 356.4 MJ or a difference of 14.0 MJ.

**Table 17: Deviations in the results for a 20% increase and decrease from the baseline amount for log transportation distances and electricity use**

| Core Mandatory Indicator | Impact Indicator | Unit | Baseline Results | Log transport distance −20 % | Log transport distance +20 % | Electricity −20 % | Electricity +20 % |
|---|---|---|---|---|---|---|---|
| Global warming potential – TRACI 2.1 | $GWP_{TRACI}$ | kg $CO_2e$ | 166.29 | 159.97 | 172.62 | 159.49 | 173.10 |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.02E-05 | 1.02E-05 | 1.02E-05 | 8.55E-06 | 1.19E-05 |
| Acidification potential of soil and water sources | AP | kg $SO_2e$ | 0.94 | 0.91 | 0.98 | 0.92 | 0.96 |
| Eutrophication potential | EP | kg Ne | 0.17 | 0.17 | 0.17 | 0.15 | 0.18 |
| Formation potential of tropospheric ozone | SFP | kg $O_3e$ | 26.32 | 25.31 | 27.33 | 26.16 | 26.48 |
| Abiotic depletion potential (ADPfossil) for fossil resources | ADPf | MJ, NCV | 2,307.07 | 2,227.95 | 2,386.20 | 2,212.27 | 2,401.83 |
| Fossil fuel depletion | FFD | MJ surplus | 356.38 | 344.50 | 368.26 | 342.37 | 370.38 |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 3,876.42 | 3,876.24 | 3,876.60 | 3,859.91 | 3,859.91 |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 3,157.62 | 3,076.96 | 3,238.28 | 2,933.40 | 2,933.40 |

In Table 18, an increase of 20% in natural gas consumption resulted in an increase of 11.4 kg $CO_2e$ from the baseline amount of 166.3 kg $CO_2e$ for the impact indicator GWP. Conversely, decreasing natural gas consumption by 20% created a reduction in the GWP indicator of 11.4 kg $CO_2e$. For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of woody biomass used reduced the MJ surplus to 345.3 MJ compared with the baseline amount of 356.4 MJ or a difference of 11.1 MJ.

**Table 18: Deviations in the results for a 20% increase and decrease from the baseline amount for natural gas and woody biomass use as fuel**

| Core Mandatory Indicator | Impact Indicator | Unit | Baseline Results | Natural gas | Natural gas | Biomass | Biomass |
|---|---|---|---|---|---|---|---|
| | | | | −20 % | +20 % | −20 % | +20 % |
| Global warming potential – TRACI 2.1 | $GWP_{TRACI}$ | kg $CO_2e$ | 166.29 | 154.85 | 177.73 | 160.92 | 171.69 |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.02E-05 | 1.02E-05 | 1.02E-05 | 9.68E-06 | 1.07E-05 |
| Acidification potential of soil and water sources | AP | kg $SO_2e$ | 0.94 | 0.93 | 0.95 | 0.88 | 1.01 |
| Eutrophication potential | EP | kg Ne | 0.17 | 0.17 | 0.17 | 0.16 | 0.18 |
| Formation potential of tropospheric ozone | SFP | kg $O_3e$ | 26.32 | 26.09 | 26.55 | 24.30 | 28.35 |
| Abiotic depletion potential (ADPfossil) for fossil resources | ADPf | MJ, NCV | 2,307.07 | 2,147.71 | 2,466.43 | 2,233.03 | 2,381.43 |
| Fossil fuel depletion | FFD | MJ surplus | 356.38 | 329.94 | 382.82 | 345.28 | 367.53 |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 3,876.42 | 3,876.37 | 3,876.47 | 3,107.38 | 4,648.76 |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 3,157.62 | 2,980.73 | 3,334.52 | 3,046.99 | 3,268.72 |

A change of ±20% in the distance trucks traveled to deliver logs from the forest to the sawmill gate results in a ±4% deviation from the baseline amount of kg $CO_2e$ for the impact indicator GWP. For the fossil fuel depletion impact indicator, a decrease of 20% in the amount of electricity used leads to a 4% reduction of the MJ surplus from the baseline amount. The greatest change (±16%) was observed for the depletion potential of the stratospheric ozone layer when electricity is increased or decreased by 20% from the original baseline amount for the depletion potential of the stratospheric ozone layer impact indicator category.

**Table 19: Sensitivity analysis results for 20% increases and decreases to baseline results for log transport distance and electricity**

| Core Mandatory Indicator | Impact Indicator | Unit | Baseline Results | Log transport distance | Log transport distance | Electricity | Electricity |
|---|---|---|---|---|---|---|---|
| | | | | –20% | +20% | –20% | +20% |
| Global warming potential – TRACI 2.1 | $GWP_{TRACI}$ | kg $CO_2e$ | 166.29 | -3.80% | 3.80% | -4.09% | 4.09% |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.02E-05 | -0.11% | 0.11% | -16.26% | 16.25% |
| Acidification potential of soil and water sources | AP | kg $SO_2e$ | 0.94 | -3.71% | 3.71% | -2.41% | 2.41% |
| Eutrophication potential | EP | kg Ne | 0.17 | -1.97% | 1.97% | -9.79% | 9.79% |
| Formation potential of tropospheric ozone | SFP | kg $O_3e$ | 26.32 | -3.83% | 3.83% | -0.61% | 0.61% |
| Abiotic depletion potential (ADPfossil) for fossil resources | ADPf | MJ, NCV | 2,307.07 | -3.43% | 3.43% | -4.11% | 4.11% |
| Fossil fuel depletion | FFD | MJ surplus | 356.38 | -3.33% | 3.33% | -3.93% | 3.93% |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 3,876.42 | 0.00% | 0.00% | -0.43% | -0.43% |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 3,157.62 | -2.55% | 2.55% | -7.10% | -7.10% |

With the same procedure as Table 19, Table 20 shows that a 20% increase in natural gas usage compared with the baseline amount results in a 7% increase compared with the baseline value for GWP. Conversely, the addition of 20% more woody biomass for fuel increases the GWP impact indicator 3.2% compared with the baseline.

**Table 20: Sensitivity analysis results for 20% increases and decreases to baseline results for natural gas and woody biomass use as fuel**

| Core Mandatory Indicator | Impact Indicator | Units | Baseline Results | Natural gas | Natural gas | Biomass | Biomass |
|---|---|---|---|---|---|---|---|
| | | | | −20% | +20% | −20% | +20% |
| Global warming potential – TRACI 2.1 | $GWP_{TRACI}$ | kg $CO_2e$ | 166.29 | -6.88% | 6.88% | -3.23% | 3.25% |
| Depletion potential of the stratospheric ozone layer | ODP | kg CFC11e | 1.02E-05 | -0.04% | 0.04% | -5.17% | 5.19% |
| Acidification potential of soil and water sources | AP | kg $SO_2e$ | 0.94 | -0.97% | 0.97% | -7.03% | 7.06% |
| Eutrophication potential | EP | kg Ne | 0.17 | -0.68% | 0.68% | -5.46% | 5.48% |
| Formation potential of tropospheric ozone | SFP | kg $O_3e$ | 26.32 | -0.87% | 0.87% | -7.66% | 7.70% |
| Abiotic depletion potential (ADPfossil) for fossil resources | ADPf | MJ, NCV | 2,307.07 | -6.91% | 6.91% | -3.21% | 3.22% |
| Fossil fuel depletion | FFD | MJ surplus | 356.38 | -7.42% | 7.42% | -3.12% | 3.13% |
| Renewable primary energy carrier used as energy | RPRE | MJ, NCV | 3,876.42 | 0.00% | 0.00% | -19.84% | 19.92% |
| Nonrenewable primary energy carrier used as energy | NRPRE | MJ, NCV | 3,157.62 | -5.60% | 5.60% | -3.50% | 3.52% |

## 6.4 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 that 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 phase 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 stated goal and scope of this project, comparisons with substitute products are not appropriate. Therefore, the LCA presented here makes to assertions that the product under investigation is superior to other alternative products.

# 7 Treatment of Biogenic Carbon

Bio-based materials, including wood, contain biogenic carbon. 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 by the ISO in ISO 21930 (ISO 2017). 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 a product or co-products or directly to the atmosphere when combusted. Mass flows for biogenic carbon in this study are listed in the LCI and have units of kg $CO_2$. Biogenic carbon indicators appear in Table 21.

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 in the boiler during the production stage creates biogenic carbon emissions ($CO_2$). Per ISO 21930, biogenic carbon exiting the product system as $CO_2$ emission 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 (2019). This method, however, does not account for removals or emissions of biogenic $CO_2$. The GWP relative to biogenic carbon, therefore, 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:

- 2,135 kg $CO_2$e ($A_1$) were removed in the production of 1.0 $m^3$ of planed dry hardwood lumber
- 1 $m^3$ of planed dry hardwood lumber stores 286 kg of carbon or 1,049 kg $CO_2$e ($C_3$/$C_4$)
- Co-products produced during lumber production account for 756.32 $CO_2$e ($A_3$) for a total "emission" in wood product leaving the system boundary of +1,049 kg $CO_2$e
- Combusted wood fuel emitted 329 kg $CO_2$e
- Packaging results in -1 kg $CO_2$e removal and +1 kg $CO_2$e emission

**Table 21: Biogenic carbon inventory indicators**

| Additional Inventory Parameters | | Units | Total | $A_1$ | $A_2$ | $A_3$ | $A_5$ | $C_3$/$C_4$ |
|---|---|---|---|---|---|---|---|---|
| | | | | kg $CO_2$ eq. | | | | |
| Biogenic Carbon Removal from Product | BCRP | kg $CO_2$ | (-2,135.00) | (-2,135.00) | - | - | - | - |
| Biogenic Carbon Emission from Product | BCEP | kg $CO_2$ | 1,805.65 | - | - | 756.32 | - | 1,049.33 |
| Biogenic Carbon Removal from Packaging | BCRK | kg $CO_2$ | (-0.95) | - | - | (-0.95) | - | - |
| Biogenic Carbon Emission from Packaging | BCEK | kg $CO_2$ | 0.95 | - | - | - | 0.95 | - |
| Biogenic Carbon Emission from Combustion of Waste from Ren. Sources Used in Production | BCEW | kg $CO_2$ | 329.35 | - | - | 329.35 | - | - |

Summarizing, total removal was -2,135 kg $CO_2$e and total "emissions" were -1085.67 kg $CO_2$e from cradle-to-gate ($A_1$-$A_3$) (Table 21). In accordance with ISO 21930, emission from packaging (BCEK) was reported in $A_5$. Emission from the main product was recorded in $C_3$/$C_4$. The system boundary for this LCA only includes modules $A_1$-$A_3$.

# 8 Discussion

This LCA updates a previous study by Bergman and Bowe (2008b). The 2008 study was not required to be in conformance with a PCR (completion of LCIA and other non LCIA indicators) as this study did, and therefore, some direct comparisons are not possible. Table 22 provides a comparison of the volume conversions found for the reporting year 2005 production in the 2008 study with those of this study. The results show comparable conversions for the two.

**Table 22: Volume conversion comparison of incoming logs to 1.0 m$^3$ of planed dry lumber for 2008 and 2017 hardwood lumber production studies**

| | Wood Volume (m$^3$ per 1.0 m$^3$) 2005[1] | Wood Volume (m$^3$ per 1.0 m$^3$) 2017 |
|---|---|---|
| **Raw Wood Material** | | |
| Incoming green log | 2.29 | 2.23 |
| Rough green lumber | 1.46 | 1.35 |
| Rough dried lumber | 1.37 | 1.25 |
| **Final Product** | | |
| Planed dried lumber | 1.00 | 1.00 |

**[1]Hardwood lumber LCI by Bergman and Bowe (2008a) reports 2005 production statistics**

When viewing data from LCAs, a strong temptation 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. Where 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 (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 23 provides a comparison of energy consumption results between the 2008 and 2019 findings. The expanded use of wood boilers and more efficient sawing practices may account for the observed differences. Sawmills in this study used 52 $MJ/m^3$ less than the sawmills in Bergman and Bowe (2008b). Similarly, a difference of 876 $MJ/m^3$ was found between the earlier study and this one for thermal energy.

**Table 23: Comparison of overall energy consumption for hardwood lumber in 2008[1] and 2019 LCA studies[1]**

| | Electrical Energy (MJ per $m^3$) | Thermal Energy (MJ per $m^3$) |
|---|---|---|
| Hardwood lumber 2008 | 597 | 5,400[2] |
| Hardwood lumber 2017 | 545 | 4,524 |

**[1]2008 data from Bergman and Bowe (2008b)**

**[2]2008 data from Bergman and Bowe (2008b) uses the higher heating values**

Mills have opportunities to reduce their fuel use further; however, there are important trade-offs to consider. One avenue to accomplish this would be reducing the moisture content 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 in which 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 contributed to kiln-dry lumber. The sawmill industry continues to adopt wood-fueled boilers into their operations. The potential benefits of this are two-fold. First, boilers dependent on wood fuel to operate provide an outlet for mill residues such as sawdust, bark, chips, and shavings. Second, the energy generated on-site necessarily reduces the mills 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. 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 reduced saw kerfs could both reduce errors introduced by manual sawing and increase mill efficiency. As 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. Our survey did not capture data on the adoption of these technologies, but future studies would benefit from doing so.

# 9 Conclusions, Limitations, and Recommendations

This study conducted a rigorous cradle-to-gate LCA for planed dry hardwood lumber production in the NE/NC U.S. The primary objective was to create LCI data and impact assessment results for planed dry hardwood lumber that could be used to develop EPDs in accordance with ULE (2019) 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 (2019) 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 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. Manufacturing emissions are higher than those from the forest resource LCI. Most impacts of note in the manufacturing process to produce hardwood lumber are associated with the drying of that lumber from an initial moisture content of 70% (dry basis) to a final moisture content of 8% (OD basis). Airborne emissions are most prevalent at the boiler and kilns. Boiler operations used electrostatic precipitators for control. Not surprisingly, the use of electrical energy is highest in the sawmill for the operation of saws and other equipment there. Advances in optimizing equipment may help lower this burden in the future. In terms of total energy consumed, hardwood lumber production ($A_3$) was the largest of the modules examined largely because of the drying found there. 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.

# 10 Critical review

To ensure that this study was consistent with the stated protocols, both internal and external reviews were conducted.

## 10.1 Internal Review

An internal review of this LCA report was conducted to ensure conformance with the PCR and to check for errors in reporting prior to submission for the external review. Careful consideration was given to technical and editorial comments provided by the reviewers. In most cases, these edits were incorporated into the final document. The internal reviews for this report were provided by Drs. Sevda Alanya-Rosenbaum and Shaobo Liang at the USDA Forest Service, Forest Products Laboratory, and James Salazar, Coldstream Consulting.

## 10.2 External Review

An external review was performed to ensure consistency between the study LCA and CORRIM methodology. The report was sent externally to Dr. Maureen Puettmann, CORRIM.

An external review can be performed to ensure consistency between the study LCA and protocols of the International Standards on LCA (ISO 2006) and the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (PCR 2019). No external review of this type has yet been conducted.

## 11 Acknowledgements

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## 12 Units

1 megajoule = 0.278 kilowatt-hour
1 gigajoule = 1,000 megajoule
1 megajoule = 948.8 BTU
1 kilowatt = 3,412 BTU per hour
1 kilogram = 2.205 pounds
1 meter = 3.281 feet
1 millimeter = 0.0394 inches
1 meter squared = 10.76 feet squared
1 meter cubed = 35.31 feet cubed (264.2 gallons)
1 meter cubed = 423.8 actual board foot
1 liter = 0.2642 gallons
1 kilometer = 0.621 miles
1 metric ton (1,000 kilogram) = 1.10 tons (2,205 pounds)

**Table 24: Conversion factors**

| To convert from: | To: | Multiply by: |
|---|---|---|
| Square meter ($m^2$) | Square foot ($ft^2$) | 10.76391 |
| kilogram (kg) | Pound (lb) | 2.204622 |
| Megajoule (MJ) | British Thermal Unit (BTU) | 947.8170 |
| Degree Celsius (°C) | Degree Fahrenheit (°F) | t/°C = (t/°F - 32)/1.8 |
| Cubic meter ($m^3$) | Cubic foot ($ft^3$) | 35.31466 |
| 1 board foot | $m^3$ | 0.0023597372 |
| Board feet planed lumber | $m^3$ | 0.00162 for 2 by 6; varies by lumber size |

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# 14 Appendices

**Appendix 1: Survey and follow up questionnaires for NE/NC hardwood lumber production**

HUBBARD HARDWOOD LUMBI

Hardwood Production Life Cycl

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