A Review of Cradle-to-Gate Greenhouse Gas Emission Factors for Canada's Harvested Wood Products

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Abstract

With the previous decade's (2010 through 2019) greenhouse gas emissions remaining the highest on record, focus on emissions mitigation efforts is paramount. Harvested wood products (HWPs) can store carbon for various timespans depending on the product and its end uses. Life cycle inventories (LCIs) are the base for life cycle analyses (LCAs), as they represent a comprehensive catalogue of the raw data essential to complete an LCA. However, most LCI documentation is in the form of case studies of different types of HWPs, with varying LCI results that reflect varied system boundaries, case-specific conditions, and assumptions. Our goal was to conduct a systematic literature review to evaluate, analyze, and synthesize previously reported Canadian HWP data and to initiate a Canadian database based on reported cradle-to-gate HWP emission factors. HWPs were categorized as lumber, traditional structural panels, mass timber, nonstructural panels, and wood pellets. Based on our analysis, we found that softwood lumber produced the lowest cradle-to-gate emission factor (61.99 kg of CO_2 equivalent [CO_2eq] per m^3 HWP) while I-joists produced the highest (218.55 kg of CO_2eq per m^3 HWP). Resource extraction emissions accounted for most of the overall emissions for softwood lumber, oriented strand board, cross-laminated timber, and glue-laminated timber. Meanwhile, manufacturing accounted for most of the emissions for plywood, I-joists, cellulosic fiberboard, particleboard, and wood pellets. Substantial gaps exist in published LCI data and, when possible, publishing detailed LCI data is encouraged to support additional HWP life cycle analyses.

While recent global efforts have contributed to decreasing greenhouse gas (GHG) emissions, average annual emission levels from 2010 through 2019 remain higher than in any previous decade (Dhakal et al. 2022). As summarized in the Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC 2023), 56 countries accounting for 53 percent of total global GHG emissions have introduced laws that focus on reducing GHG emissions, which has led to avoided or reduced emissions from various sectors.

The forestry sector has a unique role in the global carbon (C) cycle and can offer crucial GHG mitigation opportunities (Verkerk et al. 2020, Cowie et al. 2021). As concluded by the IPCC, sustainable forest management, along with improved use of harvested wood products (HWPs; e.g., material substitutions), can contribute to climate change mitigation (Nabuurs et al. 2022). Canada contains 362 million hectares of forest land (9% of global total) and is one of the world's largest HWP producers and exporters (National Resources Canada [NRC] 2022). The domestic demand for HWPs is also constant and strong, particularly as materials for residential construction, though forest harvesting has declined since 2015 (NRC 2022).

HWPs are an integral part of the forestry sector's mitigation assessment, along with forest management practices. Maximizing C storage in HWPs was identified as one of the nature-based and cost-effective solutions for Canada's forestry sector to reduce GHG emissions (Environment and

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Climate Change Canada 2022). The mitigation potential of HWPs varies largely by product type and end use, which have been extensively studied (Geng et al. 2017, Johnston and Radeloff 2019, Sahoo et al. 2021). HWPs with long service lives, e.g., those used as construction materials, offer long-term C storage and have lower GHG emissions than alternative materials such as steel or concrete (Chen et al. 2018). Moreover, wood products used to produce bioenergy provide a renewable energy source while regenerating forests on the harvested areas can help resequester the C released from burning biomass over time (Ter-Mikaelian et al. 2015). In contrast, burning fossil fuels leads to one-way C emissions to the atmosphere. Thus, to accurately assess the forest sector's future mitigation contribution, it is necessary to accurately evaluate the GHG implications of HWPs. One approach is to use life cycle analyses (LCAs) to accurately quantify a product's emissions and removals associated with its production, end use, and postservice disposal.

In general, LCAs are standardized by the International Organization for Standardization (ISO; e.g., ISO 14040 [ISO 2006a] and ISO 14044 [ISO 2006b]), but specific standards are also applied for the quantification of the C footprint and C neutrality of products (e.g., ISO 14067 [ISO 2018] and ISO 14068 [ISO 2023]). A major component to LCAs is the life cycle inventory (LCI), as it represents the comprehensive catalogue of the raw data essential to complete an LCA. LCIs include all materials, fuel, and energy that are used in a process—collectively known as *inputs*—as well as all products, byproducts, residuals, and emissions that are produced from the same process—collectively known as *outputs*—as defined by the LCA system boundary (ISO 2006b).

The IPCC outlines four LCA approaches for HWPs: stock-change, production, atmospheric-flow, and simple-decay (Rüter et al. 2019). The differences among approaches can alter the LCA results (De Rosa et al. 2018) and several studies show that the forestry sector's GHG emissions can be underestimated (Chen et al. 2014, Hudiburg et al. 2019, Zhang et al. 2020), especially for C accounting in HWPs (Green et al. 2006, Dias et al. 2007, Stewart and Nakamura 2012, Wang et al. 2022). While the methods used in HWP LCA studies meet their specific objectives, it can be difficult to compare the results for similar HWPs from different studies. Furthermore, the LCI data published alongside LCAs are inconsistent, as they can be reported as standalone units specific to certain processes (Adams et al. 2015, Abbas and Handler 2018) or as the functional unit described in the LCA (Puettmann and Salazar 2019), the latter being arguably better for comparisons among LCAs. Data presented in LCIs can also be specific to the location of the LCA; for example the functional unit of I-joists (i.e., structural supports shaped like the capitalized letter 'i') in the United States is per kilometer (Bergman and Alanya-Rosenbaum 2017b), whereas in Canada it would be measured as per cubic meter (Head et al. 2020). Often, LCI data is from private databases (Balasbaneh and Sher 2021), making access difficult and limiting opportunities to reprocess the data in future LCA studies under similar circumstances.

Despite the shortcomings of the published LCIs, LCAs are a functional research tool that can provide forest managers and policymakers insight into the mitigation potential that can result from substituting HWPs for fossil fuels and more GHG-intensive materials (e.g., concrete). Currently, Canada does not have a national HWP LCI database that supports the development of HWP LCAs. Therefore, our intent was to (1) review published HWP LCI data and identify where more comprehensive data is needed, (2) analyze emissions by energy source and HWP category, and (3) initiate a Canadian database on HWP cradle-to-gate emission factors. This review is organized into two main sections: the first outlines published Canadian- or North American–specific cradle-to-gate HWP LCI data and the second merges the previously mentioned data with global fuel and energy inputs and Canadian-specific emission factors to create nationally specific cradle-to-gate emission factors for each HWP.

A cradle-to-gate boundary (Fig. 1) was established for this review. The later stages of a HWP life cycle (i.e., in-use stage and end-of-life stage) were excluded from consideration because Canada exports a large fraction of its HWPs to other countries, thus the results are varied and more specific to end use countries. Three stages form a cradle-to-gate life cycle for HWPs: forest harvesting/fiber production, transportation, and manufacturing, hereafter referred to as A1, A2, and A3 stages, respectively. Depending on the HWP, the A1 stage can include roundwood harvesting, mill residue production, additive production, or some combination of these. During roundwood harvesting, emissions from road construction, roundwood felling, and preparing logs for transport are commonly mentioned but can also include emissions associated with site preparation, seedling

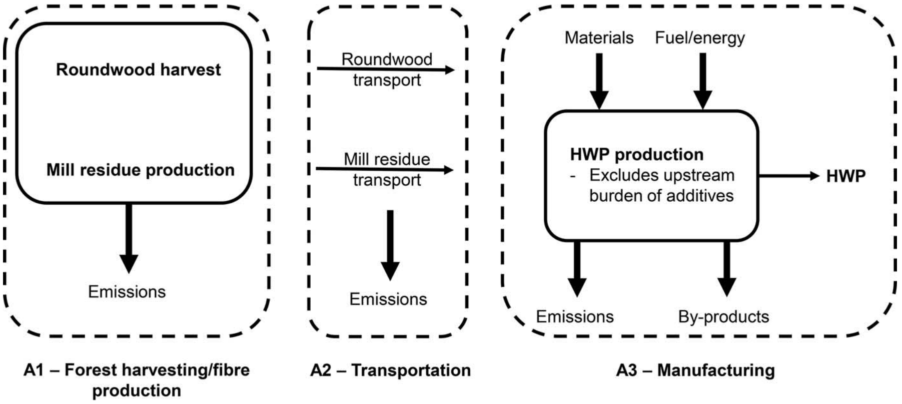

Figure 1.—The stages of a cradle-to-gate life cycle include A1 = forest harvesting/fiber production, A2 = transportation, and A3 = manufacturing.

growth, and reforestation. Mill residues are typically byproducts from the lumber industry, and as such carry a fraction of the upstream environmental burden of lumber (both emissions from harvesting and from lumber production). We found upstream production emissions from additives were not commonly reported in the A1 stage of various HWPs, though transportation of the additives to the mill were always reported. Upstream emissions from additive production are summarized in the text if they are reported. Additionally, during the A2 stage, transportation routes vary by location and can include transportation to primary and secondary mills. The amount of data associated with the A3 stage varies greatly among products. For the purposes of this review, the A3 boundary includes production data only and not data associated with downstream processes such as transportation to end users.

In this review, we examined 13 types of HWPs commonly produced in Canada: softwood and hardwood lumber, oriented strand board (OSB), plywood, cross-laminated timber (CLT), glue-laminated timber (glulam), I-joists, laminated strand lumber (LSL), laminated veneer lumber (LVL), cellulosic fiberboard (CF), medium-density fiberboard (MDF), particleboard, and conventional wood pellets (WP; i.e., pellets that are not torrefied or undergo any other postprocessing). For brevity, we aggregated the HWPs developed in Canada into the following categories: lumber, traditional structural panels, mass timber, nonstructural panels, and wood pellets. While we recognize that Canada is home to many pulp and paper mills, lack of industrial support and newly published data prevented us from producing a meaningful update for pulp and paper (Chen et al. 2013). The products associated with each category are outlined in Table 1.

Lastly, only atmospheric emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were considered in this review as these GHGs are considered the strongest drivers of anthropogenic climate change (Chen et al. 2021) and were generally well reported in the literature. Wood product LCA is often integrated with forest C stock analysis to quantify the temporal changes of the total C stocks, which account for the biogenic C emissions from decomposition and combustion of wood biomass, as well as forest C sequestration through photosynthesis. Thus, to avoid double-counting, the biogenic CO_2 emissions from wood decomposition and bioenergy production from internal use of wood during HWP manufacturing were not included in our analysis. Non-CO_2 biogenic emissions were included because their effect is additional to CO_2 emissions that are accounted for when assessing C stock changes resulting from bioenergy production.

Table 1.—The various products included in each harvested wood product (HWP) category outlined in this review. Abbreviations of the HWPs used in the text and figures are summarized in the right-most column. These products do not represent all HWPs produced in Canada but are the well-established HWP types or are emerging HWP types in the wood product industry.

HWP category	HWP	Abbreviations
Lumber	Softwood lumber	SL
	Hardwood lumber	HL
Traditional structural panel	Oriented strand board	OSB
	Plywood	PLW
Mass timber	Cross-laminated timber	CLT
	Glue-laminated timber	Glulam
	I-joist	I-joist
	Laminated strand lumber	LSL
	Laminated veneer lumber	LVL
Nonstructural panel	Cellulosic fiberboard	CF
	Medium-density fiberboard	MDF
	Particleboard	PB
Wood pellet	Conventional wood pellets	WP

Review of HWP LCIs

For a complete list of sources used in this review, please refer to Supplemental Tables SM3 through SM5.

Lumber

For Canadian softwood lumber, reports from Athena Sustainable Materials Institute (ASMI) offer the most comprehensive published data. The latest ASMI reports describe data for Canadian (ASMI 2018a, 2018b) softwood lumber, as well as softwood lumber produced in the Canadian province of British Columbia (ASMI 2021). All three reports use the SimaPro LCA software, using both primary and secondary data sources. Regardless of region, the LCA system boundary in each report is identical. The A1 stage includes emissions from forest management (i.e., thinning, fertilization, and seedling growth and replanting) and harvesting (including extraction and processing), the A2 stage includes emissions from transporting logs and ancillary material, and the A3 stage includes emissions from lumber manufacturing (i.e., sawing, kiln drying, and planing). According to ASMI's reports, softwood lumber can produce between 39.07 and 45.86 kg of CO_2 equivalent (CO_2eq) per m^3 HWP (ASMI 2018a, 2018b, 2021). In all reports, the A3 stage produces the most emissions compared to A1 and A2 stage, whereas the A2 stage produces the least emissions except in the Canadian report, where the A1 stage produces the least emissions.

A further study by Head et al. (2020) extends the work done by ASMI by covering the cradle-to-grave boundary and providing an LCI (along with a dynamic climate change assessment) for seven HWPs that are produced from the 12 most harvested softwood species from managed forests in Canada. Additionally, they provide a breakdown of GHGs (i.e., CO_2, CH_4, and N_2O) for each HWP in the A1 and A3 stage, using a cubic meter of roundwood and a cubic meter of HWP as the functional unit, respectively. While A2 transportation is part of the system boundary provided by Head et al. (2020), specific emissions associated with that transport were not provided. For softwood lumber, Head et al. (2020) found the emissions associated with the A1 stage to equal about 31.6kg of CO_2eq per m^3 roundwood, which includes emissions from harvesting, roundwood extraction, and site preparation. On the other hand, A3 emissions were estimated by Head et al. (2020) to be around 17.2 kg of CO_2eq per m^3 HWP and includes emissions from sawing, kiln drying, and planing.

For hardwood lumber, the Canadian study by Mahalle and Lavoie (2015) using the SimaPro LCA software with primary and secondary data estimates the A1 stage emissions at around 13.8 kg of CO_2eq per m^3 HWP (or about 11.6 kg of CO_2eq per m^3 roundwood) and A3 stage emissions at around 10.6 kg of CO_2eq per m^3 HWP. The A2 stage was not reported in the study. Emissions from the A1 stage include those from marking trees and harvesting (including extraction and processing) whereas the A3 emissions include those from sawing and sorting. Emissions from the A1 stage were only presented as CO_2eq and were not differentiated into CO_2, CH_4, or N_2O; however, A3 stage emissions were presented as both a CO_2eq value and numerous other emissions such as CO_2, particulates, nitrogen oxides, sulfur oxides, etc. Unfortunately, neither CH_4 nor N_2O were described by Mahalle and Lavoie (2015).

Traditional structural panel

For OSB and plywood, the study by Head et al. (2020) and various ASMI reports provided the best Canadian-specific data. Head et al. (2020) estimated A1 and A3 stage emissions for OSB at around 53.0 kg of CO_2eq per m^3 roundwood and 137.4 kg of CO_2eq per m^3 HWP, respectively. As per the ASMI OSB report, A1,A2, and A3 stage emissions were estimated at 122.9, 15.3, and 83.15 kg of CO_2eq per m^3 HWP, respectively (ASMI 2018c). The A1 stage includes emissions associated with roundwood harvesting, forest management (i.e., seedling growth and planting, site preparation, fertilization, and thinning) and the production of all ancillary materials. The A2 stage includes emissions associated with the transportation of logs and all ancillary materials and fuels, and the A3 stage emissions include those from the manufacturing and packaging of OSB.

For plywood, emission estimates by Head et al. (2020) were around 27.9 kg of CO_2eq per m^3 roundwood and 92.3 kg of CO_2eq per m^3 HWP for A1 and A3 stages, respectively. Meanwhile, ASMI describes plywood emission factors for both Canada and British Columbia, each with identical A1 through A3 stage descriptions as OSB apart from the A3 stage, which includes emissions associated with plywood manufacturing (including packaging). Emissions totaled to 129.9 kg of CO_2eq per m^3 HWP (74.1, 9.1, and 46.7 kg of CO_2eq per m^3 HWP for A1, A2, and A3 stages, respectively) and 131.7 kg of CO_2eq per m^3 HWP (88.2, 12.8, and 30.7 kg of CO_2eq per m^3 HWP for stages A1, A2, and A3, respectively) for plywood produced in Canada and British Columbia, respectively (ASMI 2018d, 2022a). For all the ASMI plywood and OSB reports, the SimaPro software was used with both primary and secondary data sources.

Mass timber

Like traditional structural panels, most data for Canadian mass timber products comes from the study by Head et al. (2020) and ASMI. Head et al. (2020) provides estimates for the A1 stage (70.5, 161.6, and 130.9 kg of CO_2eq per m^3 roundwood) and A3 stage (70.1, 160.7, 130.0 kg of CO_2eq per m^3 HWP) of CLT, I-joist, and LVL, respectively. ASMI provides emission estimates for glulam produced in British Columbia, which follows the same A1 and A2 stage system description as previously described for OSB, with the A3 stage including emissions from the manufacturing of glulam (including packaging). During the A1 through A3 stages, total emissions produced were about 59.6, 25.0, and 18.2 kg of CO_2eq per m^3 HWP, respectively (ASMI 2022b). Like previous ASMI studies, the SimaPro LCA software was used with both primary and secondary data sources.

Minimal published LCI data are available for LSL production; we found only one North American study by Sahoo et al. (2021), who used the SimaPro LCA software with both primary and secondary data sources. Their A1 stage included emissions from forest management (i.e., site preparation, regeneration, and thinning), final harvest (including extraction and processing), and cradle-to-gate emissions from resin production whereas their A2 stage included emissions from transporting logs and ancillary materials/ additives to the mill. Emissions from manufacturing LSL were included in the A3 stage, which included the debarking and stranding of the logs, drying, screening, blending, and forming/pressing of the strands, then cutting, trimming/ sanding, and packing of the LSL. From their data, 153.1, 59.0, and 62.8 kg of CO_2eq per m^3 HWP were emitted during the A1 through A3 stages, respectively (Sahoo et al. 2021). The emissions from the A1 stage include 124 kg of CO_2eq per m^3 HWP of emissions from resin production.

Nonstructural panel

Similar to LSL, data representing CF production are lacking in the literature, with no Canadian-specific studies found. Two recent North American studies, one by Puettmann et al. (2016a) and the other by Sahoo and Bergman (2021), do provide the most relevant CF production data. CF in Puettmann et al. (2016a) is produced from pulp chips, roundwood chips, construction waste, and mill residues from Canada and the US southeast and northeast–north central regions. Due to variation among forest operations in North America, the emissions associated with the A1 stage for wood resources originating in Canada and US southeast includes thinning, final harvest (with extraction), along with seedling growth, site preparation, and planting. The A1 stage emissions from wood resources originating from the US northeast–north central region includes thinning, final harvest (with extraction), and natural regeneration. For their analysis, Puettmann et al. (2016a) include transportation emissions (A2 stage) as part of their manufacturing (A3 stage) emissions. In other words, we cannot translate their manufacturing data into separate A2 and A3 stages (as defined in this review). However, they estimated 24.2 kg of CO_2eq per m^3 HWP in their A1 stage, 21.0 kg of CO_2eq per m^3 HWP of which is attributed to wood residue production, with the remaining 3.2 kg of CO_2eq per m^3 HWP attributed to forestry operations.

In Sahoo and Bergman (2021), all three stages of CF production were represented including emissions from forest management (i.e., site preparation, seedling cultivation, fertilization, and thinning), final harvest, and chipping (A1 stage), transportation of materials and additives to the mill (A2 stage), and manufacturing of the CF (i.e., pulping and refining feedstock, washing, mixing and forming fibers, then drying, finishing, and packaging CF; A3 stage). Roundwood and sawmill chips were the main feedstock (71.2%) for CF production with wood construction waste facilitating the remaining feedstock (28.8%). A total of 196.1 kg of CO_2eq per m^3 HWP was produced, with 5.3, 6.8, and 184.0 kg of CO_2eq per m^3 HWP being produced in the A1, A2, and A3 stages, respectively (Sahoo and Bergman, 2021).

For MDF (produced using mill residues such as shavings, sawdust, and chips), the latest Canadian cradle-to-gate study was done in 2013 by ASMI (ASMI 2013a). Their emissions include those from wood residue production (A1 stage), transportation of wood feedstock and materials to the mill (A2 stage), and the manufacturing of the MDF (i.e., screening and heating of wood residues, forming of the pulp, then pressing, trimming, and packaging the MDF; A3 stage). While ASMI (2013a) does include the upstream processes of mill residue production (forest harvesting and lumber production) in their A1 stage, they do not specify which processes were included. If we assume they used harvesting data from their previous work on softwood lumber (which was revised in 2018), we can presume that the A1 stage includes emissions from thinning, fertilizing, seedling growth and replanting, final harvest (including extraction), and the proportion of lumber production relative to byproduct (i.e., mill residues) manufacturing (ASMI 2018a). The A1, A2, and A3 stages produced 47.2, 29.4, and 316.9 kg of CO_2eq per m^3 HWP, respectively (ASMI 2013a).

Much like MDF, particleboard uses mainly mill residues as its wood feedstock though also includes some (9%) full logs (ASMI 2013b). Likewise, the latest Canadian study of particleboard was produced in 2013 by ASMI (ASMI 2013b) and includes the same emission sources and stages as MDF. And, while they do not specify which harvesting processes are included in their A1 stage analysis, they do allude to their previous work on Canadian softwood lumber production. Therefore, we can assume with more certainty than MDF that the A1 stage for particleboard production includes emissions from thinning, fertilizing, seedling growth and replanting, final harvest (including extraction), and the proportion of lumber production relative to by-product (i.e., mill residues) manufacturing (ASMI 2018). Meanwhile, the manufacturing steps to producing particleboard include refining, drying, screening, and blending of the wood residues, then forming, pressing, trimming, and packaging the particleboard (ASMI 2013b). Unlike MDF, particleboard produces much fewer overall emissions with the A1 through A3 stages producing around 35.0, 18.2, and 124.3 kg of CO_2eq per m^3 HWP, respectively.

Wood pellet

Wood pellets can be produced from sawmill wood residues (Magelli et al. 2009), or roundwood/harvest residues that are transported as-is (Adams et al. 2015, Ruiz et al. 2018) or chipped in-forest then transported (Quinteiro et al. 2019) to the pellet plant. These different feedstocks complicate comparisons of emissions from various studies as stage boundaries will be LCA-specific. Another complication arises when functional units of pellet LCAs are 1 MJ of thermal energy yet the amount of pellets needed to produce this metric is not stated (Giuntoli et al. 2015, Ruiz et al. 2018), which reduced the number of studies feasible for this review. The study by McKechnie et al. (2011) provides emission estimates for wood pellets produced either with standing trees or forest harvest residues in Ontario, Canada. Though this study is not organized into typical LCA stages, it is possible to interpret some of their LCI results into the stages described in this review. Emissions from the A1 stage includes those from biomass harvesting, forest renewal, and forest road construction/maintenance; the A2 stage includes those from the transportation of biomass from forest to the pellet facility; and the A3 stage includes those from pellet densification. For standing trees, 35.7 kg of CO_2eq per oven dry tonne(odt) biomass, 26.7 kg of CO_2eq per odt biomass, and 38.5 kg of CO_2eq per odt HWP were produced in the A1, A2, and A3 stages, respectively (McKechnie et al. 2011). Meanwhile, when forest harvest residues are used as a feedstock, 15.8 kg of CO_2eq per odt biomass, 26.7 kg of CO_2eq per odt biomass, and 38.3 kg of CO_2eq per odt HWP were produced in the A1 through A3 stages, respectively (McKechnie et al. 2011). It should be noted that the emissions data in the McKechnie et al. (2011) study relied heavily on the Canadian-specific wood pellet study by Zhang et al. (2010).

Lastly, the study by Magelli et al. (2009) focuses on wood pellet production in British Columbia using sawmill residues (i.e., shavings and sawdust) as the feedstock. In their study, Magelli et al. (2009) estimates emissions from roundwood harvesting and lumber production (A1 stage), transportation from the lumber mill to the pellet facility (A2 stage), and densification using sawdust as fuel (A3 stage). Using the CO_2, CH_4, and N_2O values from Magelli et al. (2009) to estimate the CO_2eq emissions, they found wood pellets to produce 31.2, 4.7, and 28.0 kg of CO_2eq per odt HWP during the A1, A2, and A3 stages, respectively.

Cradle-to-Gate Emissions of HWPs

From the previous section, noticeable gaps in the cradle-to-gate data of numerous HWPs were found. In this section, we normalize the data found in the A1 stage, estimate transportation emissions using average Canadian haul distances and Canadian-specific fuel emission factors (A2 stage), and estimate A3 stage emissions using energy and fuel inputs found in the literature with Canadian-specific energy and fuel emission factors. From these prepared data, we were able to estimate cohesive cradle-to-gate emission factors for each HWP, divided into the individual GHGs (i.e., CO_2, CH_4, and N_2O).

Scoring pedigree

A scoring pedigree (Supplemental Table SM2) was used to assess data quality while reducing possible bias. The data scoring pedigree matrix is based on the ecoinvent[1] 3.0 data quality guideline and can be used to assess the data based on "reliability" (i.e., the validity of the data), "completeness" (i.e., the representativeness of the data), "temporal correlation" (i.e., the length of time between the present study and the referenced data), and "geographic correlation" (i.e., relationship between region of present study and the referenced study; Weidema et al. 2013). Technological correlation was not assessed since the harvesting and production technology for each HWP has not changed substantially in recent decades. Temporal correlation was calculated from the year 2021. The assessed characteristics were divided into five quality levels, with 1 considered very certain and 5 very uncertain. Each assessment category was assumed equal, so data with the lowest total score represent the highest relative level of certainty and thus the data points to use for further life cycle analyses of Canada's HWPs. All references that

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[1] The ecoinvent database is used globally, with more than 18,000 industrial/agricultural process data sets. The database is not open access. For more information, visit https://ecoinvent.org/the-ecoinvent-database/.

were gathered and scored are provided in the Supplemental Material. The best-scoring Canadian data were chosen to represent their respective HWP. However, all global data with an aggregated score of ≤12 (i.e., top 50%) were chosen to represent the average HWP emission factors.

Data acquisition

A1 stage (forest harvesting/fiber production).—Sources of emissions associated with the A1 stage vary among LCAs, making it difficult to have an "apples-to-apples" comparison not only for individual HWPs but also among HWPs. For example, while all HWPs require wood biomass feedstocks, not all require full roundwood harvesting (e.g., MDF can be produced solely from mill residues). And, as mentioned previously, the emissions associated with harvesting can include some or all of access road construction, roundwood felling, preparing logs for transport, site preparation, growing seedlings, and reforestation. As such, we attempted to normalize the A1 stage data to 1 m^3 of roundwood and estimate the amount of roundwood/wood feedstock from the best representative data in the literature (Table 2).

From our scoring pedigree, the study by Head et al. (2020) results in one of the lowest tallies of all A1 stage data in the literature (6) so was considered to have the best data quality among the reviewed studies and chosen to represent the applicable HWPs (i.e., softwood lumber, OSB, plywood, CLT, glulam, I-joists, and LVL). For hardwood lumber, the data from Mahalle and Lavoie (2015) scored 10 points, remaining below the target cut-off score of 12. This slightly high score can be attributed to the temporal correlation characteristic in the pedigree, as the LCI data was developed using the production years of 2007 and 2008. Considering the data from Mahalle and Lavoie (2015) originates from a Canadian study, it was used to represent Canadian hardwood lumber; however, the newer study by Hubbard et al. (2020), an LCA of hardwood lumber from the northeast–north-central area of the US, had a similar score of 10 as it represents data from the 2017 production year and therefore scored lower in the temporal correlation characteristic of the scoring pedigree.

The LSL study by Sahoo et al. (2021) scored similarly to Head et al. (2020), with an equally low score of 6. Though the study by Sahoo et al. (2021) is North American, their low score is attributed to their data representing all LSL producers and being from the 2019 production year (i.e., giving the lowest possible score in the *completeness* and *temporal correlation* characteristics in the pedigree, respectively).

The two North American CF LCA studies by Sahoo and Bergman (2021) and Puettmann et al. (2016a) both scored below 12 (7 and 9, respectively) but the A1 stage data from the latter study includes emissions by source (i.e., CO_2, CH_4, N_2O, etc.) so was preferred. Furthermore, calculating the volume (m^3) of wood feedstock was not as straightforward as previous HWPs. Using the amount of wood feedstock required to produce 1 m^3 of CF (243.85 oven dry kilogram [odkg]) and the specific gravity (0.55) outlined by Puettmann et al. (2016a), we were able to calculate the volume of wood feedstock needed for 1 m^3 of CF (0.43 m^3 wood). This approach also allowed us to calculate the CO_2 (52.5 kg of CO_2 per m^3 wood), CH_4 (8.1E-3 kg of CH_4 per m^3 wood), and N_2O (2.8E-3 kg of N_2O per m^3 wood) emissions by cubic meter of wood.

Though the most recent Canadian LCA studies for both MDF and particleboard from ASMI were published in 2013 (ASMI 2013a, 2013b), they both scored below an aggregated score of 12 (10 and 11, respectively). Interestingly, the North American studies on MDF (Puettmann and Salazar 2019) and particleboard (Puettmann and Salazar 2018) scored the same (10) or lower (9) than the Canadian MDF

Table 2.—Roundwood (m^3) required for manufacturing 1 m^3 of various harvested wood products (HWPs) along with the emission factors associated with harvesting that roundwood (A1 stage). For HWPs without reported CO_2-equivalent (CO_2eq) data, values were calculated from the sum of the reported carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) using the 100-year global warming potentials (Forster et al. 2021). SL = softwood lumber; HL = hardwood lumber; OSB = oriented strand board; PLW = plywood; CLT = cross-laminated timber; Glulam = glue-laminated timber; LSL = laminated strand lumber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particleboard; WP = conventional wood pellet; NA = not available.

HWP	Roundwood required ($m^3 \cdot m^{-3}$ HWP)	Emissions ($kg \cdot m^{-3}$ roundwood)				Source	Region
		CO_2	CH_4	N_2O	Total (CO_2eq)		
SL	1.05	30.8	0.019	0.00087	31.60[a]	Head et al. 2020	Canada
HL	1.19	NA	NA	NA	11.62	Mahalle and Lavoie 2015	Canada
OSB	1.76	51.7	0.032	0.00147	53.04[a]	Head et al. 2020	Canada
PLW	0.93	27.2	0.017	0.00077	27.90[a]	Head et al. 2020	Canada
CLT	1.20	35.2	0.022	0.00100	36.11[a]	Head et al. 2020	Canada
Glulam	1.10	95.5	0.058	0.00270	97.98[a]	Head et al. 2020	Canada
I-joist	1.33	38.1	0.023	0.00108	39.09[a]	Head et al. 2020	Canada
LSL	2.48	NA	NA	NA	61.74	Sahoo et al. 2021	North America
LVL	1.26	37.0	0.023	0.00105	37.96[a]	Head et al. 2020	Canada
CF	0.43[b]	52.5	0.008	0.00279	56.44	Puettmann et al. 2016	North America
MDF	2.04[b]	22.0	0.040	0.00021	23.13	ASMI 2013a	Canada
PB	1.58[b]	21.0	0.011	0.00044	22.13	ASMI 2013b	Canada
WP	1.00[c]	11.0[d]	0.021[d]	0.00350[d]	12.53	Zhang et al. 2010	Canada

[a] Total emission of CO_2, CH_4, and N_2O, in which CH_4 and N_2O were converted to CO_2eq using their global warming potential factors.

[b] Required wood feedstock (not specifically roundwood).

[c] Unit is tonne of biomass per tonne of pellets.

[d] Unit is kilogram per tonne of biomass.

and particleboard studies, respectively. These differences in scores were mainly attributed to the *temporal correlation* characteristic, as the ASMI studies provided data from the 2006 calendar year (ASMI 2013a, 2013b). And much like CF, the volume of wood feedstock required to produce 1 m^3 of MDF needed to be transformed from the weighed data given in the studies. To produce 1 m^3 of MDF a total of 782.4 kg of mill residues are needed and both softwood and hardwood residues are used (ASMI 2013a). Therefore, using an average wood residue density of 383 kg per m^3, we calculated that 2.04 m^3 of wood residues are required to produce 1 m^3 of MDF.

Lastly, Magelli et al. (2009) and McKechnie et al. (2011) provide Canadian-specific data related to wood pellet production but the data from these studies could not be transformed to the declared unit used in this review (1 m^3 roundwood). Unfortunately, the only other study to score $\leq$12 for wood pellet production was Quintiero et al. (2019); however, this study focused on pellet production in Portugal and used A1 stage data from Dias and Arroja (2012), which would score higher than 12. Due to the lack of available data, we used the biomass data and forest operation emissions (i.e., road construction, natural regeneration, seedling growth and planting, and final harvest including extraction) factors from Zhang et al. (2010), which focused on pellet utilization in the Canadian province of Ontario. In their study, only harvested roundwood was used for pellet production. While Zhang et al. (2010) represents Canadian data, the study scored higher than the cut-off score of 12, arguably making it the least dependable A1 stage data available.

A2 stage (transportation).—Transportation distance for roundwood and mill residues to the primary mill can vary depending on geography, road access, forest size, or the silvicultural practices applied. Transportation distances in Canada have been reported to range from 5 km (Pa et al. 2013) to 295 km (ASMI 2013b; Supplemental Table SM6). Using distances reported in studies with an aggregated data quality score of $\leq$12, the average was 128 km, not too dissimilar to the Canadian average of 100 km described by Meil et al. (2009). Allman et al. (2021) provided fuel consumption from three different logging trucks, reporting an average of 0.61 L per km^1 or 1.63 L per m^3. Using these averages in combination with Canadian emission factors for heavy duty diesel vehicles (Government of Canada 2022), we calculated the average Canadian emission factors (Table 3) for transporting roundwood or mill residues to the mill.

A3 stage (manufacturing).—The reported values for the A3 stage (Table 4) share similar references to those found in the A1 stage, as the studies remained the most relevant for their respective HWPs with two notable exceptions. As mentioned in the previous "Nonstructural panel" review section, Puettmann et al. (2016a) combine their CF transportation data into their manufacturing data, with no feasible way of separating the two. Therefore, the data from Sahoo and Bergman (2021) were used to represent CF for A3 stage emissions, though the individual GHG components were not reported. Furthermore, the Canadian study by Magelli et al. (2009) scored the lowest tally (8) for all wood pellet studies and was chosen to represent wood pellet A3 stage emissions.

Table 3.—Average Canadian emission factors for transporting roundwood from forest to mill, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emission factors were calculated using the average fuel consumption reported by Allman et al. (2021) and the Canadian heavy duty diesel vehicle emission factors. Units presented are in kg of emission per km travelled ($kg{\cdot}km^{-1}$) and kg of emission per m^3 of roundwood transported ($kg{\cdot}m^{-3}$). CO_2-equivalent (CO_2eq) values were calculated from the averages using the 100-year global warming potentials.

	Emissions			
Unit	CO_2	CH_4	N_2O	CO_2eq
$kg{\cdot}km^{-1}$	1.64	0.00007	0.00009	1.66
$kg{\cdot}m^{-3}$	4.37	0.00018	0.00025	4.44

Similar to A1 stage emissions, most sources provided total emissions for their respective HWP; however, for some HWPs a CO_2eq value had to be calculated using the CO_2, CH_4, and N_2O emission factors (i.e., the HWPs from Head et al. 2020). Furthermore, three HWPs (i.e., hardwood lumber, LSL, and CF) had missing GHG-specific emission factors.

More importantly, the average fuel and energy inputs found in the literature were also synthesized (Table 5). We used all sources (regardless of geographical region) with an aggregated data quality score of $\leq$12 to provide more robust estimates (for a full list of sources see Supplemental Table SM7). Commonly reported energy/fuels were electricity, natural gas, wood fuel, propane, and diesel, and as such were included in our analysis. As previously mentioned, biogenic CO_2 emissions from wood fuel (generated in-house or purchased) were not included in the analysis however biogenic CH_4 and N_2O were included.

Cradle-to-gate estimation.—For the A1 stage, the emission factors found in Table 2 were used and transformed to the appropriate units (1 m^3 HWP or 1 tonne wood pellet). Unfortunately, it means that we cannot provide emission factors associated with the A1 stage for hardwood lumber and LSL. It's not that these HWPs do not produce emissions, just that related emission factors are not reported in the literature. Likewise, the emission factors for the A2 stage (transportation) were calculated from the emission factors listed in Table 3 and the amount of roundwood required to produce 1 m^3 of HWP (listed in Table 2).

In the A3 stage for each HWP, global averages of fuel and energy inputs (Table 5) were supplemented with Canadian fuel and energy emission factors (from the year 2021; see Supplemental Table SM1). For the production data of I-joists, emission factors from Head et al. (2020) were used exclusively since fuel and energy inputs were not found in any of the studies reviewed. Similarly, energy and fuel data for CLT and LSL were taken exclusively from Puettmann et al. (2018) and Sahoo et al. (2021), respectively, as these were the only sources to score $\leq$12 for these HWPs.

Cradle-to-gate results.—Using the data described above, we provide a cohesive list of emission factors for CO_2, CH_4, and N_2O for each HWP throughout the cradle-to-gate life cycle using 1 m^3 of HWP or 1 tonne of wood pellets as the declared unit (Table 6). This list is not meant to replace total emission values for each HWP but

Table 4.—Reported carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission factors for manufacturing various harvested wood products (HWP) along with their reported total CO_2-equivalent (CO_2eq) emissions (A3 stage). For HWPs without reported CO_2eq data, values were calculated from the sum of the reported CO_2, CH_4, and N_2O using the 100-year global warming potentials. SL = softwood lumber; HL = hardwood lumber; OSB = oriented strand board; CLT = cross-laminated timber; Glulam = glue-laminated timber; LSL = laminated strand lumber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particleboard; WP = conventional wood pellet; NA = not available.

	Emissions (kg·m^{-3} HWP)					
HWP	CO_2	CH_4	N_2O	Total (CO_2eq)	Source	Region
SL	16.0	0.037	0.00051	17.24[a]	Head et al. 2020	Canada
HL	3.26E-5	NA	NA	10.61	Mahalle and Lavoie 2015	Canada
OSB	177.6	0.651	0.00366	137.40[a]	Head et al. 2020	Canada
Plywood	82.7	0.307	0.00162	92.29[a]	Head et al. 2020	Canada
CLT	63.8	0.207	0.00187	70.48[a]	Head et al. 2020	Canada
Glulam	30.3	0.221	0.00039	45.34[a]	Head et al. 2020	Canada
I-joist	145.7	0.501	0.00363	160.67[a]	Head et al. 2020	Canada
LSL	NA	0.006[b]	0.07090	62.81	Sahoo et al. 2021	North America
LVL	115.8	0.477	0.00308	130.86[a]	Head et al. 2020	Canada
CF	NA	NA	NA	184.04	Sahoo and Bergman 2021	North America
MDF	278.3	1.377	0.00072	316.91	ASMI 2013a	Canada
PB	74.72	12.15	0.12426	124.26	ASMI 2013b	Canada
WP[d]	27.8[c]	0.005[c]	0.00018[c]	47.97	Magelli et al. 2009	Canada

[a] Total emission of CO_2, CH_4, and N_2O, in which CH_4 and N_2O were converted to CO_2eq using their global warming potential factors.

[b] Includes 0.0059 kg biogenic CH_4.

[c] Using wet sawdust as fuel for drying incoming wood biomass.

[d] Unit is kg/tonne of wood pellets.

instead is a complementary database of emission factors to support research efforts. Since we could not calculate all stage emission factors for hardwood lumber and LSL (since no GHG-specific emission factors for A1 stage were reported in the literature), these two HWPs were removed from further analyses.

From our investigation of all sources to score $\leq$12 for each HWP, electricity, natural gas, and purchased wood fuel account for most of the energy/fuel input during production (Figure 2a). The A1 stage contributed the most emissions (>50%) for softwood lumber, OSB, CLT, and glulam whereas the A3 stage contributed the most emissions for plywood, I-joists, CF, MDF, particleboard, and wood pellets (Figure 2b). The A2 stage accounted for the least emissions for all HWPs except wood pellets.

While we have defined wood pellets by weight (i.e., per tonne; as is standard in reporting), this approach reduces its impact relative to the other HWPs. In Figure 3, we converted the units for wood pellets to a per–cubic meter basis using the average Canadian bulk density (690.5 kg per m^3) outlined by Tarasov (2013). Of the products with emission factors for all 3 stages, glulam had the highest overall A1 stage emission factor (107.65 kg of CO_2eq per m^3) with OSB slightly lower (93.26 kg of CO_2eq per m^3; Figure 3a). The emission factors and the amount of roundwood required per cubic meter of HWP used to calculate these values were

Table 5.—Average energy and fuel inputs for manufacturing 1 m^3 of harvested wood products (HWP) and 1 tonne of wood pellets. Averages were calculated using reported data from sources in the database that scored $\leq$12 cumulative quality points (see Supplemental Material for all sources; see Section 3.1 for scoring details). Upper and lower data limits are shown in parentheses to provide context on the variation of reported values. SL = softwood lumber; HL = hardwood lumber; OSB = oriented strand board; CLT = cross-laminated timber; Glulam = glue-laminated timber; LSL = laminated strand lumber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particleboard; WP = conventional wood pellet; NA = not available.

HWP	Electricity (kWh·m^{-3})	Purchased wood fuel (odkg·m^{-3})	Propane (L·m^{-3})	Natural gas (m^3·m^{-3})	Diesel (L·m^{-3})
SL	81.61 (60.87–114.52)	6.13 (0–26.69)	0.15 (0.04–0.28)	3.81 (0.80–6.81)	2.00 (0.86–2.92)
HL	92.74 (33.02–152.45)	0	0.09	27.94	5.03 (1.56–8.51)
OSB	146.58 (141.15–152.00)	7.45 (0–14.90)	0.45	13.67 (5.83–21.50)	0.87 (0.41–1.33)
Plywood	144.36 (137.46–157.53)	34.38 (0–120.00)	0.47 (0.41–0.53)	18.22 (1.27–28.00)	1.43 (1.15–1.84)
CLT[a]	98.90	0	NA	4.18	0.05
Glulam	74.32 (67.19–84.52)	0	2.48	1.95 (0.05–4.52)	0.76 (0.57–0.94)
LSL[a]	276.01	0	9.78	0.40	2.48
LVL	87.82 (77.44–98.20)	0	0.63 (0.47–0.79)	16.05 (12.80–19.30)	0.54 (0.35-0.74)
CF	195.73 (186.46–205.00)	23.70	0.72 (0.34–1.09)	42.97 (39.27–46.66)	0.41 (0.28–0.53)
MDF	303.80 (63.60–432.80)	144.25 (52.50–236)	0.50 (0.31–0.76)	44.42 (42.70–47.56)	0.81 (0.43–1.40)
PB	88.68 (27.85–149.50)	53.70	0.43 (0.43–0.58)	14.84 (1.90–27.78)	2.43 (0.46–4.40)
WP	138.23[b] (93.70–163.00)	0	0.58[b]	37.50[b]	0.55[b] (1.02–0.08)

[a] Data are not averaged (CLT data from Puettmann et al. [2018]; LSL data from Sahoo et al. [2021]).

[b] Units are per tonne of wood pellet.

Table 6.—Estimated cradle-to-gate emission factors for each harvested wood product (HWP) described in this review. Emissions in the A3 stage were calculated based on their respective averaged reported fuel/energy data and Canada-specific emission factors. CO_2-equivalent (CO_2eq) values of CH_4 and N_2O were calculated using their 100-year global warming potentials. SL = softwood lumber; HL = hardwood lumber; OSB = oriented strand board; PLW = plywood; CLT = cross-laminated timber; Glulam = glue-laminated timber; LSL = laminated strand lumber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particle board; WP = conventional wood pellet; NA = not available.

	Emissions (kg·m^{-3})									
	A1 – harvesting			A2 – transportation			A3 – manufacturing			
HWP	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	Total (kg CO_2eq·m^{-3})
SL	32.34	0.020	0.0009	4.59	0.0002	0.0003	21.17	0.014	0.0096	61.99
HL	NA	NA	NA	5.20	0.0002	0.0003	77.26	0.012	0.0077	84.96
OSB	90.99	0.056	0.0026	7.69	0.0003	0.0004	44.26	0.017	0.0115	148.95
PLW	25.30	0.015	0.0007	4.06	0.0001	0.0002	54.43	0.015	0.0099	87.61
CLT	42.24	0.026	0.0012	5.24	0.0002	0.0003	18.15	0.001	0.0003	66.90
Glulam	105.05	0.064	0.0030	4.81	0.0002	0.0003	17.01	0.003	0.0024	130.30
I-joist	50.67	0.031	0.0014	5.81	0.0002	0.0003	145.70[a]	0.501[a]	0.0036[a]	218.55
LSL	NA	NA	NA	10.84	0.0004	0.0006	49.84	0.030	0.0202	67.20
LVL	46.62	0.028	0.0013	5.51	0.0002	0.0003	42.42	0.002	0.0009	96.08
CF	22.58	0.003	0.0012	7.95	0.0003	0.0005	105.31	0.006	0.0037	131.40
MDF	44.88	0.082	0.0004	8.91	0.0004	0.0005	119.71	0.030	0.0202	182.42
PB	33.18	0.018	0.0007	6.90	0.0003	0.0004	44.90	0.011	0.0075	88.13
WP[b]	11.00	0.021	0.0035	6.33	0.0003	0.0004	89.11	0.023	0.0157	113.03

[a] Data from Head et al. 2020.

[b] Unit of emissions is kg/tonne of wood pellet and kg CO_2eq/tonne of wood pellet.

selected from the values summarized by Head et al. (2020), which is one of the lowest scoring studies examined in this review (i.e., it had the highest data quality). Much like our study, glulam was also the highest emitting HWP in the A1 stage in Head et al. (2020), though the reason for the higher emissions remains unclear. Aside from LSL, OSB has the highest roundwood to product ratio (1.76 m^3 roundwood per m^3 OSB; Head et al. [2020]).

Unsurprisingly, A3 stage emission factors increased as manufacturing complexity increased (Figure 3b). Lumber, arguably the most straightforward product to manufacture, had the lowest A3 stage emissions (24.18 kg of CO_2eq per m^3). Unfortunately, due to a lack of published data for hardwood lumber, this metric is based solely on softwood lumber, which (aside from the A1 stage) generally has lower emission factors for both A2 and A3 stages compared to hardwood (as seen in Table 5). Structural panels and mass timber (52.41 and 59.85 kg of CO_2eq per m^3, respectively) on the other hand require additional inputs (i.e., resins, glue) and increased energy to manufacture and therefore have higher emission factors than lumber. Furthermore, nonstructural panels, which are manufactured from numerous bio-feedstocks with different moisture contents and require numerous materials (i.e., resins, wax, catalysts), have an even higher A3 stage emission factor of 93.27 kg CO_2eq per m^3. Meanwhile, when converted to volume, wood pellet production results in more CO_2eq emissions (64.96 kg of CO_2eq per m^3) during the A3 stage than most HWPs, other than I-joists, CF, and MDF.

Of the overall cradle-to-gate emission factors, we found softwood lumber had the lowest value (61.99 kg of CO_2eq per m^3) while I-joists had the highest value (218.55 kg of CO_2eq per m^3). I-joists make for an interesting HWP, as they use LVL, OSB, plywood, and finger-jointed lumber as feedstock along with various resins and polymers (Bergman, 2015). How production emissions from the numerous HWPs are allocated to create I-joists likely affects its overall emission factor. The high emission factor produced from I-joists was surprising, but the lack of published data meant that we did not have a good database for comparison. Also, the Canadian emission factors provided by Head et al. (2020), used exclusively for the A1 and A3 stage of our analysis, are based on volume (m^3) whereas studies in the United States use distance (km) as their declared unit (Bergman 2015, Bergman and Alanya-Rosenbaum 2017a), making comparisons between the two countries untenable.

Discussion

Our review focused on consolidating previously published cradle-to-gate Canadian HWP data while attempting to provide updated individual cradle-to-gate emission factors using high-quality global input data and Canadian-specific fuel/energy emission factors. This work builds on an earlier study by Chen et al. (2013) who provided cradle-to-grave C analysis of various HWPs including lumber, plywood, OSB, particleboard, MDF, and pulp and paper. An earlier study by Upton et al. (2007) provided total GHG emissions for the overall wood product and pulp and paper sectors in Canada for the years 1990 and 2005. Much like the current study, Upton et al. (2007) combined high-quality input data (i.e., data directly from industrial surveys) with their current fuel emission factors to estimate overall GHG emissions. However, direct comparisons with the study by Upton et al. (2007) aren't plausible as they make the distinction between forest product sectors instead of HWPs and combine wood fiber procurement (without describing what processes the procurement entails) and transportation emissions into one overall emission. The aim of the current study was to organize the data so readers can fit it into their work and provide comparative analysis.

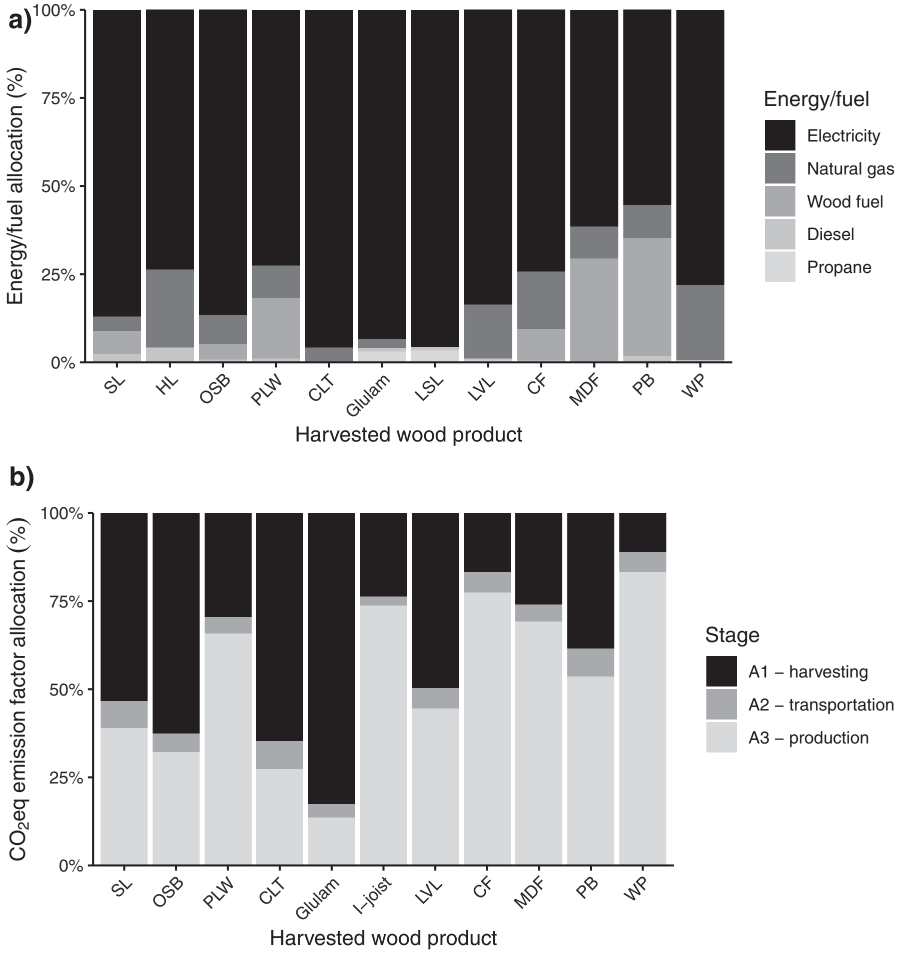

Figure 2.—The percent allocations for (a) the fuel and energy inputs required to produce 1 m^3 of various harvested wood products (or 1 tonne of wood pellets) and (b) the CO_2-equivalent (CO_2eq) values in each stage of the cradle-to-gate life cycle of the production of 1 m^3 of harvested wood products. SL = softwood lumber; HL = hardwood lumber; OSB = oriented strand board; PLW = plywood; CLT = cross-laminated timber; Glulam = glue-laminated timber; LSL = laminated strand lumber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particleboard; WP = conventional wood pellet.

Our estimated A3 stage values (based on global energy and fuel inputs with Canadian-specific emission factors) often underrepresent the reported A3 stage values, except for softwood lumber and wood pellets. For softwood lumber and wood pellets, our estimated emission factors were 40 and 51 percent higher, respectively, than the emissions factors reported in Head et al. (2020) and Magelli et al. (2009), respectively. While the increase for softwood lumber seems high, the actual increase is only about 5 kg of CO_2eq per m^3 HWP, unlike the 46 kg of CO_2eq per odt HWP increase seen in our wood pellet estimate. In Magelli et al. (2009), the authors separated the fuel used during wood pellet production so that either wet sawdust or natural gas was used. In our estimates, both wood fuel and natural gas, along with electricity, propane, and diesel, were used as energy/fuel. If we were to combine the natural gas and wood fuel used during production in the study by Magelli et al. (2009), the overall A3 stage emission factor would increase by almost 500 percent (or an additional 239 kg of CO_2eq per odt HWP), resulting in our estimate being 67 percent smaller in comparison. Furthermore, Magelli et al. (2009) provided estimates from wood pellet production in British Columbia, a province that has almost eight times fewer emissions associated with electricity generation than all of Canada, which could have also played a role in our higher estimates.

By using average energy/fuel inputs from other studies, we allow our estimates the flexibility to represent varying production systems while aligning with Canadian-specific energy/fuel emission factors. This can be said for the other HWP estimates, which were all smaller than the referenced reported values outlined in Table 4. On average our estimates were about 58 percent less than the referenced reported values, with plywood showing the least amount of difference (−38%) and CLT showing the most (−74%). Head et al. (2020) provided the referenced reported values for plywood and CLT, though it is difficult to ascertain the energy and fuel inputs used in their study. The average energy/fuel inputs we used in our estimates for plywood came from the studies by ASMI (2018b, 2022a), and Puettmann et al. (2016b, 2016c), two of which are Canadian studies, and the other two are American. Meanwhile, the only CLT study to provide energy/fuel inputs was by Puettmann et al. (2018), which is a North American study. Overall, the energy/fuel inputs used in this study is representative of systems used in North America.

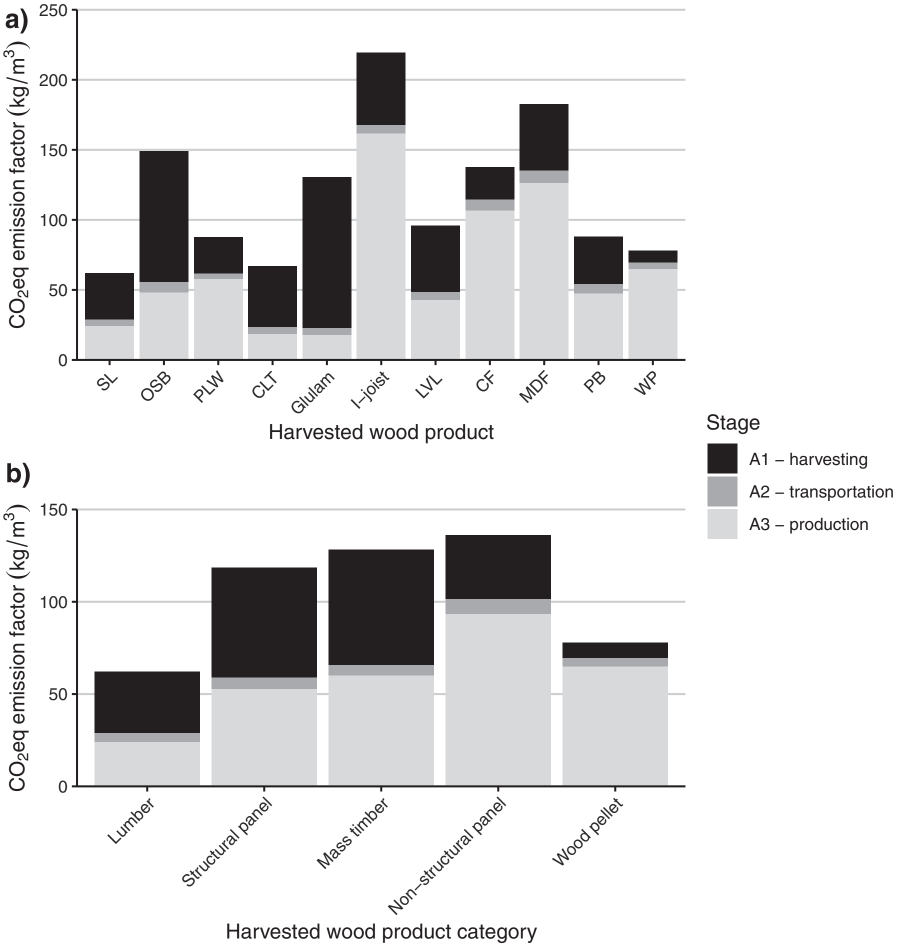

Figure 3.—The (a) total cradle-to-gate CO_2-equivalent (CO_2eq) emission factors (kg·m^{-3}) for the harvested wood products (HWP) and (b) mean cradle-to-gate CO_2eq emission factors (kg·m^{-3}) for the HWP categories summarized in this review. CO_2eq values were calculated using the 100-year global warming potentials. SL = softwood lumber; OSB = oriented strand board; PLW = plywood; CLT = cross-laminated timber; Glulam = glue-laminated timber; LVL = laminated veneer lumber; CF = cellulosic fiberboard; MDF = medium-density fiberboard; PB = particleboard; WP = conventional wood pellet.

Interestingly, upstream production emissions from additives (i.e., resins, starch, wax, etc.) are mostly absent in most LCA A1 stages. For example, all nonstructural panel studies outlined in this review acknowledge the use of additives for the HWP and include the transportation emissions for moving the additives to the mill, but do not include emissions associated with the production of those additives. The only study outlined in this review to include additive production emissions in their A1 stage was by Sahoo et al. (2021), who described the cradle-to-gate LCA of LSL. The omission of these additional upstream emissions could potentially lead to underestimating overall emission factors.

For comparative analysis in this review, 100-year global warming potentials (GWPs) were used to summarize the emission factors into CO_2eq values. However, shortcomings of this ubiquitous climate metric require consideration, as evidence is increasing that GWPs do not sufficiently account for the contrasting consequences of short- and long-lived pollutants (Lynch et al. 2020). Instead, a proposal by Allen et al. (2018), and slightly revised by Cain et al. (2019), suggests using the newly denoted GWP* that allows for short- and long-lived pollutants to more consistently and reliably be expressed through their warming effects, resulting in a CO_2-warming-equivalent (CO_2w.e) value. As demonstrated by Lynch et al. (2020), the GWP* illustrates the importance of time-dependency of pollutants, which is consistent with dynamic LCAs, as first proposed by Levasseur et al. (2010). Therefore, more accurate metrics such as CO_2w.e, and methods such as dynamic LCAs, can further increase the viability of climate-focused research and improve policies that are reliant on 100-year CO_2eq values.

A caveat is that the results highlighted in Table 5 do not account for forest C stocks (i.e., the C removed from the forest during harvesting), as it was beyond our project scope. Our exclusion of forest C stocks should not diminish their importance in LCA work, as a complete assessment of emissions associated with these products must be supplemented with an analysis of the effects on forest C stocks. By assuming net C neutrality in forests, one runs the risk of oversimplifying the LCI and therefore oversimplifying the resulting potential effects on climate change (Head et al. 2019). These effects have been discussed at length in reviews by Helin et al. (2013), De Rosa et al. (2018), Leinonen (2022), and Fehrenbach et al. (2022), to name a few.

Due to species-specific variations in wood density, it is recommended that the amount of C in roundwood required for the manufacturing of 1 m^3 of HWP be calculated exclusive to the LCA study and its regionality. For context, we provide the average reported C content per cubic meterof HWP from all the sources that scored ≤12 cumulative quality points in Table 7 (see Supplemental Table SM8 for individual data). For wood pellets, we provide C content based on the bulk density and single-pellet density described in Tarasov (2013). We assumed that few to no additives were used in wood pellet production and so 50 percent of the pellets by weight is C. Differences associated with the C content in HWPs are mainly associated with the amount of wood contained per cubic meter, with highly compressed products typically containing more C per cubic meter. For example, nonstructural panels such as particleboard contain more wood per cubic meter than structural panels, such as plywood, or lumber products, such as softwood lumber (Meil et al. 2009) resulting in larger C content per cubic meter of product.

From our analysis, structural HWPs used for construction in Canada (including lumber and mass timber) can store between 211 and 313 kg C per m^3 and nonstructural panels can store between 116 and 364 kg C per m^3. The global C stock in HWPs was estimated at 441 Mt of CO_2eq per year by 2030, though it is highly dependent on evolving markets (Johnston and Radeloff 2019). One approach to increase C stock in HWPs is to demonstrate their potential as alternatives to high GHG-emitting products through comparative LCAs. Though this method has challenges associated with access to relevant data (Teshnizi et al. 2018) and determining the appropriate, functionally equivalent scenario (Xie et al. 2023), it remains the preferred way to illustrate comparisons. Through comparative LCAs that do not account for forest C stocks, using HWPs, such as lumber and plywood, for construction has been shown to substantively reduce emissions relative to concrete and steel products (Smyth et al. 2017, Balasbaneh et al. 2022, Hafner and Özdemir 2023). Comparative LCAs that did account for forest C, e.g., Skullestad et al. (2016), also showed reduced emissions.

Table 7.—The average carbon (C) content (kg) per m^3 of harvested wood products (HWP). Averages were calculated using reported data from sources that scored ≤12 cumulative quality points (see Section 2.2. for scoring details). Upper and lower data limits are shown in parentheses to provide context on the variation of reported values.

HWP	Carbon content (kg C·m^{-3} HWP)
Lumber	
Softwood lumber	218.6 (204.0–255.0)
Hardwood lumber	210.9 (135.88–286.0)
Structural panel	
Oriented strand board	285.4 (268.0–307.0)
Plywood	221.4 (204.0–251.5)
Mass timber	
Cross-laminated timber	224.8 (181.0–268.6)
Glue-laminated timber	239.0 (181.0–295.3)
I-joist[a]	218.0
Laminated strand lumber[a]	312.6
Laminated veneer lumber	236.6 (177.0–271.4)
Non-structural panel	
Cellulosic fiberboard	115.9 (109.8–122.0)
Medium density fiberboard	363.8 (336.5–391.0)
Particleboard	309.4 (272.7–346.0)
Wood pellet	
Conventional wood pellets[a]	345.3[b]/635.3[c]

[a] Data not averaged (I-joist data from Head et al. [2020]; laminated strand lumber data from Sahoo et al. [2021]; wood pellet data from Tarasov [2013]).

[b] C content based on bulk density.

[c] C content based on single pellet density.

A major challenge in this analysis was the availability and accessibility of relevant data. Most LCI data are not typically published in LCA studies as these data stem from databases that are not open access or are directly from manufacturers who do not want the raw data to be publicly available. While these constraints are understandable, it nevertheless hinders an open-access approach. From this study, we found that Canadian data for hardwood lumber, MDF, particleboard, and wood pellets were not current (>10 years) and that no Canadian-specific data for LSL or CF was found in the literature. These substantial gaps in the data can lead to missing data points (e.g., harvesting data for hardwood lumber, LSL, and MDF) and can cause disparities in future modelling research that will rely on published data. A national HWP database with up-to-date emission factors would be beneficial for Canada (and beyond) and is necessary to help improve our understanding of HWP life cycles.

Furthermore, we focused on the more popular HWPs being produced in Canada, but new and innovative products such as delignified wood are being designed and studied worldwide, which can lead to new avenues in the Canadian wood product industry. These products have various applications (as summarized by Li et al. [2021]) that can extend HWP C storage and/or CO_2 capture (Singh et al. 2022). Although our review did not focus on pulp and paper products, notable advances occurring for these materials could potentially revitalize that industry in Canada. For example, wood pulp can be used to create lignin-containing microfibrillated celluloses (LMFCs), packaging material that can be used to substitute synthetic, fossil-derived plastics (Spence et al. 2010) or as a reinforcement agent to polyactic acid, a biodegradable polymer commonly used for biomedical implants (Yetiş et al. 2020). Recent studies have focused on improving LMFC tensile strength and water resistance (Lahtinen et al. 2021), microfibrillation rate (Ämmälä et al. 2021), energy consumption (Vera-Loor et al. 2022), and yield (Ämmälä et al. 2022). A review of cellulose and lignin nanomaterials by Dorieh et al. (2022) outlines recent progress on these types of materials and demonstrates the growing interest in LMFCs as well as other lignin-containing products.

Lastly, our findings can contribute to improved analyses of HWP-related forestry mitigation assessment, to better support forest management and policy development. Interest in HWPs as a means for climate mitigation has grown over the years, and generating long-lived HWPs has been shown to have a high mitigation potential (Smyth et al. 2018). Regional differences in ecosystems and management priorities can alter the effectiveness of general mitigation strategies (Smyth et al. 2020), causing regionally specific data to be an influential factor for mitigation analyses. Our estimates of specific GHG emissions for the various stages of numerous HWPs using Canadian-specific fuel and energy emission factors can therefore help support more accurate forestry mitigation assessments.

Conclusions

From our review on Canadian-specific emissions stemming from the cradle-to-gate life cycle of HWPs, we found substantial gaps in the literature (outdated data, non–Canadian-specific data, etc.). For the studies we did find that had useful emission factors, a scoring pedigree was used to assess the data quality to reduce bias. The best-scoring Canadian data were chosen to represent their respective HWP and all global data with an aggregated score of ≤ 12 were chosen to represent the average HWP emission factors. Calculated emission factors for all three stages of the cradle-to-gate life cycle were then calculated based on the best supporting data. The highest emission factor during the A1 (harvesting) stage was from glulam (107.65 kg of CO_2eq per m^3 HWP) whereas the highest emission factor for the A3 (production) stage was from I-joists (160.66 kg of CO_2eq per m^3 HWP). For all HWPs analyzed, the A2 (transportation) stage resulted in the lowest overall emissions.

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