



Case Study on the Cradle-to-Gate Life Cycle Assessment of Softwood Lumber Production in New Brunswick, Canada

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ABSTRACT

The construction sector increasingly emphasizes renewable materials like wood from sustainably managed forests due to wood's low embodied carbon and carbon storage potential, contributing to climate change mitigation. This study applies life cycle assessment (LCA) to evaluate the environmental impact of softwood lumber manufacturing in New Brunswick, Canada. Data were gathered from a local softwood sawmill through survey questionnaires and on-site visits, capturing details on raw material extraction, production processes, and fuel sources used to power the sawmill. A life-cycle inventory (LCI) was developed using mass allocation for primary products and co-products such as chips and sawdust. The LCA software SimaPro, with the North American impact method TRACI 2.1, was employed to conduct the life cycle impact assessment (LCIA) and analyze emissions. Results indicated that kiln-dried sawed lumber's greenhouse gas (GHG) emissions amounted to 43 kg CO₂eq/m³. Manufacturing processes with various unit processes, particularly kiln-drying, contributed over 60% of emissions. Carbon storage in the final lumber product was calculated at 204 kg, translating to approximately 748 kg of CO₂eq/m³, which was 12 times greater than its cradle-to-gate emissions. In this cradle-to-gate LCA, the stored biogenic carbon was counted as a potential credit. This value reflects only the upfront carbon balance and did not represent the entire life cycle, where end-of-life emissions could change this outcome. When used in long-life building constructions, the stored carbon could act as a temporary carbon sink.

KEYWORDS

Cradle-to-gate; greenhouse gas emission; global warming potential; life-cycle assessment; softwood lumber; SimaPro

SUSTAINABLE DEVELOPMENT GOALS

SDG 13: Climate action

Introduction

The Intergovernmental Panel on Climate Change (IPCC) warns that a temperature increase beyond 2 degrees Celsius (°C) could have irreversible consequences (Allen et al., 2018). Greenhouse gas (GHG) emissions are projected to raise global temperatures by 3.5°C by the end of century (Government of New Brunswick, 2018). Therefore, it is necessary to have a deep understanding and accurate estimation of GHG emissions in order to help determine the best actions to mitigate climate change. The building industry is a significant contributor to GHG emissions and consumes a large amount of natural resources due to the manufacturing, transportation, installation, maintenance, and disposal of building

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materials, which refers to the embodied carbon. Globally, buildings account for 42% of carbon dioxide emissions, with 15% of embodied carbon originating from structural materials (Architecture 2030 (n.d.)). In response, many countries are committed to achieving the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2023), leading to increased interest in materials with lower environmental impacts (Sahoo et al., 2021). The Government of New Brunswick has implemented policies to reduce GHG emissions, aligning with Canada's carbon neutrality target by 2050 and the UN Sustainable Development Goals (Government of New Brunswick, 2018; United Nations, 2023). The 2016 Climate Change Action Plan outlines 118 strategies, including Action Plan 21, which integrates wood products with favorable Life Cycle Assessment (LCA) outcomes, and Action Plan 61, which promotes wood as a renewable construction material through building code updates (Government of New Brunswick, 2016).

Wood is a natural and renewable resource that can play a critical role in reducing negative impacts on the climate and environment when sourced from sustainably managed forests (Gong, 2022). The carbon absorbed during tree growth remains stored in harvested wood products throughout their active service lives, delaying the release of sequestered carbon into the atmosphere (Gu et al., 2022), particularly in structural materials with a lifespan of more than 50 yr. This is a significant advantage over fossil fuel-intensive materials such as steel and concrete. At the end of their useful lives, wood products can be repurposed as biomass energy feedstock instead of being discarded in landfills (Werner et al., 2005). However, the environmental benefits of wood-based products must be appropriately quantified using relevant tools (Kutnar & Hill, 2017).

LCA is an internationally accepted, science-based method that assesses the environmental impact of a product or service by identifying and quantifying energy and materials used and emissions released to the environment at various stages during the life cycle of the product or service (ISO, 2006a, 2006b). LCA studies can either evaluate the entire product life cycle, commonly known as "cradle-to-grave," or focus on specific stages such as "cradle-to-gate" or "gate-to-gate" (Puettmann et al., 2021). The cradle-to-gate LCA methodology used in this case study measures the environmental effect from the extraction of raw materials through production until the product is ready to be shipped from the manufacturing site. The LCA process involves four major steps: defining the goal and scope, developing a life-cycle inventory (LCI), performing a life-cycle impact assessment (LCIA), and interpreting the results (ISO, 2006b).

Scientific documentation, such as the international standard ISO 14025, and environmental product declarations (EPD), provide verified data on the environmental performance of products and services to stakeholders such as architects and builders, consumers, regulating agencies, and policymakers (ISO, 2006c). Quantifying environmental performance for structural wood products such as lumber and EPDs of building products play a crucial role in optimizing the overall environmental impact of buildings, while also supporting compliance with green certifications like the Leadership in Energy and Environmental Design (LEED), Green Globes, and other green building rating systems. Despite the availability of EPDs for many wood products, there remains a need for case-specific LCAs considering regional factors such as harvesting methods, transportation distances, and energy sources during manufacturing. Previous studies have shown that these variables in different regions could

significantly influence GHG emissions and other environmental indicators. Abbas and Handler (2018) conducted a study of LCA on hardwood and softwood harvest and transport operations in Tennessee, USA, where forests are primarily hardwoods, comprising 71% oak-hickory, 12% oak-pine, 10% loblolly-shortleaf pine, 5% oak-gum-cypress, and 2% other types. Using the SimaPro LCA tool, and they found that transportation distances significantly influenced GHG emissions in wood supply chains, while harvesting methods, such as chainsaw-based versus feller buncher-based systems, yielded varying energy demands and emissions. Gu et al. (2022) carried out a cradle-to-gate LCA study to examine the environmental impacts associated with transporting mass timber products for a mid-rise institutional building in New Brunswick, Canada. By comparing a steel-frame design with a mass timber alternative, they found that the latter had higher impacts on smog formation, acidification, and eutrophication. These increases were primarily linked to the longer haul distances and the higher diesel consumption needed to deliver mass timber components to the region. Moreover, regional energy mixes influenced environmental impacts; for example, the hydro-dominated electricity in the Pacific Northwest led to lower GWP than the coal-reliant electricity mix in the Southeast United States (Milota & Puettmann, 2017). Meil et al. (2009) assessed energy use in the Canadian wood products sector and found that manufacturing, especially kiln drying, was the most energy-intensive stage, accounting for the largest share of energy consumption in lumber production. Bergman and Bowe (2008) used LCI methodology to analyze hardwood lumber manufacturing and found that, compared to softwood lumber, it required more thermal and electrical energy because of its higher density and longer drying duration. Furthermore, Puettmann and Lippke (2012) applied SimaPro LCA software to assess the impact of replacing natural gas with wood pellets, mill residues, or forest waste for electricity generation or heat production during drying. Their results showed that using woody biomass could substantially lower carbon emissions compared to using fossil fuels. Therefore, the present study was aimed at conducting a cradle-to-gate LCA of softwood lumber production in New Brunswick, Canada. Unlike many existing EPDs or generalized LCA datasets, this research incorporated region-specific factors, including local harvesting practices, transportation distances, and energy sources, which showed a significant impact on environmental outcomes. By focusing on softwood lumber, a primary structural material widely used in the Canadian building sector, this study addressed the current lack of localized LCA data and evaluated how its production aligned with the New Brunswick Climate Change Action Plan, particularly Action Plan 21 and Action Plan 61. The findings were expected to provide robust, region-specific data to support sustainable material selection, inform future cradle-to-grave LCA analysis, and contribute to policies promoting the circular economy in the province.

Methods

Goal and scope of LCA

The goal of this study was to conduct an attributional LCA of the softwood lumber produced by a local mill in New Brunswick, Canada. The LCI of the material flow, energy

use, and emissions on a per unit basis are collected from local producers to conduct the cradle-to-gate life cycle assessment of the softwood lumber products produced in the region. The scope of this study is described in detail in the following sections.

Functional unit

Defining a reference unit for inputs and outputs is necessary for LCAs to properly evaluate environmental impacts. Since the cradle-to-gate stage rather than the whole life cycle (cradle-to-grave) was the focus of this study, a functional unit of 1 m³ of planed dried softwood lumber was used as the reference. Thus, based on a per functional unit basis, the LCI flows and the LCIA findings were provided.

System boundary

This study considered the cradle-to-gate system boundary of softwood lumber, which begins with the material harvesting from the forest in the New Brunswick region (A1); resource and material transportation from suppliers to the mill (A2); and ends in the sawmill with various types of softwood lumber produced, packaged at the plant gate, ready to be shipped (A3). The main unit processes in the manufacturing of softwood lumber were log yard, sawing, drying, and planing. On-site heat energy generation is also included in the system boundary (Figure 1). Separating the LCI into these unit processes is necessary to ensure accurate allocation of burdens associated with the final product of softwood lumber and its co-products in each unit process. All allocation was based on the mass of the products and co-products.

Biogenic carbon storage in the final lumber product was also considered based on the oven-dry mass of wood and reported separately from fossil-based GHG emissions. Since this study followed a cradle-to-gate system boundary and did not include the end-of-life phase, the stored biogenic carbon was not assumed to represent a net removal of CO₂ from

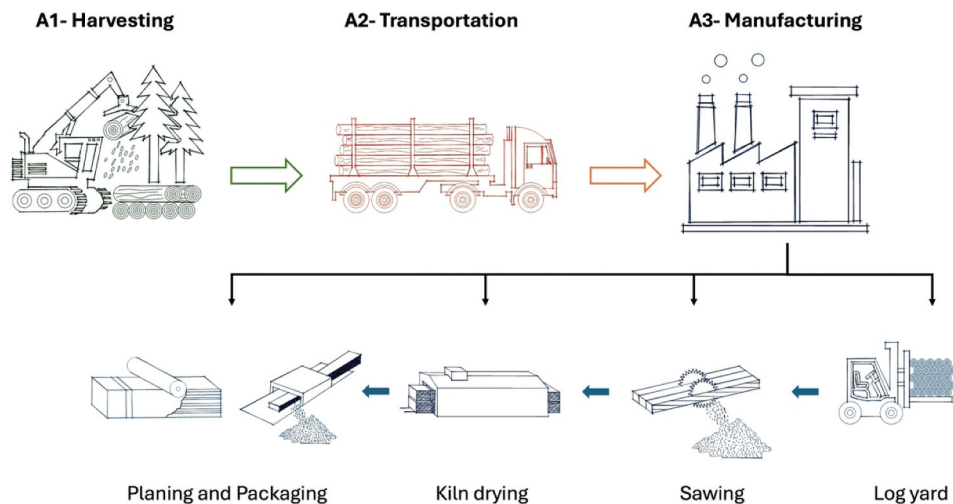


Figure 1. Illustration of the manufacturing processes for producing softwood lumber in New Brunswick, Canada.

the atmosphere, as it could eventually be released depending on future disposal or reuse scenarios of the wood.

The system boundary does not include forest operations (growing seedlings in a nursery, planting the seedlings), managing the forest, such as thinning and fertilization. The only first-hand data reported related to the A1 (resource extraction) was final harvesting with the logs brought to a forest landing.

Apart from producing heat on-site, the system's boundaries also included the extraction, processing, and delivery of purchased primary fuels, such as diesel, and primary fuels needed for generating electricity.

The significant ancillary materials (e.g., hydraulic fluids, motor oils, greases, plastic strapping, lumber wrap) were also included within the system boundary.

Inventory approach

Primary data, such as the annual energy and material consumption, were collected directly from the logging company and the large-scale softwood mill, both based in New Brunswick, Canada. These data were used to build the LCI of the softwood lumber manufacturing processes on a functional unit basis, using an input/output process-based modeling approach for the LCI method, ensuring consistency and accuracy in the analysis. Mass balances of the material (ins and outs) for each unit operation were also calculated to develop the LCA model.

Secondary data of the LCIs for diesel, gasoline, propane, grid electricity mix, auxiliary materials, and transport were provided by the SimaPro software's DataSmart LCI database (LTS, 2023), which integrates and updates data from US LCI v.1.60 and Ecoinvent v.2.2 to appropriately represent U.S. operations (LTS, 2023).

Resource extraction

In this study, the majority of harvested wood came from private forest landowners. The major softwood species harvested are Balsam Fir (*Abies balsamea*) (55%), Black Spruce (*Picea mariana*) (27%), and Jack Pine (*Pinus banksiana*) (8%) (personal communication with forestry company 2024). Additionally, 10% of hardwoods, such as Birch (*Betula sp.*) and Maple (*Acer sp.*), were included in the mix of harvesting from the forest stands. The harvesting process is mainly mechanized, with only 1% involving manual chainsaw felling. Primary equipment used included feller-bunchers and forwarders. Gasoline-powered trucks were used for log transportation in the woods. Overall, diesel and gasoline were the main energy inputs for harvesting, while hydraulic fluid, lubricating fluid, motor oil, grease, and antifreeze served as ancillary materials to maintain harvesting equipment. The main product of this process was logs destined for lumber mills. The co-product, non-merchantable slash, is generally left at a landing disposed of; however, in this study, the survey respondents did not track the amount of residues generated during the operation.

The energy and ancillary material used by the logging company that participated in the survey were calculated based on 1 m³ of the roundwood harvested and shown in Table 1.

Transport of logs from the extraction site to the sawmill

Logs were transported by diesel trucks to the mills on public roads. The transportation value of 67 tonne-kilometer (tkm) was determined based on the weighted average distance

Table 1. LCI of resource extraction.

Resource	Inputs	Unit	Amount per m ³ of roundwood
Energy	Diesel fuel	litre	2.94
	Gasoline	litre	0.14
	Propane	litre	0.02
Ancillary Materials	Hydraulic fluid	litre	0.05
	Lubricating fluid	litre	0.08
	Motor oil	litre	0.02
	Greases	kg	0.0029

Table 2. Input/Output per m³ of logs to the mill via transportation.

		Amount	Unit	Allocation (%)
Output	Log at mill (including bark)	1	m ³	100
Input	Log at forest road (including bark)	1	m ³	–
	Transport, combination truck	67	tkm	–

traveled by logging trucks, which was 103 km (one way), and the green log density of 645 kg/m³, or 0.645 tonnes, at 67% moisture content (MC). Transportation was modeled as a stand-alone unit process rather than as an input to the logyard process (Table 2) to separately demonstrate the impacts of transportation on the overall impacts.

Product manufacturing

This research separated the four primary unit operations of lumber manufacture into log yard, sawing, drying, and planing. A boiler was also included, which produced steam for drying. In 2022, the surveyed sample mill produced around 71,780 thousand board feet (MFBM) (169,402 m³) of rough green lumber, in which about 10% left the system boundary in the sawing unit process and were sold as rough green lumber. Following that, the remaining rough green lumber was fed into the drying unit process, and all the rough dry lumber was planed and packaged to be shipped.

The lumber size profile produced by the sample mill was dominated by the production of 2 × 4 planed kiln-dried lumber, taking about 63.64% of the production. Table 3 displays the sizes, types, and contributions of lumber produced in the surveyed sawmill in 2022.

Annual lumber product output (including rough green, rough dry, and planed dry) was reported by mill in MFBM. Forintek cubic meter conversion factors per MFBM lumber (Nielson et al., 1985), and mill data were employed to convert MFBM to m³. A standard

Table 3. The average size and type breakdown of softwood lumber produced in the surveyed sawmill in New Brunswick.

Size	Types of lumber	Contribution (%)
1 × 4	Rough green	2.80
2 × 4	Rough green	5.39
2 × 4	Surfaced dry	63.64
2 × 6	Rough green	0.90
2 × 6	Surfaced dry	25.57
1 × 3	Rough green	0.30
1 × 6	Rough green	0.02
2 × 3	Rough green	1.38
Total		100

conversion rate from MBFM to cubic meters for rough green lumber was $2.36 \text{ m}^3/\text{MBFM}$, based on information from Nielson et al. (1985). The assumed conversion factor for rough dry lumber was $1.97 \text{ m}^3/\text{MBFM}$, derived from measuring sample shrinkage at a reported MC of 14%. Additionally, the sawmill provided a conversion factor of 1.62 m^3 per MBFM for planed dry lumber (final product). These ratios demonstrate that for 1.0 m^3 of planed dry lumber produced, 1.46 m^3 of rough green lumber and 1.22 m^3 of rough dry lumber were required.

Species, moisture content, and specific gravity of the lumber examined

The wood species in the production of softwood lumber include black spruce (*Picea mariana*) (55%), Balsam Fir (*Abies balsamea*) (40%), and Jack pine (*Pinus banksiana*) (5%). To determine the moisture content (MC) and specific gravity (SG) of the lumber, samples were gathered from the softwood sawmill, representing various species used in lumber manufacturing. These samples were then transported to the Wood Science and Technology Center (WSTC) at the University of New Brunswick, Fredericton, Canada, for research analysis. Following the ASTM D143 (ASTM International [ASTM], 2023) standard, volume and weight of the samples were measured, and physical properties of the samples, such as their specific gravity (i.e., relative density) and MC, were then determined. These properties are essential for accurate conversion and analysis in the context of the LCA study, particularly to ensure precision in the mass balance.

In Table 4, a weighted-average green and dry specific gravity of 0.386 and 0.408, respectively, were calculated based on the species distribution percentages obtained from the mill data and each individual species' specific gravity from measuring the green and dry samples of different species. Moreover, an initial MC of 67% and a final weighted-average MC of 14% were determined for the green and dry lumber, respectively.

The oven dry (OD) weight of each coproduct, such as chips, sawdust, bark, and shavings, was measured using the samples randomly collected from the sawmill, with an aim to determine the MC of the co-products. The MC values obtained for the co-products were as follows: green chips at 92%, sawdust at 135%, bark at 150%, and dry shavings at 14%.

Lumber manufacturing mass balance

Mass balance involves accounting for all material inputs and outputs within a defined system boundary, considering all processes. This is crucial for accurately evaluating the products and co-products based on the unit of the final product (e.g., 1 m^3 of planed dry lumber). Three primary stages of production (i.e., sawing, drying, and planing) and boiler operation, and the entire value-chain process were considered to track material flow for the

Table 4. Average physical properties of the species sawn into lumber.

Species	Contribution (%)	Specific gravity (green)	Specific gravity (dry)	Green MC ¹ (dry basis) (%)	Dry MC ² (dry basis) (%)
Black Spruce	55	0.404	0.427	58	13
Balsam Fir	40	0.359	0.378	83	15
Jack Pine	5	0.402	0.431	46	14
Weight average		0.386	0.408	67	14

¹The moisture content of wood when freshly cut, expressed as a percentage of dry weight.

²The moisture content of wood after drying to stable moisture levels.

mass balance. All flow analyses of the products and coproducts in the process were determined on an OD weight basis, using the properties found in sample measurements and provided by the surveyed mill. Total of 1109.1 kg OD weight of incoming softwood logs, including bark with a density of 645 kg/m³, produced 1.0 m³ of planed dry lumber with an MC of 14%. Sawing produced 502 kg of rough green lumber, calculated by multiplying the green specific gravity (386 kg/m³) by the volume (1.46 m³) of rough green lumber used to produce 1 m³ of planed dry lumber. Additionally, the rough green lumber that remained within the system boundary to produce the planed dry lumber was almost 89% of the total lumber production, which was also multiplied to determine that 502 kg of rough green lumber is required to produce 1 m³ of planed dry lumber. For the co-products, the OD weight of the total value reported by the mill was calculated per m³ of planed dry lumber; the drying process did not result in any loss of wood substance. Planing reduced the 502 OD kg of rough dry lumber to 408 OD kg of planed dry lumber, for roughly a 19% reduction in mass. Boilers burned 61 OD kg of both green and dry mill residue (wood) fuel produced on-site (Table 5). Overall, a log excluding bark was reduced to almost 37% of its original mass in conversion to the final products of planed dry lumber. Table 5 provides a mass balance for a representative mill in New Brunswick’s softwood lumber manufacturing sector.

Gate-to-gate energy and material input/output

Material flows, energy use, and emissions data were normalized to the volume basis of 1 m³ output at each unit process. As said, all the survey data for each unit process were converted to each functional unit: per m³ of log for the log yard, per m³ of rough-green lumber for the sawmill, per m³ of rough-dry lumber for drying, and per m³ of planed-dry lumber for planing.

Log yard

Unloading log trucks, scaling logs (reporting logs for volume in m³), storing logs on decks, and moving logs to the sawmill were all of the activities included in the log yard process. Fuel types for equipment, such as loaders and forklifts used in the process of moving logs, are gasoline and diesel. There was also grease, antifreeze, hydraulic oil, and lubricant used in the equipment. In the log yard, a small quantity of electricity was used and considered in the calculation. The output at the log yard was the log with bark coming into the log yard; no wood material quantity changed in this unit process (Table 6).

Table 5. Mass balance for 1 m³ of planed dry lumber (all values are converted to OD kg).

Material	Sawing process		Boiler process	Drying process		Planing process		All Processes Combined		
	Input	Output		Input	Output	Input	Output	Input	Output	Diff
Logs	998.1							998.1	0.0	−998.1
Green chips		346.2						0.0	346.2	346.2
sawdust		89.6	39.6					39.6	89.6	50.0
Bark	111.0	111.0						111.0	111.0	0.0
Rough green lumber		501.7		501.7				501.7	501.7	0.0
Rough green lumber, sold		60.7						0.0	60.7	60.7
Rough dry lumber					501.7	501.7		501.7	501.7	0.0
planed dry lumber							408.0	0.0	408.0	408.0
Dry Shavings			34.5				91.0	34.5	91.0	56.5
Sum	1109.1	1109.1	74.0	501.7	501.7	501.7	499.0	2186.0	2110.0	−76.7

Table 6. Unit process inputs/outputs for log yard activities to produce 1 m³ of green logs.

		Amount	Unit	Allocation (%)
Output Input	Log at log yard (Including Bark)	1	m ³	100
	Log at mill (Including Bark)	1	m ³	
	Gasoline	0.00637	l	
	Diesel	0.787	l	
	Hydraulic fluid	0.0159	kg	
	Motor oils	0.00362	l	
	Grease	0.000265	kg	
	Antifreeze	0.0000748	l	
	Electricity	0.258	kWh	

Sawing (production of rough green lumber)

The sawing unit process involved several stages, including debarking logs, transforming logs into rough green lumber, sorting rough green lumber by size, and stacking the lumber for drying. Key inputs included logs with bark, diesel, and gasoline as fuels, and ancillary materials such as lubricant oil, hydraulic oil, grease, and antifreeze. Notably, the sawing process consumed the most electrical energy among all unit processes. The process generated outputs including green lumber at 45.2%, green chips at 31.2%, green sawdust at 8.1%, and bark at 10%. There was also 5.5% of the rough green lumber, which was sold and left the system boundary in the sawing unit process. Allocation of products and coproducts was based on oven-dry mass. While most wood residues were sold as coproducts, some were combusted as fuel for onsite heat generation to dry lumber. Table 7 summarizes the products and co-products outputs, as well as inputs required for the sawing process, which produces 1 m³ of rough sawed green lumber in the New Brunswick softwood sawmill.

Kiln-drying (production of rough dry lumber)

Rough-green stacked lumber had to be loaded into kilns to dry. Then the rough-dry stacked lumber would be unloaded from the kilns. These were the surveyed activities in the drying process. The primary inputs were rough green lumber, electricity, and diesel/gasoline used, and thermal energy produced by the boiler. The mill under the survey used continuous kilns, which are more energy efficient for drying softwoods than batch kilns (Salin &

Table 7. Inputs/Outputs for sawing unit process to produce 1 m³ of rough green softwood lumber.

		Amount	Unit	Allocation (%)
Output	Rough green lumber	1	m ³	45.2
	Rough green sold	42	kg	5.5
	Green chips	237.64	kg	31.2
	Sawdust	61.5	kg	8.1
	Bark	76.19	kg	10.0
Input	Roundwood	2.21	m ³	
	Gasoline	0.00649	l	
	Diesel	0.936	l	
	Hydraulic fluid	0.0736	l	
	Motor oils	0.00246	l	
	Grease	0.00117	kg	
	Antifreeze	0.000254	l	
	Electricity	46.99	kWh	
	Lubricant fluid	0.142	l	
	Paint	0.00127	kg	

Table 8. Unit process inputs/outputs for kiln drying to produce 1 m³ of rough dry softwood lumber.

		Amount	Unit	Allocation (%)
Output	Rough dry lumber	1	m ³	100
Input	Rough green lumber	1	m ³	
	Gasoline	0.000648	l	
	Diesel	0.0801	l	
	Hydraulic fluid	0.00367	l	
	Motor oils	0.000737	l	
	Grease	0.0000539	kg	
	Electricity	12.73	kWh	
	Paint	0.000380	kg	
	Heat, on-site boiler	1356	MJ	

Wamming, 2008). Rough dry lumber was the output of the drying process (Table 8). The softwood lumber is typically dried to a moisture content of 14%. In this surveyed sawmill, all the output rough-dried lumber would go to the planing process.

Boiler process (on-site heat production)

The combustion of wood in the boiler to generate heat was analyzed as a separate unit process within this survey. Also, water emissions from this process were reported based on the mill's water discharge test results. The boiler process primarily focused on producing heat energy for the kilns. The surveyed sawmill exclusively used wood-fuel boilers for supplying heat during the kiln-drying process, with no natural gas-fired alternatives. Wood fuel burned in the boiler is 100% from on-site produced material, comprising 56% sawdust and 46% planer shavings as inputs. Higher heating value (HHV) conversion was employed to represent the energy content of wood fuel combustion, assuming 20.9 MJ of energy produced per kg of OD wood. Table 9 shows the input and output of this unit process. Water emissions and a small amount of wood ash were reported as outputs from the mill's boiler process.

Table 9. Inputs/outputs for boiler unit process producing onsite heat.

		Amount	Unit	Allocation (%)
Output	Heat, on site boiler	20.9	MJ	100
	Wood ash	0.00236	kg	
Input	Water, process, well	0.00446	kg	
	Sawdust	0.562	kg	
	Shavings	0.438	kg	
	Gasoline	0.0000100	l	
	Diesel	0.00123	l	
	Hydraulic fluid	0.0000567	l	
	Electricity	0.00214	kWh	
	Motor oil	0.0000114	l	
	Grease	0.000000831	kg	
	Antifreeze	0.000000156	l	
Emission to Water	BOD	0.0268	mg	
	Suspended solids	0.0803	mg	
	Chromium	0.00446	µg	
	Iron	10.437	µg	
	Aluminum	2.101	µg	
	Nickel	0.00446	µg	
	Lead	0.00357	µg	
	Zinc	0.0178	µg	
	Metal Ion	0.201	mg	

Planing (production of packaged planed dry lumber)

The planing process involved several steps: unstacking rough dry lumber, planing the lumber, trimming, grading, sorting, stacking, strapping, and packaging the lumber, as well as transporting it within the planer mill to prepare for shipment. Inputs for this process included rough dry lumber, electricity, diesel, gasoline, lubricant oil, hydraulic oil, grease, antifreeze, plastic strapping, and lumber wrap. The outputs were packaged, planed dry lumber, sorted by type, size, and grade, as well as planer shavings (as shown in [Table 10](#)). This stage marks the final step in the surveyed manufacturing process. Some dry wood residue was burned on-site in boilers for energy, while some was sold as a co-product. The planed dry lumber takes up 82% of the total mass of the products and co-products from this process, with shavings making up the remaining 18%. The lumber is bundled, banded with plastic strapping, and wrapped for shipping.

Secondary data sources

[Table 11](#) lists the secondary LCI data used in this modeling of the LCA study for raw material inputs, ancillary materials and packaging, transportation, fuels, and energy for manufacturing.

Table 10. Inputs/outputs for planing unit process to produce 1 m³ of planed dry softwood lumber.

		Amount	Unit	Allocation (%)
Output	Planed dry lumber	1	m ³	82
	Shavings	91	kg	18
Input	Rough dry lumber	1.22	m ³	
	Gasoline	0.00306	l	
	Diesel	0.378	l	
	Hydraulic fluid	0.0173	l	
	Motor oils	0.00348	l	
	Grease	0.000286	kg	
	Electricity	26	kWh	
	Plastic strapping	0.0741	kg	
	Lumber wrap	0.169	kg	
	Lubricant fluid	0.0501	l	
	Antifreeze	0.0000479	l	

Table 11. Material LCI data drawn from the DataSmart database (LTS, 2023).

Data	LCI Data Source ¹
Diesel	US EI 2.2 (DataSmart2023): Diesel, combusted in Industrial equipment NREL/US U
Gasoline	US EI 2.2 (DataSmart2023): gasoline, combusted in industrial equipment/US
Propane	US EI 2.2 (DataSmart2023): Liquefied petroleum gas, combusted in industrial boiler/US
Electricity	Electricity mix, New Brunswick/CA U
Hydraulic fluid, Lubricant oil	US EI 2.2 (DataSmart2023): Lubricating oil, at plant/US- US-EI U
Motor oil, Greases	US EI 2.2 (DataSmart2023): Diesel, at refinery/l NREL /US
Antifreeze	US EI 2.2 (DataSmart2023): ethylene glycol, at plant/US - US-EI U
Paint	US EI 2.2 (DataSmart2023): Alkyd paint, white, 60% in H2O, at plant/US-US-EI U
Plastic strap	US EI 2.2 (DataSmart2023): Polyethylene, HDPE, granulate, at plant/ US- US-EI U
Lumber wrap	US EI 2.2 (DataSmart2023): Polypropylene resin, at plant NREL /RNA
Trucking	US EI 2.2 (DataSmart2023): Transport, combination truck, Diesel powered NREL/US U

¹⁾All data are for North America, except electricity (Canada), and reflect the year 2018.

Life cycle impact assessment (LCIA)

Linking the LCI to potential impacts on the environment is the goal of the LCIA phase. SimaPro (v9.6.0.1) was used to model the LCA of this cradle-to-gate softwood lumber product system (PRé Sustainability B.V [PR], 2024). Within SimaPro, all process data, including inputs and outputs, were considered and modeled to represent each unit process. The midpoint impact categories for acidification, eutrophication, global warming, smog, and ozone depletion were all determined using the TRACI method (Bare, 2011). Although the TRACI method addresses fossil fuel depletion on a global scale, it does not report primary energy use as an impact category. Therefore, the Cumulative Energy Demand (CED) method was also employed. CED calculates the total energy derived from all sources directly extracted from the Earth, including natural gas, oil, coal, biomass, nuclear, and hydropower (Frischknecht et al., 2007). This total primary energy is further categorized into nonrenewable fossil, nuclear, and renewable energies.

Cradle-to-gate environmental performance results for all reporting indicators are listed in Table 12 for softwood lumber produced in the New Brunswick region. It showed the values for A1-resource extraction, A2-transportation, and A3-softwood lumber production. About 62% of the CO₂eq (GWP) came from the lumber production process (26.6 kg CO₂eq/m³ of softwood lumber). Within the A3 stage, 37% of the GWP impact was from the lumber drying, which was the highest contribution. Followed by that is the sawing unit process, with 28%, due to notable electricity usage in this stage. Planing and log yard unit processes contributed 25% and 10%, respectively. 23% of the GWP impact resulted from the harvesting operations with 10 kg CO₂eq per m³ of softwood lumber product. Transportation, which is primarily the transport of logs to the sawmill, was 6.34 kg CO₂eq/m³ of softwood lumber or 15% of the cradle-to-gate GWP impact.

Lumber production (A3) represented the highest impacts for the ozone depletion, Acidification, Eutrophication, and fossil fuel depletion environmental impact categories compared with the resource extraction (A1) and transportation (A2). However, resource extraction (A1) had the highest impact on the smog category, only surpassing the lumber production process (A3) by a very small margin.

Table 12 also provides the values of energy and resources. The total energy consumption was 2,377 MJ/m³, with more than 50% of that being renewable energy consumption. Approximately 1,370 MJ/m³ of renewable biomass energy was consumed, most of which

Table 12. Cradle-to-gate environmental performance of 1 m³ planed dry softwood lumber based on mass allocation for New Brunswick, Canada.

Environmental Indicator		Unit	Total	A1	A2	A3
Impact Category	Global Warming	kg CO ₂ eq	43.02	10.06	6.34	26.62
	Acidification	kg SO ₂ eq	0.35	0.13	0.035	0.18
	Eutrophication	kg N eq	0.063	0.01	0.0032	0.050
	Smog	kg O ₃ eq	9.28	4.23	1.01	4.03
	Ozone Depletion	kg CFC-11eq	2.34E-06	8.36E-08	1.06E-08	2.25E-06
	Fossil Fuel Depletion	MJ surplus	69.94	20.06	11.23	38.66
Energy Consumption	Total primary energy	MJ	2377.16	152.73	85.48	2138.94
	Non-renewable fossil	MJ	610.33	150.50	84.26	375.56
	Non-renewable nuclear	MJ	380.75	2.09	1.15	377.51
	Renewable biomass	MJ	1369.85	0.06	0.03	1369.77
	Renewables (solar, wind, hydro and geothermal)	MJ	16.23	0.09	0.04	16.10

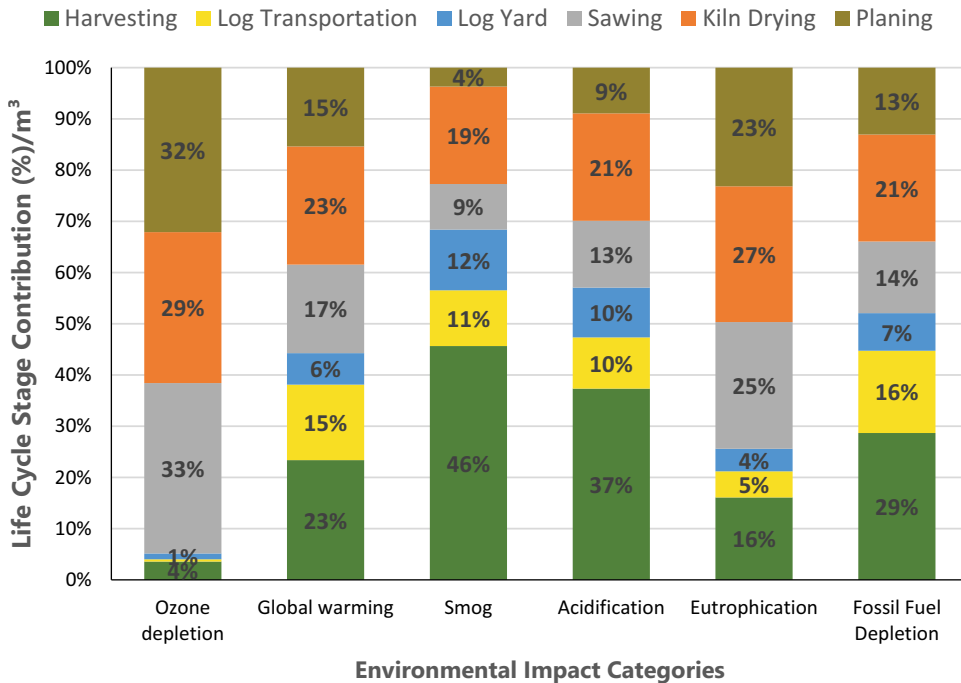


Figure 2. Contribution of unit processes in environmental impacts for the cradle-to-gate life-cycle stages of 1 m³ planned dry softwood lumber produced at one sawmill in New Brunswick, Canada.

came from the on-site combustion of wood for drying purposes (1,356 MJ/m³). Fossil energy amounted to 610 MJ/m³, primarily used for machinery, transportation, and electricity.

Figure 2 shows the contribution of the resource extraction and transportation stages and each unit process in the manufacturing stage (A3) separately in the six midpoint environmental impacts for the cradle-to-gate life-cycle stages of softwood lumber production. Compared with all stages and unit processes, harvesting had the largest impact in smog, acidification, and fossil fuel depletion with 46%, 37% and 29%, respectively. For the global warming impact, the harvesting process contributed equally to the kiln drying unit process, each at 23%. This was followed by the sawing unit process at 17%, and the planing unit process and transportation (A2), both contributing 15%. The lowest global warming impact was attributed to the log yard unit process (6%). Moreover, sawing, planing, and drying caused most of the impact in the ozone depletion impact category with 33, 32, and 29%, respectively.

Biogenic carbon

The production of 1 m³ of planned dry softwood lumber at a sawmill in New Brunswick resulted in approximately 43 kg CO₂eq of fossil-based greenhouse gas emissions from cradle to gate. The same volume of lumber contains about 408 kg of oven-dry wood, which corresponds to 204 kg of stored biogenic carbon (assuming a 50% carbon content (Bergman et al., 2014)). Using the molecular weight ratio of CO₂ to C (44/12), this equals

748 kg CO₂ of biogenic carbon stored in the product, approximately 17 times greater than the fossil emissions generated during the same system boundary. While this illustrates the potential for wood products to act as temporary carbon sinks, such results must be interpreted with caution, as end-of-life emissions are not included. The study by Andersen et al. (2021) showed that some LCAs reporting low or even negative embodied GHG emissions often applied the -1/+1 approach inconsistently by including carbon uptake during production while omitting carbon release at EOL. In contrast, their study did not apply the -1/+1 approach and did not assume carbon neutrality. The biogenic carbon content is reported separately and transparently, without being treated as a credit against emissions. The actual climate impact of stored biogenic carbon heavily depends on the end-of-life fate of the wood, which can vary significantly depending on whether the material is landfilled, incinerated, reused, or recycled. As Zahabi et al. (2025) and others have pointed out, these end-of-life scenarios can substantially influence net emissions outcomes. Therefore, future work should incorporate dynamic or cradle-to-grave modeling approaches to more accurately capture long-term biogenic carbon flows and their implications for climate change mitigation.

Discussion

In 2018, the Athena Institute released an LCA report on the lumber produced in Eastern Canada using the SimaPro LCA tool, covering Ontario, Quebec, and one sawmill in New Brunswick (Athena Sustainable Materials Institute, 2018). The primary data were collected based on the 2015 calendar year production of 4 mills and were weighted and aggregated with data for 10 other facilities based on the 2006/2007 data in order to increase the overall sample size. The report mostly relied on secondary sources as assumptions for the specific gravity, MC, and other wood properties. In this study, all the properties of the wood were determined by actual measurement of samples from the surveyed mill. The measured values were found to be very close to the previous study.

Table 13 shows the comparison between the previous study by Athena Sustainable Materials Institute (2018) and this study (2022 data). The total GWP in the current study increased by 10% compared to the previous report, primarily due to a 30% higher GWP impact during the manufacturing stage. This study reported no usage of gas in the boiler, whereas the previous report indicated that approximately 0.8 m³ of natural gas was used

Table 13. LCIA comparison between previous data (Athena Sustainable Materials Institute, 2018, based on different regions in eastern Canada) and current study data (based on New Brunswick industry surveys in 2022) on softwood lumber production.

Impact Category	Units	Current Study	Past Study	Percent change (%)
Global warming potential	kg CO ₂ eq	43.02	39.06	10
Acidification	kg SO ₂ eq	0.35	0.45	-22
Eutrophication potential	kg N eq	0.064	2.46E-02	158
Smog potential	kg O ₃ eq	9.28	10.46	-11
Ozone depletion potential	kg CFC11e	2.34E-06	1.39E-06	69
Total primary energy	MJ	2377.16	2508.8	-5
Non-renewable fossil	MJ	610.33	598.99	2
Non-renewable nuclear	MJ	380.75	109.33	248
Renewable biomass	MJ	1369.85	1756.26	-22
Renewables (solar, wind, hydro and geothermal)	MJ	16.23	44.22	-63

per m³ of planed dry lumber. This saving was compensated by the higher electricity usage per m³ of planed dry lumber in the production stage of this study (86 kWh) compared to the previous one (71 kWh/m³). Additionally, all the electricity used in this surveyed sawmill was purchased, with no on-site renewable electricity generation reported.

Moreover, there was a 5% decrease in total primary energy use in the production of softwood lumber in this study (2,377 MJ/m³) compared with the previous study (2,509 MJ/m³ using the higher heating value of all fuel – energy inputs) (Athena Sustainable Materials Institute, 2018). The use of nonrenewable fossil energy also had a slight increase, with almost 2% in the current study, bringing it to 610 MJ/m³. However, the renewable biomass energy consumption was 22% lower in the current study, which is mainly due to lower wood OD kg combustion on-site to generate energy in this study.

The environmental impacts of a product are significantly influenced by the technology and the fuel types used in regional electricity generation. The evidence was shown by the study of comparisons of wood product manufacturing across different geographic locations (Puettmann & Wilson, 2005). This study found a 40% increase in nonrenewable energy use and a 23% decrease in renewable energy use compared to the Athena Institute report, which represents the average data from various eastern Canadian provinces. Specifically, non-renewable nuclear energy usage increased by 248% in this study, while renewable energy sources (such as solar, wind, and hydro) decreased by 63%. These differences were primarily due to New Brunswick's high reliance on nuclear power at 38% and low reliance on hydro at 20%, in contrast to other eastern provinces like Quebec, which relied 94% on hydropower (LTS, 2023).

A study by Siddiqui and Dincer (2017) analyzed the environmental impacts of nuclear, wind, and hydropower plants in the Province of Ontario, Canada, using a cradle-to-grave LCA and CML 2001 methods. They found that wind power had the highest eutrophication impact, while hydropower had substantially lower impacts. Despite similar wind and hydropower percentages in New Brunswick and Ontario's electricity profile (11 and 23%, respectively) (LTS, 2023; Siddiqui & Dincer, 2017), Quebec's near-total reliance on hydropower led to lower eutrophication impacts in the Athena Institute's LCA study on lumber produced in eastern Canada (Athena Sustainable Materials Institute, 2018). In contrast, this study's focus on New Brunswick resulted in a 158% increase in eutrophication impacts. Overall, these differences are attributed to variations in raw material usage and energy sources across different regions. This underscores the importance of regionalizing LCI data to accurately capture local environmental impacts.

In addition, with growing interest in reducing embodied carbon in the built environment, especially through material substitution and improved carbon accounting, having accurate and region-specific LCI data is essential. This study provided updated primary data from New Brunswick, helping address a key gap: the lack of reliable, localized information about wood product emissions. As highlighted by the CSA Group [CSA] (2024), one of the key challenges in enabling circular wood construction is the lack of accurate, up-to-date information on material inventories and end-of-life pathways. The transparent GHG data at the product level in this study contribute to filling this gap. In the future, such studies can support the development of regionally adapted frameworks for tracking and modeling end-of-life pathways of wood products in New Brunswick, ultimately informing more realistic carbon accounting methods and supporting long-term policy goals in sustainable construction.

Conclusions

This study conducted a cradle-to-gate LCA analysis on planed kiln-dried softwood lumber from a single sawmill in New Brunswick, using both primary production data and secondary material/energy LCI data from the DataSmart database. The following conclusions were drawn from the study:

- 77% of overall energy consumption was attributed to the lumber production, with sawing and kiln drying contributing the most to GWP within the production stage.
- Harvesting had significant impacts on smog formation (46%), acidification (37%), and fossil fuel depletion (29%).
- Renewable energy, primarily woody biomass, accounted for 58% of total energy consumption, while 42% came from nonrenewable sources. Transportation and harvesting contributed 14 and 25%, respectively, to nonrenewable fuel usage.

To further reduce the overall use of nonrenewable energy and the associated environmental impacts, increasing the use of renewable biomass sources, such as mill or forest residues, directly and indirectly, especially throughout the production stages, would be recommended. Utilizing these residues could provide a sustainable energy alternative throughout the production stages, thereby reducing reliance on fossil fuels and minimizing the environmental footprint of softwood lumber production in New Brunswick. Implementing these strategies could greatly contribute to more sustainable industry practices and, more broadly, the findings provide region-specific LCA data that can serve as a valuable reference for advancing sustainability policies and developing low-carbon building standards in New Brunswick.

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Data availability statement

The data that support the findings of this study are available within the paper, and additional data are available upon request.

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