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The Cradle-to-Gate Life Cycle Assessment on Hardwood Lumber Production in New Brunswick, Canada

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Abstract: This case study conducted a cradle-to-gate life cycle assessment (LCA) on the production of hardwood lumber in New Brunswick, Canada, evaluating the environmental impacts from raw material extraction to the point where lumber exited the mill as rough green lumber, the primary input for manufacturing pallets and railway ties. Data on annual production, material flow, and energy use for harvesting and sawmilling were gathered through survey questionnaires and on-site visits. The life cycle inventory (LCI) was developed in SimaPro software, the life cycle impact assessment (LCIA) was conducted using the North American TRACI method to quantify impact categories, and the cumulative energy demand (CED) method was employed to analyze the total energy consumption. It was found that rough green hardwood lumber production emitted approximately 41 kg $CO_2{}^{-}eq/m^3$ (excluding biogenic carbon storage), with manufacturing accounting for 42% of total emissions and consuming 736 MJ/m^3 of total energy, 98% of which came from non-renewable sources. The carbon stored in lumber was 975 CO_2 eq/m^3, 24 times greater than its cradle-to-gate emissions, highlighting its significant environmental benefit. Future research will aim to conduct a cradle-to-grave LCA on hardwood production by including drying and planing and increase the number of sawmill samples.

Keywords: biogenic carbon; carbon emission; cradle-to-gate life cycle assessment; cumulative energy demand; environmental impact; hardwood lumber production

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1. Introduction

The growing urgency to address climate change has made carbon neutrality the priority of global environmental goals [1]. Carbon neutrality refers to the state in which the net amount of carbon dioxide (CO_2) or other greenhouse gases (GHGs) emitted into the atmosphere is balanced by an equivalent amount being removed or offset, resulting in zero net emissions and minimizing the impact on the climate [2].

Wood, as a natural, renewable, reusable, and recyclable resource, plays a critical role in reducing environmental impacts and contributing to carbon neutrality [3]. During growth, trees sequester carbon dioxide from the atmosphere, storing it as carbon within the wood [4,5]. This stored carbon remains in wood products throughout their active service lives until disposal or combustion [6,7]. In the context of wood, carbon neutrality assumes that carbon emissions from the combustion or decomposition of wood biomass—classified as biogenic carbon—are part of the natural carbon cycle and are offset by the carbon absorbed by newly planted trees [8]. Recent studies in material science have extensively analyzed the role of wood in carbon sequestration and its comparative advantages over steel and concrete in construction [9–12], as well as in reducing the CO_2 emissions [13].

Gustavsson and Sathre stated that the CO_2 emissions produced in an apartment buildings using traditional construction was up to 5.6 times higher than the apartment buildings using mainly wood-based construction materials [14]. However, achieving true carbon neutrality for wood requires consideration of carbon emissions across the entire lifecycle of wood products, including those generated during production processes such as harvesting, sawing, drying, and transportation. Additionally, sustainable forestry practices, forest regrowth, and the proper end-of-life management of wood products are essential to maximize the duration of carbon storage [15–18]. The Government of New Brunswick, Canada, has set regulations and policies to reduce GHG emissions, which are, under the RCP 8.5 scenario reported in the IPCC Fifth Assessment Report (AR5), projected to increase global temperatures by approximately 3.5 °C by the end of the century [19,20]. These regulations support the goal of carbon neutrality by 2050 set by the Government of Canada, as well as the commitment to achieving the United Nations' Sustainable Development Goals (SDGs) [21]. The Action Plan outlines 118 strategies to promote sustainability across various sectors, including construction. Among these, Action Plan 21 integrates wood products with favorable life cycle assessment (LCA), recognizing their potential to reduce environmental impacts, while Action Plan 61 promotes wood as a renewable construction material through updated building codes and standards [22]. Forest landowners and wood product manufacturers must adapt to strict environmental regulations and enhance their market competitiveness. By prioritizing sustainable practices and using renewable materials like wood from managed forests, industry can reduce the environmental footprint and increase opportunities for green marketing [23]. However, careful evaluations are crucial for making well-informed choices about responsibly and sustainably using valuable forest resources [24], and the environmental benefits of wood-based products must be appropriately quantified using relevant tools [25–27]. 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 a product or service [28,29]. 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 [29]. LCA 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" [30]. Milota (2015) conducted a gate-to-gate LCA of softwood lumber production, covering the process from log delivery to dry lumber output but excluding forestry and disposal stages [31]. In contrast, Puettmann and Wilson (2007) performed a cradle-to-gate LCA that ranged from forest regeneration to product transportation to the building site [32]. The environmental impacts of wood-based products vary due to differences in harvesting methods, transportation distances, and manufacturing technologies. The harvesting of trees uses a lot of fossil fuels since it entirely depends on diesel for large machines and gasoline for chainsawing and crew transportation [33]. Abbas and Handler (2018) conducted an LCA study on the harvesting and transportation of hardwood and softwood species in Tennessee, USA, focusing primarily on hardwood species, such as oak (*Quercus*) and hickory (*Carya*), and some softwood species, such as pines (*Pinus*). Using the SimaPro LCA tool, they found that transportation distances significantly influence GHG emissions in wood supply chains, while harvesting methods, such as chainsaw-based versus feller buncher-based systems, yield varying energy demands and emissions [34]. Gu et al. (2022) conducted a cradle-to-gate LCA to evaluate the environmental impacts of transporting mass timber products for a mid-rise institutional building in New Brunswick, Canada. Their study compared a steel frame building with a mass timber alternative and found that the mass timber design resulted in greater impacts on smog formation, acidification, and eutrophication. These increased impacts were attributed to the longer transportation distances and greater diesel fuel consumption required to transport mass timber components to New Brunswick [35]. Studies have shown that manufacturing contributes the most to CO_2 emissions and energy consumption in product life stages. According to Miner (2010), manufacturing accounted for 55% of total emissions across the value chain, equating to around 490 million tonnes of CO_2 equivalent annually [36]. The leading cause of these emissions was the burning of fuel in manufacturing plants, which significantly impacts the sector's GWP [37]. Meil et al. (2009) examined the status of energy use in Canadian wood products sector, and they discovered that kiln drying was the most energy-intensive process, consuming 66% of the total energy required to produce the softwood lumber, while 73% of natural gas and 97% of biomass thermal fuels were used for kiln drying [38]. This aligns with findings indicating that the drying process was a significant energy consumer in lumber production [39–41]. Other energy-consuming unit processes include sawing, surface planing, and packaging. Also, several studies have concluded that the sawing process consumed the highest percentage of electrical energy [38,39,42–44]. However, most of the thermal energy and electricity needed at the mill is produced by burning a fuel, such as wood, natural gas, or leftover green wood waste. Thermal energy is typically produced on-site from biomass or wood residues [44], primarily for drying timber. However, electricity from off-site sources like coal and natural gas is mainly used for sawing, though some mills utilize co-generation from wood residues for electricity generation. Puettmann and Lippke (2012) used SimaPro LCA software to study the effects of substituting natural gas with wood pellets, mill waste, and forest waste for electricity generation or heat production during drying. They found that using woody biomass significantly reduced carbon emissions compared to fossil fuels [45]. Considering the other factors, which affect the manufacturing LCA result of the wood products, Bergman and Bowe (2008) studied hardwood lumber manufacturing using the LCI methodology and reported that hardwood lumber production required more thermal and electrical energy than softwood lumber due to its higher density and longer drying time [39]. Chen et al. (2019) conducted a comprehensive LCA on CLT produced in the Western Washington region of the United States. They aimed at analyzing the environmental impacts related to transportation, location, and the mix of wood species in CLT panels. The study considered the entire lifecycle, from seedling to transportation and construction on-site, located in Seattle, WA, USA. The results indicated that sourcing local lumber and using lighter wood species in CLT manufacturing facilities could lead to a 14% reduction in the overall GWP of the CLT panels [46]. Moreover, the sources of energy can be different in the different regions of product manufacturing, which can also play a significant role in the environmental impacts due to the variation in technology and fuel used to produce electricity or other energy sources in different areas. For instance, hydro-based energy in the Pacific Northwest resulted in lower GWP compared to coal-based energy in the Southeast USA [42]. These findings emphasize the importance of various factors in LCA outcomes.

This case study was aimed at conducting a cradle-to-gate LCA of the production of hardwood lumber in an effort to understand how well it aligns with New Brunswick's Action Plan as set out in 2016. Our analysis measured the environmental impacts from the extraction of raw materials, including harvesting in this case, and continuing through to the production of rough green hardwood lumber in New Brunswick, Canada, at the point at which the hardwood lumber was the raw material used to produce the products without experiencing kiln-drying, such as pallets and railway ties. Therefore, the findings of this study could provide a foundational base for conducting cradle-to-grave LCAs for secondary hardwood products.

2. Materials and Methods

2.1. Goal and Scope of LCA

The objective of this study was to evaluate the cradle-to-gate environmental performance of the production of hardwood lumber and to develop an LCI for producing hardwood lumber in New Brunswick, Canada. Additionally, this study was aimed at comparing the results with the cradle-to-gate LCA of the production of softwood lumber in the same region. The scope of this study is given as follows.

2.1.1. Functional Unit

To assess a product's total life cycle environmental impact, the functional (reference) unit of the product must be first defined to assemble the inputs and outputs for different environmental impacts. Given that the analysis focused on the primary hardwood lumber product, 1 m^3 of rough green hardwood lumber was defined as the functional unit in this LCA study.

2.1.2. System Boundary

The system boundary of this study is cradle-to-gate, encompassing the extraction of resources (i.e., tree harvesting), transportation of harvested trees to the sawmill plants, and the production of hardwood lumber, and focusing on debarking and sawing processes only (Figure 1). Drying and planing unit processes were excluded from this study because the focus was on the production of rough green hardwood lumber, which is primarily used to produce pallets and railway ties in the mill examined.

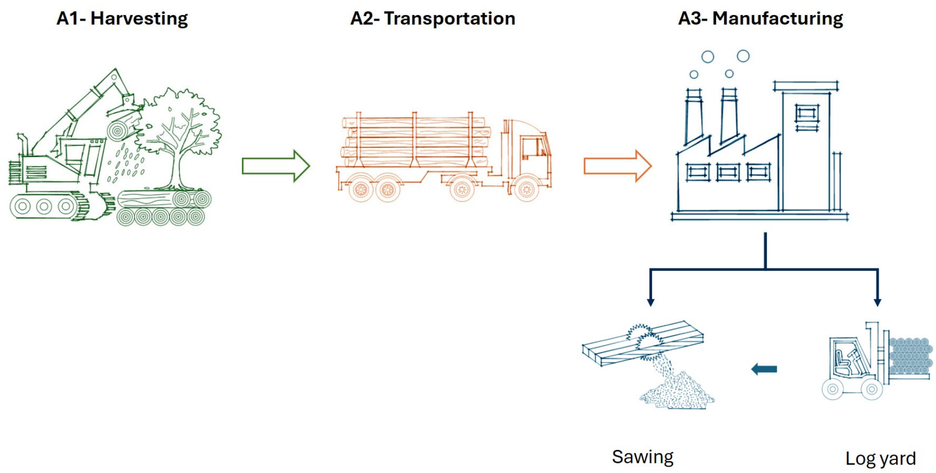

Figure 1. Diagram of the lumber manufacturing process for producing hardwood lumber in New Brunswick, Canada.

Forest management activities such as fertilization, thinning, planting seedlings, and nursery operations were not included. Only the final harvesting phase provided first-hand (data) information as resource extraction.

Major fuels like diesel, gasoline use, and the primary fuels used to generate electricity were collected for modeling the LCA within the system boundary. Additionally, important ancillary materials, such as hydraulic fluids, motor oils, greases, and plastic strapping, were considered within the system boundary.

2.2. Life Cycle Inventory (Data Collection and Calculations)

In this study, data on material and energy inputs were collected via survey questionnaires for log harvesting and site visits for sawmill manufacturing. The samples included one logging company and two types of hardwood sawmills in a facility in New

Brunswick: one mill focused on producing pulp chips in addition to rough green lumber from low-quality logs, and the other primarily producing lumber from high-quality logs.

The year 2022 was chosen as the representative year for this analysis. Material and energy consumption values for hardwood lumber production were determined by surveying one hardwood logging company and two types of hardwood mills, including hardwood sawlogs (high grade) and hardwood pulpwood/pallet, in New Brunswick, Canada. Detailed questionnaires, follow-up emails, and site visits were conducted to gather the data. Data from the mill questionnaire were weight-averaged using Equation (1):

$$\overline{P}_{Weighted} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i} \quad (1)$$

where 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.

The secondary data of life cycle emissions from use of diesel, gasoline, propane, grid energy mix, auxiliary materials, and transport were sourced from the DATASMART LCI database [47], which is specifically built for North American SimaPro users. The DATASMART LCI database provides comprehensive LCI data tailored to North America, incorporating U.S.-specific geographic and technological details. It is based on foundational datasets from US LCI v.1.60 and Ecoinvent v.2.2. The US LCI database v.1.60 provides detailed inventory data for energy production, industrial processes, and transportation specific to the United States. Ecoinvent v.2.2 complements this by offering extensive global data for processes and materials not covered in US LCI. DATASMART builds on these datasets by incorporating additional regional data developed via long-trail sustainability (LTS), ensuring that it is comprehensive and tailored to North American contexts.

2.2.1. Resource Extraction

Total production of harvested logs, including bark, in 2022 was 305,000 m^3 from the one harvesting company that participated in the survey. Overall, four hardwood species, namely, yellow birch (*Betula alleghaniensis*), white birch (*Betula papyrifera*), sugar maple (*Acer saccharum*), and red maple (*Acer rubrum*), represented 70% of the species mix harvested. Twenty percent was aspen (*Populus tremuloides*), and a small amount of softwood was also harvested from mixed forest stands. As reported, hardwood trees on average returned 10% high-grade saw logs, 30% pallet-grade logs, and 60% pulp-wood grade logs. Fully mechanized systems were used for harvesting. Diesel and gasoline served as the process's primary energy inputs, with the utilization of ancillary materials such as motor oil, grease, hydraulic fluid, lubricating fluid, and antifreeze. The equipment used included a feller buncher, a forwarder, a single-grip processor, a grapple skidder, a delimber, and a slasher. Moreover, 18 trucks were used to transport logs in the woods, as well as 13 self-loader trucks and 5 quads with a loader. The main product of this process was logs destined for lumber mills. The co-product, non-merchantable slash, was generally recovered or left on the ground. However, the survey respondents in this study assumed the residues left to decay during harvesting to be about 0.165 m^3 per m^3 of roundwood. The energy and ancillary material inputs used per m^3 of roundwood by the logging company that participated in the survey is shown in Table 1.

Table 1. Inventory data of resource extraction.

Resource	Inputs	Unit	Amount per m^3 of Roundwood
Energy	Diesel fuel	liter	3.69
	Gasoline	liter	0.70
	Propane	liter	0.01
Ancillary Materials	Hydraulic fluid	liter	0.054
	Motor oil	liter	0.02
	Greases	kg	0.0017
	Antifreeze	liter	0.0014

2.2.2. Transport of Raw Materials from the Extraction Site to the Sawmill

Logs were transported by diesel trucks to the mills, with an average one-way distance of 118 km. This transportation was modeled as a stand-alone unit process rather than an input to the log yard process (Table 2). The calculation of 104 tkm (tonne–kilometers) was based on the average green mass of 1 m^3 logs, calculated as 883 kg, and the transportation distance in kilometers.

Table 2. Inventory for transportation to the sawmills.

		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	104	tkm	-

2.2.3. Product Manufacturing Process

This study considers lumber manufacturing processes, specifically focusing on log yard and sawing operations, with an emphasis on producing "green" lumber.

In 2022, the surveyed sample mills produced approximately 68,429 thousand board feet (MFBM) (161,493 m^3) of rough green lumber. Annual lumber product output (rough green) was reported by the mill in MFBM. A conversion factor from MFBM to m^3 for rough green lumber was assumed to be 2.36 m^3/MBFM. It was assumed that 100% of the production was sold either as lumber to an external client or transferred (sold) to another mill for further transformation.

2.2.4. Species, Moisture Content, and Specific Gravity of the Woods Examined

Birches, aspens, and maples were included among the types of wood species used to produce hardwood lumber in both mills, as reported by the sawmill manufacturing.

Samples from different parts of the tree logs, including full-length logs and tree-top logs, were taken from the hardwood sawmills to determine the moisture content (MC) and specific gravity (SG) of the lumber. A full-length log refers to the main trunk section(s) of a tree, which is longer and typically of higher quality, used predominantly for lumber products. A tree-top log, on the other hand, is the smaller section(s) near the crown of the tree and are generally of lower quality, often utilized for by-products such as chips, pulpwood, or biomass energy.

The samples were then sent to the University of New Brunswick's Wood Science and Technology Center (WSTC) in Fredericton, Canada, for measuring the volume and weight of the samples and physical properties such as MC and SG following ASTM D143 standard [48]. These two attributes were crucial for data calculation and conversion in the following LCA analysis, ensuring an accurate mass balance.

Table 3 shows that the average MC was 67%, and the average green SG was 0.532 for the lumber examined. These values were calculated based on the weighted average of species distribution percentages, MC, and SG for each species. Data on both green and oven-dry weights were used to calculate the MC, while green volume and oven-dry weight were used to calculate the SG for samples from each mill.

Table 3. Average physical properties of the log species sawn into lumber.

Species	Contribution	MC	Green SG
Birch (*Betula* spp.)	50%	65%	0.530
Maple (*Acer* spp.)	32%	58%	0.594
Aspen (*Populus* spp.)	17%	89%	0.421
Weighted average		67%	0.532

In order to calculate the oven-dry (OD) weight of the chips, sawdust, and bark, the weighted average MC of these by-products was determined using the sample measurement method. Samples were cut to include both heartwood and sapwood. The sapwood MC was assumed to be the same as the MC of the bark and sawdust, while the MC of chips was considered a mix of sapwood and heartwood MC [49]. Consequently, the reported co-products included green chips with an MC of 67%, and sawdust and bark with a MC of 71%.

2.2.5. Lumber Manufacturing Mass Balance and Conversion Efficiencies

Mass balance involves accounting of all material inputs and outputs within a defined system boundary, including all the processes. In this study, mass balance was performed based on the oven dry mass of roundwood inputs and process outputs (i.e., rough green lumber and co-products) using the properties found in sample measurements and provided by the surveyed sawmills. A total of 1461 oven dry (OD) kg of incoming hardwood logs, including bark with a density of 883 kg/m^3, produced 1.0 m^3 (532 OD kg) rough green lumber for an approximately 64% reduction in mass. For the co-products, the OD weight of the total value reported by the mills was calculated per m^3 of rough green hardwood lumber. Table 4 provides a mass balance for New Brunswick hardwood lumber manufacturing.

Table 4. Wood mass balance for 1 m^3 of rough green lumber (values in oven dry kg).

Material Type	Sawing Process	
	Input (kg)	Output (kg)
Logs	1336.4	
Green chips		692.5
Sawdust		111.9
Bark	124.7	124.7
Rough green lumber		532
Total OD Mass	1461.1	1461.1

Cubic lumber recovery (CLR) was calculated by determining the m^3 of lumber produced per m^3 of log input. In this study, the breakdown of logs into rough green lumber during sawing resulted in a weighted average CLR of 0.36 m^3 of rough green lumber per m^3 of logs. This means that, on average, 2.75 m^3 of logs are sawn to produce 1.0 m^3 of rough green lumber. Therefore, the total volume conversion from incoming logs to lumber products is 36.4%.

2.2.6. Gate-to-Gate Energy and Material Input/Output

The lumber manufacturing process for producing the rough green lumber was divided into two unit processes: log yard and sawing. The weighted average material flows and energy use in the lumber manufacturing process were normalized to 1.0 m^3 volume of each unit process, i.e., per m^3 of logs in the log yard and per m^3 of rough-green lumber in the sawmill.

2.2.7. Log Yard

The log yard process included unloading log trucks, scaling logs (reporting logs for volume in m^3), sorting logs on decks, and moving logs to the sawmill. Diesel was the most-often-used fuel for the equipment—such as loaders, forklifts, and other on-site transportation—used to move logs around the log yard, with gasoline being used to a lesser extent. There was also grease, antifreeze, hydraulic oil, and lubricant utilized. In the log yard, a small quantity of electricity was used. Outputs include logs with bark at the log yard (Table 5).

Table 5. Unit process inputs/outputs for log yard activities to produce 1 m^3 of green logs.

		Amount	**Unit**	**Allocation**
Output	Log at log yard (including bark)	1	m^3	100%
Input	Log at mill (including bark)	1	m^3	
	Gasoline	0.02	L	
	Diesel	3.03	L	
	Hydraulic fluid	0.04	L	
	Motor oils	0.0074	L	
	Grease	0.00077	kg	
	Antifreeze	0.00094	L	
	Electricity	0.143	kWh	

2.2.8. 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. Electricity was the primary energy input in the sawing process. The mills also burned their own wood wastes in an industrial boiler for heating the facility. However, the data of their consumption were not reported. The process generated outputs, including green lumber at 36%, green chips at 47%, green sawdust at 8%, and bark at 9%. The allocation of products and coproducts was based on oven-dry mass. Chips were either sold to external clients (paper mills) or used by the pellet plant. Sawdust was similarly used in the pellet plant for making pellets. Bark was either sold or used in the boilers for heating and drying purposes.

Table 6 summarizes the products and co-products outputs, as well as inputs required for the sawing process, which yields 1 m^3 of rough sawn green lumber in the New Brunswick hardwood sawmills.

Table 6. Unit process inputs/outputs for sawing to produce 1 m^3 of rough green hardwood lumber.

		Amount	Unit	Allocation
Output	Rough green lumber	1	m^3	36%
	Green chips	692.50	kg	47%
	Sawdust	111.9	kg	8%
	Bark	124.67	kg	9%
Input	Roundwood	2.75	m^3	
	Gasoline	0.00513	L	
	Diesel	0.814	L	
	Hydraulic fluid	0.0373	L	
	Grease	0.00372	kg	
	Electricity	61.44	kWh	
	Lubricant fluid	0.437	L	
	Plastic strapping	0.116	kg	

2.2.9. Secondary Data Sources

Table 7 lists the secondary LCI data sources used in this LCA study for raw material inputs, ancillary materials and packaging, transportation, and fuels and energy for manufacturing. The assumptions are based on the DATASMART LCI database, utilizing U.S. Life Cycle Inventory (US LCI v1.60) and Ecoinvent v2.2 datasets. These datasets are adapted to reflect the North American context, including the electricity mix specific to New Brunswick.

Table 7. Secondary data sources [47]. All data are for North America, except electricity (Canada), and reflect the year 2018.

Data	LCI Data Source
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
Plastic strap	US EI 2.2 (DataSmart2023): polyethylene, HDPE, granulate, at plant/US-US-EI U
Trucking	US EI 2.2 (DataSmart2023): transport, combination truck, diesel-powered NREL/US U

3. 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 [50] was used to generate LCIA results of this cradle-to-gate hardwood lumber product system. All inputs and outputs for each unit process were carefully modeled within SimaPro to ensure accurate representation of the processes involved. The midpoint impact categories for acidification, eutrophication, global warming, smog, and ozone depletion were determined using the TRACI method [51] due to its characterization factors, which specifically designed to quantify environmental impacts in alignment with U.S. These factors ensure consistent, accurate assessments, producing results that are both scientifically valid and regionally relevant. While the TRACI method considers fossil fuel depletion, it does not include primary energy use as an impact category. Consequently, the cumulative energy demand (CED) method [52] was also utilized. CED calculates the total energy derived from all sources directly extracted from the earth, including natural gas, oil, coal, biomass, nuclear, and hydropower. This total primary energy is further categorized into non-renewable fossil, nuclear, and renewable energies.

Cradle-to-gate environmental performance outputs for the reported indicators are listed in Table 8 for one m^3 of hardwood rough green lumber produced in the New Brunswick region. It separates the impact values of the A1 stage (resource extraction), A2 stage (transportation), and A3 stage (hardwood rough green lumber production). About 42% of the CO_2 eq or the global warming potential (GWP) came from producing lumber (17 kg CO_2 eq). Thirty four percent is from harvesting operations with 13.8 kg CO_2 eq. Transportation, which is primarily the transport of logs to the sawmill, was 9.8 kg CO_2 eq or 24% of the cradle-to-gate GWP impact. The total cradle-to-gate GWP impact to produce one cubic meter (1 m^3) of rough green hardwood lumber is 40.7 kg CO_2 eq.

Table 8. Cradle-to-gate environmental performance of 1 m^3 rough green hardwood lumber based on mass allocation for New Brunswick, Canada.

	Environmental Indicator	Unit	Total	A1	A2	A3
Impact Category	Global warming	kg CO_2 eq	40.67	13.82	9.84	17.01
	Acidification	kg SO_2 eq	0.40	0.18	0.054	0.17
	Eutrophication	kg N eq	0.045	0.014	0.005	0.026
	Smog	kg O_3 eq	12.07	5.74	1.57	4.76
	Ozone depletion	kg CFC-11 eq	9.88×10^{-7}	6.42×10^{-8}	1.64×10^{-8}	9.08×10^{-7}
	Fossil duel depletion	MJ surplus	73.71	27.28	17.43	29.00
Energy Consumption	Total primary energy	MJ	736.08	207.75	132.69	395.64
	Non-renewable fossil	MJ	583.66	204.74	130.79	248.13
	Non-renewable nuclear	MJ	141.32	2.82	1.78	136.71
	Renewable biomass	MJ	5.09	0.074	0.045	4.98
	Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	0.11	0.063	5.83

Table 8 also provides the values for the energy resources. The total energy consumption was 736 MJ/m^3, with 54% of that being for the manufacturing stage. Following this was harvesting and transportation, with 28 and 18%, respectively. In this study, 98% of the total energy consumption was non-renewable, mainly from fossil sources used for machinery and transportation, amounting to 583.6 MJ/m^3. Due to the exclusion of drying processes, and also the lack of on-site electricity generation, which typically involve biomass energy combustion, the total renewable energy consumption was significantly low, at just 11 MJ/m^3, making up only 2% of the total energy consumption (Figure 2). Moreover, electricity in New Brunswick does not mainly rely on renewable sources, with about 30% coming from fossil sources such as hard coal and natural gas. Harvesting, on the other hand, was a fossil energy-intensive process that relied on diesel use for heavy machinery and gasoline for crew transport.

Figure 3 shows the contributions of the resource extraction, transportation, and manufacturing stage (A3) in the six midpoint environmental impacts for the cradle-to-gate LCA of hardwood lumber production. Compared with all stages, lumber production (A3) represented the highest impacts for ozone depletion, global warming, eutrophication, and fossil fuel depletion environmental impact categories, with 92, 42, 58, and 39%, respectively. However, resource extraction (A1) had the largest effects on the smog and acidification impact category, differing from lumber production (A3) by a very little margin.

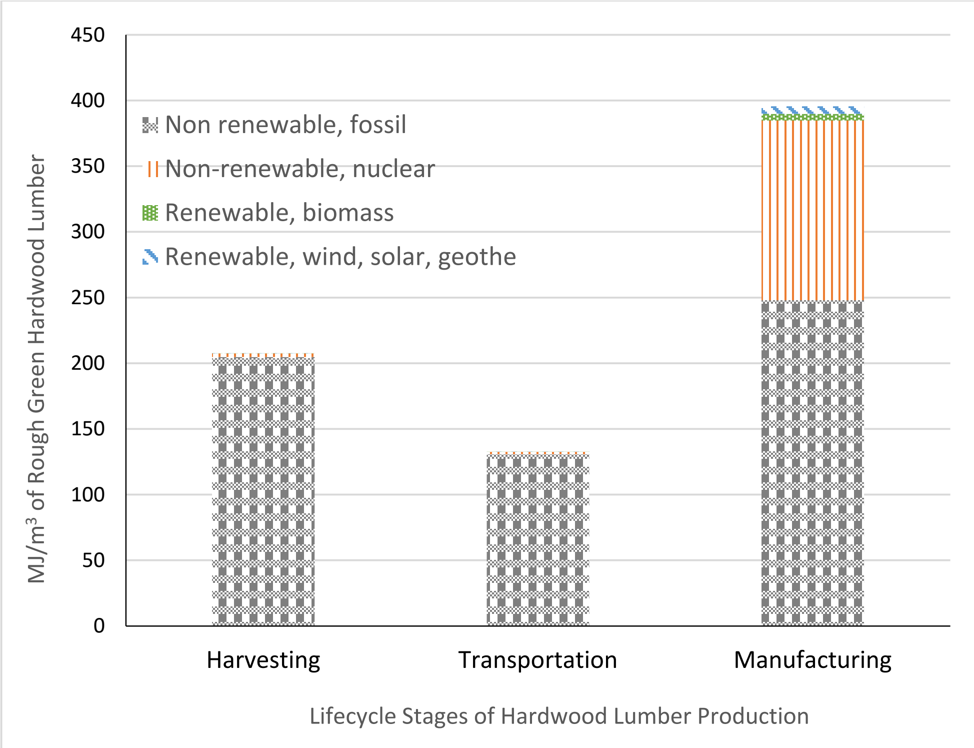

Figure 2. Energy consumption across different stages of producing 1 m^3 of rough green hardwood lumber in New Brunswick, Canada.

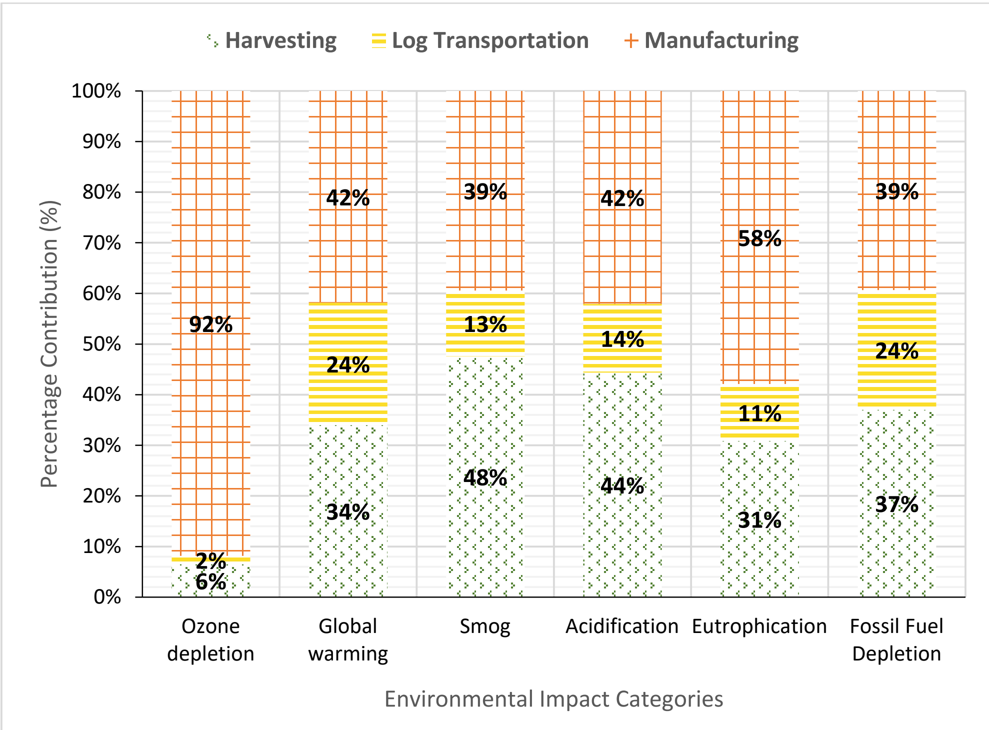

Figure 3. Contribution of stages in environmental impacts for the cradle-to-gate life-cycle stages of 1 m^3 rough green hardwood lumber produced in New Brunswick, Canada.

4. Biogenic Carbon

Hardwood lumber in service stores carbon. The production of 1 m^3 of rough green hardwood lumber in New Brunswick emitted 41 kg CO_2 eq. However, the carbon stored in the same 1 m^3 of lumber was assumed to be 50% by mass of OD wood [53]. Therefore, the carbon stored in 1 m^3 (532 OD kg) of rough green hardwood lumber amounts to 266 kg of carbon. Multiplying the 44/12, which accounts for the conversion of carbon (atomic weight of 12) to carbon dioxide (molecular weight of 44), this equates to 975 kg of CO_2 stored, which is approximately 24 times greater than the carbon emitted during the cradle-to-gate LCA study.

$$\text{Carbon stored} = 0.50 \times 532\ \text{kg} = 266\ \text{kg C}$$
$$CO_2\ \text{stored} = 266\ \text{kg} \times 44/12 = 975\ \text{kg}\ CO_2\ \text{eq}$$

5. Variation and Sensitivity Analysis

Sensitivity analysis was used with the aim to assess the reliability of the model outputs by evaluating the effects in model-predicted results when making changes in input parameters. In this study, due to variations among different data of two hardwood sawmills, some uncertainty existed in the results. Table 9 shows various statistics for the most significant modeling parameters in hardwood lumber production, such as CLR and electricity used in sawing. The standard deviation for each parameter, calculated from the sample data, was used to conduct a sensitivity analysis.

Table 9. Data statistics analysis for selected parameters.

Inventory Parameter	Units	Weighted Average	Std. Deviation	Min	Max	Mean
Electricity (A3 input)	kWh	61.44	33.03	39.61	86.32	62.96
CLR (A3 input)	m^3 rough green lumber /m^3 log	0.36	0.21	0.26	0.56	0.41

With this purpose, significant inventory parameters were altered to investigate their effect on the LCIA results. The proportion of their alternation was calculated based on the standard deviation and baseline value of each parameter. For instance, the baseline value for CLR was 0.36, with a standard deviation of 0.21, representing 58% of the baseline value. As lumber recovery increased, a larger share of the impact was allocated to the main product. Table 10 shows that altering the CLR baseline by 58% and the electricity baseline by 54% resulted in an 11% and approximately 8% increase in total GWP, respectively. Additionally, both parameters significantly affected indicators, including ozone depletion potential and primary energy use (non-renewable nuclear and renewable energy).

Table 10. Sensitivity analysis.

Impact Category	Unit	Baseline Results	Electricity (%)		CLR (%)	
			−54	+54	−58	+58
Global warming potential	kg CO_2 eq	40.67	−9	8	−11	11
Acidification	kg SO_2 eq	0.40	−4	4	−7	7
Eutrophication potential	kg N eq	0.045	−18	18	−21	21
Smog potential	kg O_3 eq	12.07	−1	1	−4	4
Ozone depletion potential	kg CFC11e	9.88×10^{-7}	−40	40	−49	49
Total primary energy	MJ	736.08	−17	16	−19	19
Non-renewable fossil	MJ	583.66	−8	7	−11	11
Non-renewable nuclear	MJ	141.32	−51	51	−52	52
Renewable biomass	MJ	5.09	−19	19	−53	53
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	−51	51	−53	53

6. Discussion

The hardwood lumber production processes included in the manufacturing stage are log-yard operations and primary log breakdown (sawing). To compare this with a cradle-to-gate LCA study of softwood lumber produced in New Brunswick, Canada [54], the same system boundary up to the sawing stage was considered. Therefore, the drying and planing unit processes in the softwood LCA study were not included to ensure comparability.

The LCI for softwood lumber production showed less electrical consumption in the sawing unit process, at 47 kWh per m^3 of rough green lumber, compared to hardwood, which was 61 kWh per m^3. This difference could be attributed to the fact that hardwoods are generally denser than softwoods, and since hardwood lumber is typically sawn to thinner dimensions, more electrical energy is consumed in the sawing process [39]. Table 11 summarizes the differences in data between softwood and hardwood sawmills, focusing on resource extraction, transportation and sawing stages, including inputs and outputs. However, as mentioned in detail in Section 5, the value represented the weighted average of two types of hardwood sawmills (sawlogs or high grade and hardwood pulpwood/pallet), which might have caused significant differences between the LCI values for each hardwood mill. This was evidenced by the finding that the electricity consumption for hardwood logs converted to high-grade lumber was almost half that of pallet lumber production. Additionally, the CLR was twice as high in high-grade sawlog production compared to the pallet lumber plant.

Table 11. Differences in data between softwood and hardwood sawmills, focusing on resource extraction, transportation, and sawing stages.

	Per m^3 of Lumber	Softwood	Hardwood
Resource Extraction Stage	**Ancillary materials** (hydraulic fluid, motor oil, grease)	Almost the same	Almost the same
	Energy		
	Diesel fuel (L)	2.94	3.69
	Gasoline (L)	0.14	0.70
	Propane (L)	0.02	0.01
Transportation		67 tkm	104 tkm
Log yard and Sawing Stage	Sawing yield (log/m^3 lumber)	2.21	2.75
	Energy		
	Gasoline (L)	0.013	0.025
	Diesel (L)	1.72	3.84
	Electricity (kWh)	47.25	61.58
	Ancillary materials		
	Hydraulic fluid, lubricant oil (L)	0.23	0.51
	Grease (kg)	0.0014	0.0045
	Motor oil (L)	0.0063	0.0074
	Antifreeze (L)	0.00033	0.00094

Table 12 compares the results of the previous study (rough green softwood lumber) and this study (rough green hardwood lumber). The total GWP in the current study was 54% higher than that reported for softwood production. This increase was primarily attributed to a 69% higher GWP impact during the manufacturing stage, which encompassed the activities such as log yard operations and sawing processes. The higher GWP impact was driven by lower hardwood lumber yields, which necessitate processing more logs to produce the same volume of lumber, combined with increased diesel and electricity consumption during production. As reported by Bergman and Bowe (2008), hardwood lumber production required more electrical energy because of their higher density and smaller dimensions relative to softwoods. These factors collectively contributed to the higher energy inputs and associated GWP impacts in hardwood lumber production [39]. These impacts could be mitigated by adopting on-site energy generation for electricity, particularly through the use of biomass from sawmill by-products, which can reduce reliance on off-site energy sources. Other significant differences in the impacts included smog, acidification, and eutrophication, with increases of 68, 63, and 40%, respectively. While the higher diesel consumption in manufacturing and harvesting for hardwood lumber production significantly influenced these impact categories, the higher green density of hardwood lumber and the longer transportation distance found in this study compared to the softwood one, as well as its associated impacts, were probably the primary causes of the increased eutrophication, acidification, and smog effects. This agrees with the findings by Gu et al. (2022), who aimed to understand the environmental impacts of transporting mass timber products (MTPs) for a mid-rise institutional building in New Brunswick, Canada. Their research compared the environmental performance of a steel frame building with an alternative mass timber design using a cradle-to-gate LCA. Using SimaPro software and the TRACI impact assessment method, that study found that the mass timber had lower global warming and ozone depletion impacts compared to a steel frame design. However, it also showed higher impacts in smog formation, acidification, and eutrophication due to the longer transportation distance of mass timber components to New Brunswick and the increased diesel fuel consumption during transportation [35].

Table 12. LCIA comparison between the cradle-to-gate LCA of softwood lumber production (up to the sawing stage) and that of hardwood lumber production (this study) in New Brunswick, Canada.

Impact Category	Unit	Rough Green Hardwood Lumber, NB	Rough Green Softwood Lumber, NB	Change
Global warming potential	kg CO_2 eq	40.67	26.48	54%
Acidification	kg SO_2 eq	0.40	0.24	63%
Eutrophication potential	kg N eq	0.04	0.03	40%
Smog potential	kg O_3 eq	12.07	7.16	68%
Ozone depletion potential	kg CFC11e	9.88×10^{-7}	8.99×10^{-7}	10%
Total primary energy	MJ	736.07	520.38	41%
Non-renewable fossil	MJ	583.66	376.17	55%
Non-renewable nuclear	MJ	141.31	133.67	6%
Renewable biomass	MJ	5.09	4.75	5%
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	5.70	5%

Moreover, there was a 41% increase in total primary energy use in the production of hardwood lumber in this study (736 MJ/m^3) compared with the softwood study (520 MJ/m^3), which was mainly due to the greater use of non-renewable fossil energy, with an almost-55% increase in the current study. However, the non-renewable nuclear, renewable biomass, and other renewable sources of energy consumption did not change significantly as the sources of raw materials were the same, and both studies were conducted in New Brunswick, concerning the same regional source of energy.

Kelley et al. (2020) pointed out that it was essential to reduce fossil fuel dependence in lumber production, transitioning to renewable energy for on-site electricity generation [55]. Sawmills could utilize biomass energy from by-products such as sawdust and bark for co-generation, reducing reliance on grid electricity in New Brunswick, which derived about 30% of its energy from fossil sources, such as hard coal and natural gas, and nearly 40%

from nuclear power [47]. Additionally, improving lumber yield through advanced sawing technologies and better material handling practices could significantly enhance efficiency and reduce waste.

Due to the exclusion of processes in this study, such as drying and planing, as well as other stages, such as use and end-of-life stages, the findings from this study failed to fully assess the environmental impact across the entire lifecycle of the production of hardwood lumber. Extending the analysis to a cradle-to-grave framework in future studies would provide a more comprehensive understanding of the production of hardwood lumber in New Brunswick, Canada. Furthermore, this study's reliance on data from a small number of hardwood sawmills, due to incomplete data and limited willingness of sawmills to share operational information, restricts the representativeness of the results. Expanding the dataset to include a larger number of sawmills is essential to obtain more diverse and comprehensive data, ultimately improving the accuracy and reliability of the LCA analysis on the production of hardwood lumber in the province.

7. Conclusions

A cradle-to-gate LCA of the production of rough green hardwood lumber in New Brunswick, Canada, was conducted, integrating impact assessments and LCI data on forest resource extraction, transportation, and manufacturing processes, using both primary and secondary data sources. The following conclusions can be drawn:

- The manufacturing stage accounted for 54% of total primary energy consumption and had the highest GWP impact at 42%, with most electricity at mill sites sourced off-site, with 98% relying on non-renewable energy and only 2% on renewable sources.
- Harvesting and transportation contributed approximately 28 and 18%, respectively, to the overall energy consumption.
- The higher manufacturing energy consumption and GWP in hardwood production compared to softwood were primarily attributed to the greater electrical energy required for sawing hardwood and its lower lumber yield.
- Rough green hardwood lumber stored 24 times more carbon than its cradle-to-gate CO_2 eq emissions released.

It is recommended that on-site energy generation using wood residues has the potential to reduce dependence on non-renewable fossil fuels while significantly lowering emissions, particularly in electricity generation processes. Moreover, improving lumber yield rate through adopting advanced sawing technologies, such as artificial intelligence, would enhance the efficiency of lumber production and reduce the GWP impact. Future research should incorporate cradle-to-grave LCAs and foster collaboration with more sawmills to provide more reliable data representativeness.

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