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Environmental impacts of structural lumber production in Japan

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Abstract

Low-rise buildings in Japan are predominantly made of wood. Furthermore, the government promotes the use of wood in mid- and high-rise buildings to tackle climate change. Therefore, the environmental impact of structural lumber should be assessed. In this study, we evaluated greenhouse gas (GHG) emissions and resource consumption associated with structural lumber production using life cycle assessment. Herein, we focused on Japanese Agricultural Standard certified structural lumber (artificially dried lumber and machine-grade structural lumber) made from Japanese roundwood. To ensure representativeness, 15 companies and 15 sawmills covering more than 50% of Japan's structural lumber production were selected and data on their production were collected. The results show that the GHG emissions and resource consumption of Japanese structural lumber are 7.99×10 kg-CO_2e/m^3 and 1.77×10^{-3} kg-Sb eq./m^3, respectively. The major sources of GHG emissions are electricity and roundwood production. Roundwood and metal tools significantly affect resource consumption. The recycling of rare metals in tools is essential for reducing resource consumption. A significant amount of heat energy is utilized for drying, and this heat energy is supplied from both biomass and fossil fuels. GHG emissions and resource consumption are 5.3 and 1.6 times higher, respectively, if biomass fuel is replaced by fossil fuel. Policies supporting the introduction of biomass boilers have been highly effective. It is recommended to further promote measures such as replacing fossil fuel-based boilers with biomass boilers and effectively utilizing biomass boilers in multiple regional sawmills. In addition, switching from grid electricity to electricity generated by renewable energy sources is effective for further reducing environmental impacts. The long-term use of structural lumber is valid for combating global warming because it fixes carbon for decades. In this study, the CO_2 emissions from biomasaluated in terms of carbon neutrality. Appropriate forest management is a prerequisite for carbon neutrality, and the promotion of sustainable forest management, such as reforestation after logging, is crucial.

Keywords Life cycle assessment (LCA), Greenhouse gas emissions, Resource consumption, Sawn wood, Timber, Biomass, Sawmill, Allocation

Introduction

Wood is used for various purposes, including building materials, furniture, civil engineering materials, paper, and as an energy source. In Japan, 860,000 new houses were constructed in 2022, of which 478,000 (or 56%) were wooden structures [1]. Based on total floor area, of the 66 million m^2 of housing constructed in 2022, 45 million m^2 (65%) is wooden. Structural lumber is used to satisfy this requirement. In 2021, 77% of roundwood lumber was for domestic use, and 7,277,000 m^3 of lumber was shipped for construction purposes [2]. Softwood

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accounts for >99% of the roundwood used for domestic lumber production [2]. Japanese cedar (*Cryptomeria japonica*) is the main plant material used, followed by Japanese cypress (*Chamaecyparis obtusa*).

Reducing greenhouse gas (GHG) emissions is a crucial issue for the building sector. Life-cycle assessment (LCA) is a technique used to assess the environmental impact of products and services throughout their life cycles, from resource extraction to manufacturing, use, and end-of-life. ISO 14040 [3] defines the LCA framework as the international standard, and the LCA method for assessing the environmental impact of building products is defined in ISO 21930 [4]. Moreover, there are various LCA case studies on buildings and building materials.

During the lifecycle of a building, GHG emissions are mostly attributed to energy consumption during the use phase. However, the number of buildings achieving virtually zero energy consumption during the use phase is increasing. This is achieved by, for example, improving insulation and installing photovoltaic power generation equipment. Such structures are called zero-energy houses (ZEH) and zero-energy buildings (ZEB), respectively. The Japanese government has set a goal of ensuring energy-saving performance at the level of the ZEH standard for new houses to be built by 2030 and beyond.

Energy consumption decreases during the use phase; thus, GHG emissions from other phases, such as the production of building materials, have become relatively conspicuous [5, 6]. Wood products are produced through several processes, including forest management, harvesting, transportation, and sawing. Fossil fuels are used in these processes, and it is thus necessary to analyze their environmental impacts. Furthermore, LCA data are essential for assessing the environmental impact of wooden buildings. Therefore, several LCA studies have been conducted [7].

In the USA, LCA studies have been conducted for softwood lumber in northeastern and north-central regions [8], western and southern regions [9], and the Pacific Northwest and southeastern regions [10]; studies on hardwood lumber in southeastern USA were also conducted [11]. In Europe, an LCA case study of sawn coniferous wood was conducted in Spain [12]. Also in Spain, another study determined the carbon footprint of sweet chestnut (*Castanea sativa*) sawn timber products and compared GHG emissions between natural drying and fossil fuel drying; the results showed that natural drying reduces GHG emissions [13]. A study in Brazil reported that GHG emissions from transportation increased if roundwood was transported over long distances [14].

In Japan, LCA case studies have been used to evaluate CO_2 or GHG emissions of Japanese cedar in northern Nagano Prefecture, Japanese larch (*Larix kaempferi*) lumber in eastern Nagano Prefecture [15], Japanese cedar in Niigata Prefecture [16], and Japanese cedar in Akita Prefecture [17]. Fuchigami et al. clarified the carbon footprint of lumber certified by Kyoto Prefecture [18] and indicated that using local roundwood is effective in reducing GHG emissions [19]. Nambu et al. reported CO_2 emissions from domestic lumber; however, only one domestic sawmill was surveyed [20]. A common feature of these previous studies is the high energy consumption during artificial drying. If the energy for drying is supplied by biomass fuels, GHG emissions from fossil fuels would be lower.

Generic LCA data for structural lumber are required to perform LCA for wooden buildings in Japan. However, as discussed, previous LCAs for structural lumber in Japan have focused on specific regions or only a small number of sites. IDEA [21], the Japanese LCA inventory database, includes LCA data on lumber. However, these data are derived from statistics, and there are no data on named structural lumber because of the lack of statistical classification of structural lumber.

Japan is promoting the use of wood in buildings as a measure to address climate change issues. In 2010, it enacted an Act for Wood Use Promotion in Public Buildings. In 2021, this Act was amended to the Act for the Promotion of Use of Wood in Buildings Contributing to a Decarbonized Society. This has led to the popularization of wood use not only in public buildings but also in private buildings. LCA data for structural lumber are essential for promoting these policies from an environmental perspective. Therefore, through this study, we aimed to develop generic LCA data for structural lumber in Japan and identify points of high environmental impact.

Methods

Goal and scope definition

The goal of this study was to produce generic LCA data for structural lumber produced in Japan and identify points of high environmental impact. We focused on kiln-dried structural lumber from domestic roundwood. To evaluate the environmental impact of lumber products, LCA was conducted based on ISO 14040 [3]. The products evaluated were Japanese Agricultural Standard (JAS) [22]—certified structural lumber (artificially dried lumber and machine-grade structural lumber). JAS is the Japanese national standard established by the Ministry of Agriculture, Forestry, and Fisheries (MAFF) in the fields of food, agriculture, forestry, and fisheries. Structural lumber is made of softwood and used as the main structural load-bearing component of buildings. A functional unit was defined as the production of 1.00 m^3 of the structural lumber. The system boundary was defined as cradle-to-gate and included the process from forest management to transportation and sawing (Fig. 1). We assessed the environmental impact of climate change and resource consumption. The government is promoting the use of wood in buildings as a measure to reduce GHG emissions; thus, it is necessary to quantify the GHG emissions of wood products and determine how to reduce them. Wood is a renewable resource; however, it is also produced using nonrenewable resources. Therefore, resource consumption was included in this assessment.

Table 1 Production volume of the surveyed sawmills

Production volume: x (m^3/year)	Surveyed factory
x ≥ 100,000	2
100,000 > x ≥ 50,000	1
50,000 > x ≥ 25,000	5
25,000 > x ≥ 12,500	1
12,500 > x ≥ 6,250	4
6250 > x	1

Data quality

To ensure the geographical representativeness of the generic LCA data for JAS structural lumber made from Japanese roundwood, the sawmills surveyed were selected such that the total production volume was at least 50% of the market share. In total, 15 companies and 15 sawmills were selected based on the production volume determined from internal data of the Forestry Agency, Japan [23].

The geographically valid scope of this study lies within the Japanese context. There was a sharp drop in lumber production volume in 2020 owing to the COVID-19 pandemic. Moreover, there was a sharp rise in lumber prices in 2021 (the so-called *wood shock*). Accordingly, we collected data for a 1-year period from January to December 2019 that was unaffected by these unusual events. Some sawmills were affected by equipment upgrades and market conditions in 2019, and the collection period was adjusted such that the data were for a 1-year period when the sawmills were in normal operation.

The production volume of the surveyed sawmills is summarized in Table 1. This study encompassed a range of sawmills, from large- to small-scale. The geographical distribution of the surveyed sawmills is illustrated in Fig. 2. In 2019, there were a total of 4382 sawmills in Japan, of which 2583 had a power output of < 75 kW [24]; there were 73 large-scale factories with a power output of 1000 kW or more [24]. Japan has a significant number of small-scale sawmills. Approximately 270 sawmills received JAS structural lumber (kiln-dried) certification. The production volume of JAS structural lumber (kiln-dried) using domestically sourced roundwood in 2019 was 2.01×10^5 m^3 [23]. The production volume at the surveyed sawmills was 1.50×10^5 m^3. While it's not possible to calculate the exact share due to the use of production data from years other than 2019 in some sawmills, a simple calculation suggests that this survey covered over 70% of the share.

Primary data collection

Input (e.g., roundwood and fuel electricity) and output (e.g., lumber production volume) data were collected from each sawmill. No intentional cutoff values were used. The sawmills purchased roundwood either from

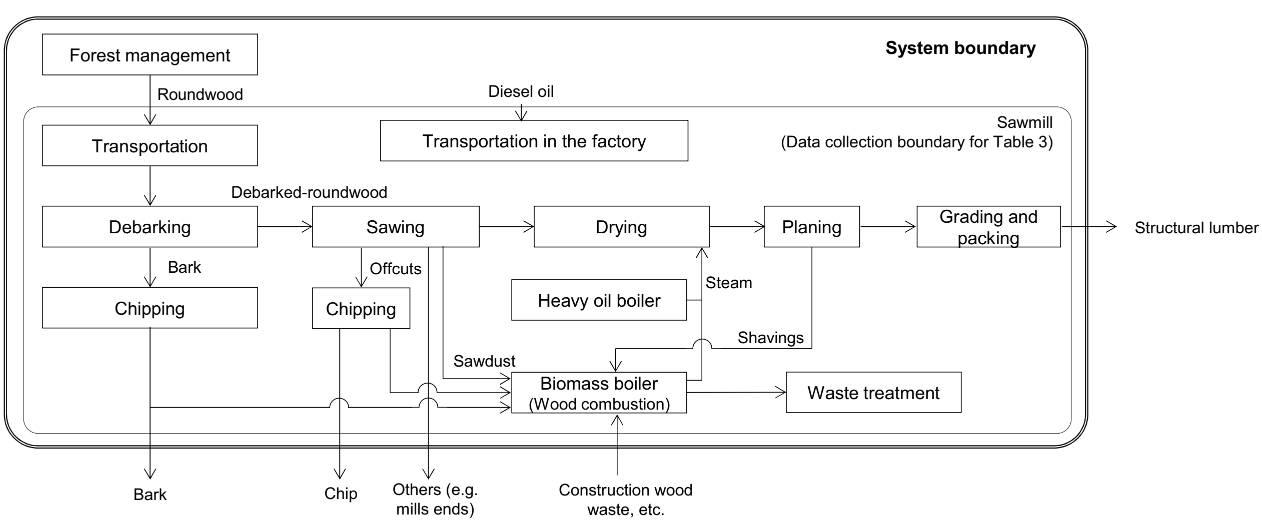

Fig. 1 System boundary

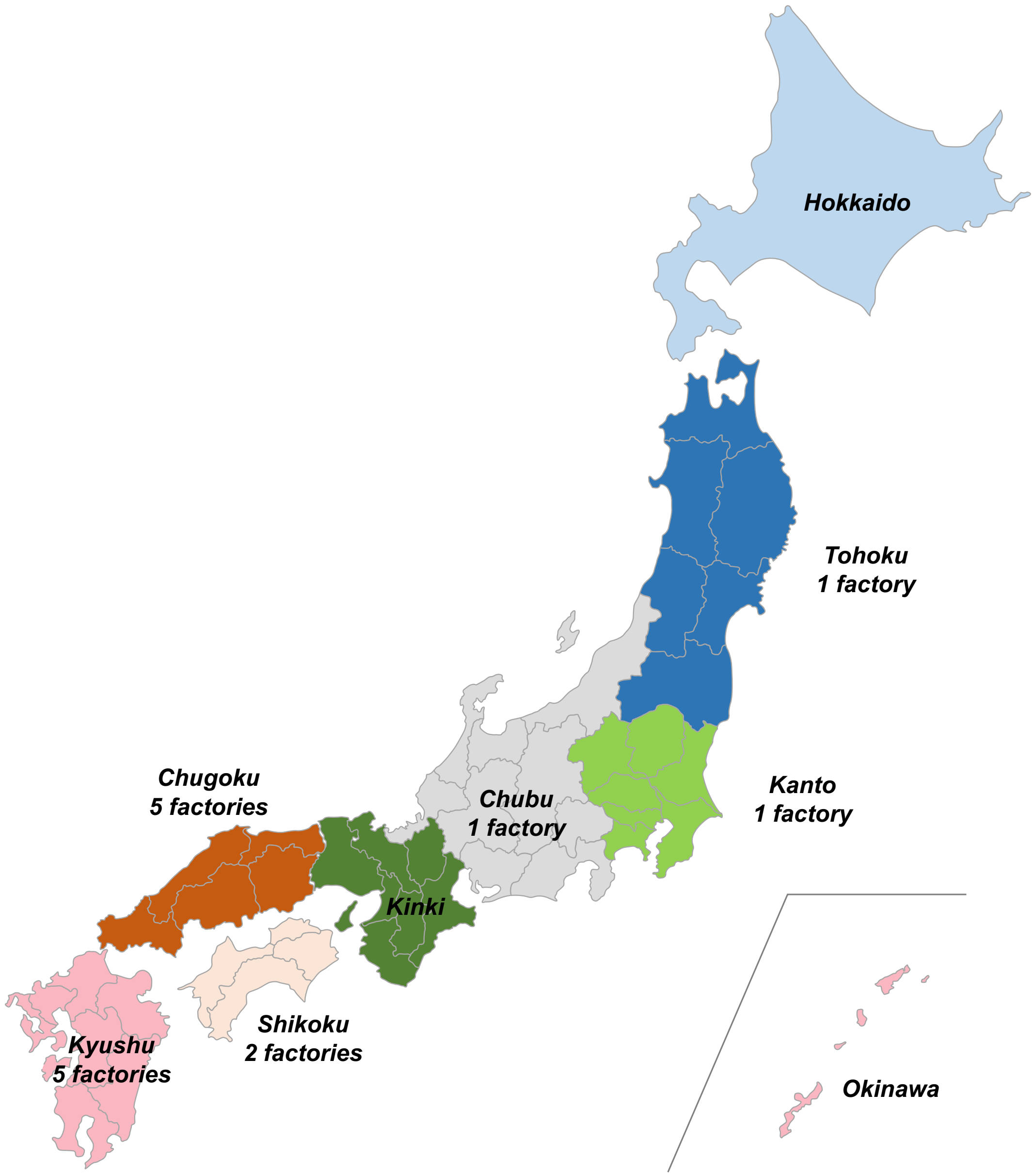

Fig. 2 Number of factories surveyed by region

the timber market or directly from forestry operators. Therefore, we calculated the transport volume based on the respective distances and purchase quantities. In this study, 14 of the 15 mills operated biomass boilers and used steam to dry the wood. Biomass boilers use chips, sawdust, and bark as fuels. Most of these co-products are generated inside the sawmills, and no commercial transactions are conducted; therefore, many sawmills did not measure the quantity of biomass fuel used. The amount of biomass fuel consumed was estimated from the amount of steam produced and boiler specifications. Heavy oil boilers were used as a backup to biomass boilers, and fossil fuel consumption data were collected.

Each sawmill had different production volumes; thus, a weighted average of the production volumes was calculated to obtain a representative value for Japan. Sawmills also produce structural lumber of equivalent performance, without JAS certification. Therefore, the production volume of each sawmill included JAS-certified structural lumber and equivalent structural lumber.

The moisture content of roundwood varies with season and region. The moisture content tends to be higher in summer and lower in winter. Chips, sawdust, and bark, which are co-products of the sawing process, are affected by the moisture content of roundwood. In addition, their moisture content varies depending on how they are managed in a sawmill (e.g., stored outdoors or indoors). As wood is an important raw material for paper chips, its moisture content is typically measured. However, for other co-products, these data were not obtained unless the results of the moisture content measurements were requested by their customers. In this study, the apparent density, moisture content, and price of the products were established based on literature [24–29] and interviews with sawmill personnel (Table 2).

Background data and impact assessment method

IDEA ver. 3.1 [21] was used as the background LCA database, and the climate change IPCC 2013 GWP 100a method was used to calculate the GHG emissions as CO_2 equivalents. The impact assessment model for resource consumption was the Life cycle Impact assessment Method based on Endpoint modeling 2 (LIME2) [30, 31]. LIME2 is a life cycle impact assessment method that considers Japanese environmental conditions. LIME2 uses the inverse of minable reserves to produce characterization factors. The results are expressed as antimony equivalents.

Unit process data for Japanese cedar and Japanese cypress [32] were adopted to assess the environmental impacts of roundwood production. IDEA ver. 3.1 was used as the background data to calculate the upstream side of the roundwood.

Allocation method

Structural lumber and other products, such as other lumber and wood chips, are produced from roundwood in sawmills. The selection of an allocation method for these co-products has a significant effect on analysis results [33, 34], and ISO 14044 [35] states that allocation should be avoided if possible as step 1. However, allocation was inevitable in this study because the evaluation targeted only the structural lumber. As step 2, when allocation is unavoidable, inputs and outputs of the process should be allocated in a way that reflects the underlying physical relationships [35]. Klein et al. [36] suggested allocation by mass, because economic allocation is variable by region and time. Therefore, the carbon mass in the product was used as the allocation criterion. This is practically the same as allocation based on absolute dry mass. The market prices of the main products (lumber) and co-products (e.g., sawdust) differ significantly, and economic allocation is widely applied to wood products [37]. The economic allocation method is exemplified as step 3, in which physical relationships alone cannot be established or used as the basis for allocation [35]. Therefore, an allocation based on market prices was conducted as a sensitivity analysis.

The inputs and outputs related to specific products were allocated only to these products. For example, the inputs/outputs of boilers that produce steam for drying

Table 2 Apparent density, moisture content, and price of products

Item	Apparent density (t/m^3)	Moisture content (%)[j]	Price
Roundwood	0.83 [25]	120[c]	–
Sawn lumber	0.38[a]	15 [22]	71,715 JPY/m^3[e]
Wood chip for paper making	0.25 [25]	120[b]	14,500 JPY/BDt[k] [24]
Wood chip for biomass boiler	0.25 [25]	120[c]	4678 JPY/BDt[f]
Sawdust	0.23 [25]	55[b]	1241 JPY/m^3[g]
Bark	0.18 [25]	58[b]	1241 JPY/m^3[h]
Mills ends	0.46[b]	49[b]	4678 JPY/BDt[i]
Planer shavings	0.10[b]	15[d]	1241 JPY/m^3[h]

[a] Weighted average of Japanese cedar (0.314 g/cm^3) [26] and Japanese cypress (0.401 g/m^3) [26] with 15% moisture content

[b] Weighted average of surveyed sawmills

[c] Assumed to be the same as the wood chip for paper making

[d] Assumed to be the same as the sawn lumber

[e] Weighted average of Japanese cedar (67,850 JPY/m^3) [24] and Japanese cypress (86,600 JPY/m^3) [24]

[f] Excluded standard transportation costs [28] from the price of wood chip for biomass boiler including transportation[27]

[g] Excluded standard transportation costs [28] from the price of sawdust including transportation[29]

[h] Assumed to be the same as the sawdust

[i] Assumed to be the same as the wood chip for biomass boiler

[j] Dry basis

[k] Bone Dry tonne

were allocated only to lumber (i.e., the product to be dried using steam). Packaging materials were allocated only to lumber because they are used for lumber. Tools (e.g., saw and cutter) were allocated to both the main product (lumber) and co-products (e.g., chips). Only the tools used to produce chips were allocated to the chips. The inputs/outputs related to the entire sawmill, such as forklifts and dust collectors, were allocated to all products. Some co-products, such as sawdust, are used as fuels in sawmill biomass boilers. Allocations were made during the co-product generation stage. The input and output of the co-products consumed for lumber drying were allocated to the lumber.

Results

The carbon flow in a sawmill is illustrated in Fig. 3. In addition to roundwood, sawmills also receive construction waste that is converted into biomass fuel. Overall, 82% of roundwood is sold as valuable material, including lumber (41%) and chips (29%). Chips are the primary raw materials used in papermaking. In addition, 3% is sold as fuel and 15% is consumed to produce steam in the sawmill biomass boiler; less than 1% of the waste is disposed.

Table 3 lists the inventory data obtained after the allocation. Allocation by mass resulted in 1.19 m^3 of roundwood as the raw material and 1.00 m^3 of lumber produced. The species composition of the roundwood was found to be 5.62×10^{-1} m^3 and 6.25×10^{-1} m^3 for Japanese cedar and Japanese cypress, respectively. The electricity consumption was 5.53×10 kWh.

In the sensitivity analysis, the economic allocation resulted in 8.99×10^{-1} m^3 for Japanese cedar and 9.48×10^{-1} m^3 for Japanese cypress. In terms of economic allocation, 1.85 m^3 of roundwood is required to produce 1.00 m^3 of structural lumber. The price of lumber is higher than that of chips and sawdust, and more input is allocated compared with mass-based allocation. The input/output used only in boilers for drying is allocated only to the lumber; therefore, the values do not change when the allocation method is changed. Therefore, some inputs, such as industrial water and construction wood waste, have the same value. The heat input to the biomass boiler consisted of roundwood and construction wood wastes. For each 1.00 m^3 structural lumber, 4.49×10^3 MJ-LHV was input.

Impact assessment results

The results of the mass-based and economic allocation methods are summarized in Table 4; GHG emissions were 7.99×10 and 1.19×10^2 kg-CO_2e/m^3, respectively, while resource consumption was 1.77×10^{-3} and 2.82×10^{-3} kg-Sb eq., respectively. Thus, economic allocation increased the environmental impact.

Figure 4 shows the breakdown of the mass-based allocation results. Electricity was the largest contributor to GHG emissions (39%), followed by roundwood (33%). Transportation also made a non-negligible contribution of 12%. Transportation includes the transport of logs, auxiliary materials, and waste. GHG emissions from wood combustion are primarily attributed to the impact of CH_4 and N_2O emissions generated during biomass combustion. In terms of resource consumption, roundwood and cutting tools had an impact of 42%. The impact of electricity was 12%. Analyzing the results by elementary flow, it was found that tungsten, used in the production of cutting tools, contributed 39%.

Discussion

Sawmills in Japan produce not only structural lumber but also wood chips and biomass fuel. Less than 1% of the output from sawmills is disposed of as waste. For example, wood chips are used as raw materials for pulp and board.

In this study, the weighted averages of 15 sawmills were calculated. If arithmetic averages are calculated, the GHG emissions are 1.20×10^2 kg-CO_2e/m^3, or 1.5 times higher. This is because one sawmill uses only heavy oil boilers for drying, although the production volume is low. The standard deviation of GHG emissions was 1.38×10^2 kg-CO_2e/m^3. However, it reduced

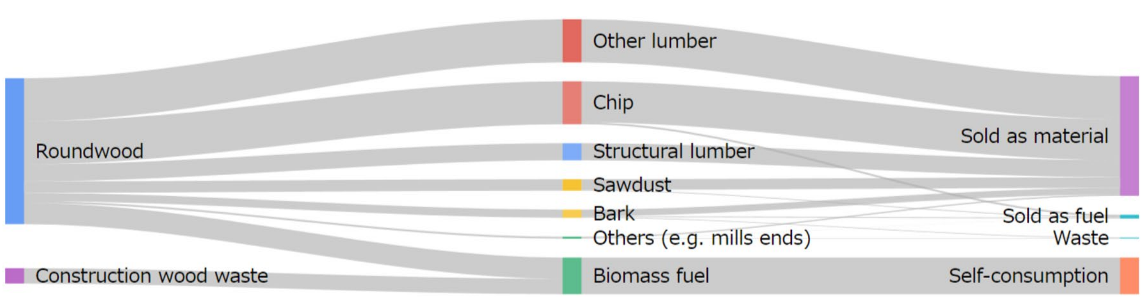

Fig. 3 Carbon flow in Sawmills

Table 3 Inventory data of 1.00 m^3 structural lumber production (gate-to-gate)

Type	Item	Amount of activity		Unit
		Mass[a]	Economic[b]	
Material	Roundwood, Japanese cedar	5.62E−01	8.99E−01	m^3
	Roundwood, Japanese cypress	6.25E−01	9.48E−01	m^3
Energy	Diesel oil	4.25E+01	6.57E+01	MJ-HHV[c]
	Electricity	5.53E+01	8.62E+01	kWh
	Kerosine	6.93E−03	1.19E−02	MJ-HHV
	Heavy oil A	5.54E+01	5.54E+01	MJ-HHV
	Construction wood waste	4.17E+01	4.17E+01	MJ-LHV
Water	Industrial water	2.22E−01	2.22E−01	m^3
	Domestic water	2.79E−01	2.79E−01	m^3
Energy	Construction wood waste	4.17E+01	4.17E+01	MJ-LHV[d]
Auxiliary materials	Lubricating oil	6.52E−02	1.02E−01	L
	Hydrazine hydrates	3.18E−02	3.18E−02	kg
	Saw, cutter, etc	1.90E−02	3.16E−02	kg
Package	Polypropylene	3.10E−02	3.10E−02	kg
	Polyethylene, high density	9.26E−02	9.26E−02	kg
	Corrugated board	1.38E−03	1.38E−03	kg
Service	Waste treatment, combustion residue	1.00E−01	1.00E−01	kg
	Waste treatment, wood residue	2.00E−02	2.00E−02	kg
Transportation of roundwood	Truck, 20 t, load factor 100%	9.45E+01	1.37E+02	tkm
	Truck, 15 t, load factor 100%	2.21E+01	3.91E+01	tkm
	Truck, 10 t, load factor 100%	7.94E+00	1.34E+01	tkm
	Truck, 10 t, load factor 75%	1.98E−03	7.04E−03	tkm
	Truck, 4 t, load factor 100%	9.23E−01	1.72E+00	tkm
	Diesel oil	1.75E+00	3.75E+00	MJ
Transportation of auxiliary materials	Truck, 4 t, average load factor	4.93E−02	4.93E−02	tkm
Transportation of waste	Truck, 10 t, load factor 100%	1.38E−02	1.38E−02	tkm
	Truck, 10 t, average load factor	3.47E−03	3.47E−03	tkm
	Truck, 4 t, load factor 100%	9.40E−03	9.40E−03	tkm
	Truck, 4 t, load factor 50%	2.86E−03	2.86E−03	tkm
	Truck, 4 t, average load factor	9.42E−03	9.42E−03	tkm
	Truck, 2 t, load factor 100%	1.03E−02	1.03E−02	tkm
	Truck, 2 t, load factor 50%	3.33E−05	3.33E−05	tkm

[a] Mass-based allocation

[b] Market-price-based allocation

[c] Higher heating value

[d] Lower heating value

Table 4 Greenhouse gas (GHG) emissions and resource consumption of structural lumber production (cradle-to-gate)

	Mass-based allocation	Economic allocation
GHG emissions (kg-CO_2e)	7.99×10	1.19×10^2
Resource consumption (kg-Sb eq.)	1.77×10^{-3}	2.82×10^{-3}

to 2.63×10 kg-CO_2e/m^3 when the sawmill using only heavy oil boilers was excluded from the calculation. As in previous studies, the boiler heat source was the most important factor.

The impact of tools on resource consumption is also significant. When used tools are recycled as steel scrap, rare metals such as tungsten are not recovered as

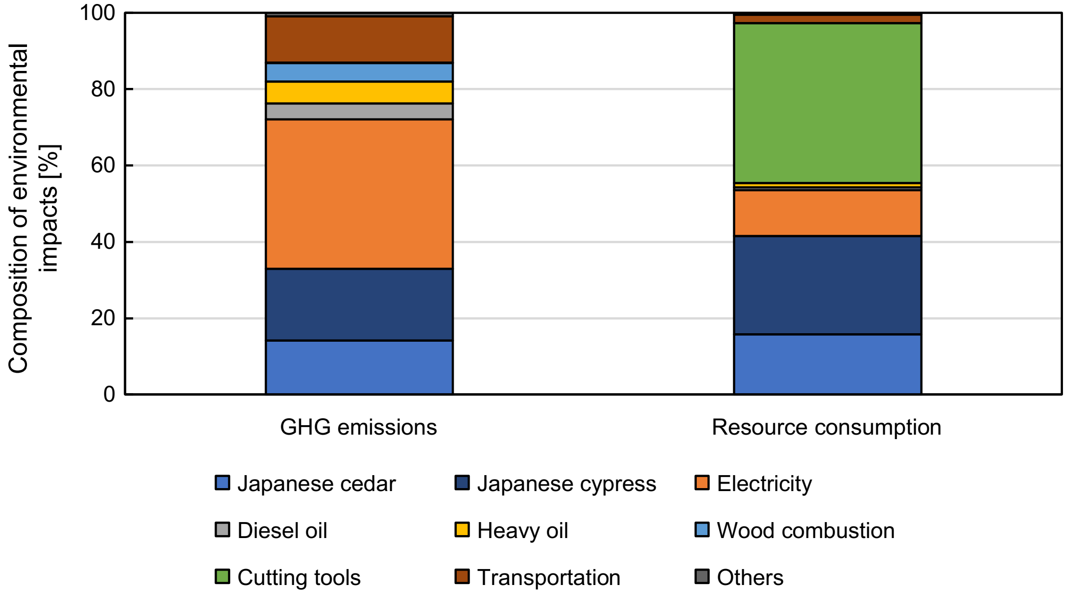

Fig. 4 Greenhouse gas (GHG) emissions and resource consumption of structural lumber production (cradle-to-gate) based on mass-based allocation

individual elements. Although some parts are lost during processing, it is recommended to recycle tools considering their rare metal components.

Heat source for lumber dry kiln

In this study, data were collected mostly from large-scale sawmills, many of which contain biomass boilers. The Japanese government has promoted policies to replace heavy oil boilers in sawmills with biomass boilers through subsidies and other measures. However, some sawmills, mainly small-scale sawmills, still use heavy oil boilers. While small-scale sawmills may contribute a smaller percentage to the overall production volume, their large numbers suggest that the consumption of fossil fuels may be higher than that indicated by the results of this study. There are challenges associated with the introduction of small-scale biomass boilers, including relatively high initial investments. Therefore, for sensitivity analysis, we analyzed a case in which all the drying heat sources were provided by heavy oil boilers instead of biomass boilers. The heat input to a biomass boiler is 4.49×10^3 MJ-LHV/m^3, and the calculation was made assuming that an equivalent amount of heavy oil was combusted. An increase in the number of products eligible for allocation was also considered because the biomass fuel currently consumed in sawmills can be sold as a product. In contrast, a case in which all heavy oil boilers were replaced with biomass fuel was also estimated because heavy oil boilers are still used in sawmills. The biomass fuel was assumed to be made from co-products such as sawdust, which is subject to allocation. Consequently, the number of products eligible for allocation decreases in this case.

The results of the sensitivity analysis are shown in Fig. 5. If all heat sources were replaced by biomass fuels,

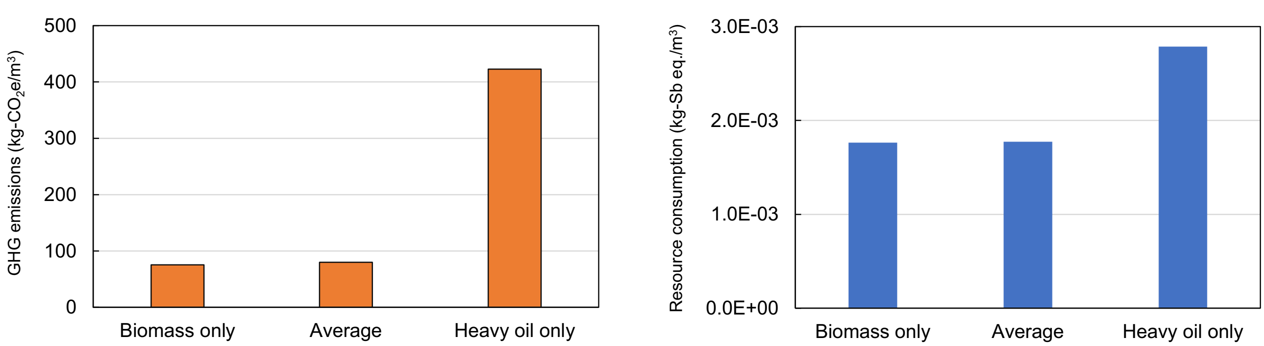

Fig. 5 Sensitivity analysis: change on fuel source for drying process

the GHG emissions and resource consumption would be 7.56×10 kg-CO_2e/m^3 and 1.76×10^{-3} kg-Sb eq./m^3, respectively. Although this is an improvement over the weighted average, its contribution was not significant. This is because the sawmills surveyed in this study have already reached a biomass fuel utilization rate of 98.8%, leaving little room for improvement.

In contrast, if all heat sources were replaced with heavy oil A, GHG emissions and resource consumption would be 4.23×10^2 kg-CO_2e/m^3 and 2.79×10^{-3} kg-Sb eq./m^3, respectively, that is, GHG emissions are 5.3 times higher and resource consumption is 1.6 times higher compared with using biomass fuel. The Japanese government has promoted policies to replace heavy oil boilers in sawmills with biomass boilers through subsidies and other measures. This sensitivity analysis confirms that policies to replace heavy oil boilers with biomass boilers are effective in reducing environmental impacts. However, some small sawmills use fossil fuels in their boilers, although others have established communal drying plants and operate biomass boilers. In fact, there are some examples of intensive drying in large sawmills, and promoting these activities is crucial.

Other important factors

Of the 14 sawmills using biomass boilers, we compared the arithmetic mean of the three with the highest GHG emissions to that with the lowest GHG emissions (Fig. 6). The largest difference was in the GHG emissions associated with the use of heavy oil A. Sawmills with higher GHG emissions mainly use biomass boilers; however, they also use heavy oil boilers on weekends and at night because biomass boilers are difficult to regulate and require a professional operator. Therefore, it is important to improve the utilization rate of biomass boilers. The next largest difference was in the GHG emissions from electricity. The differences in the amount of electricity consumption may be caused by factors such as production efficiency, increase in the power required for cutting owing to saw blade wear, and idle time of sawing machines and conveyors. Electricity can also be decarbonized by generating it from renewable energy sources. Some sawmills generate electricity from biomass; however, this electricity is sold entirely to the grid under a feed-in tariff (FIT) scheme. The FIT scheme is only available for a limited period of time, and after the FIT period ends, sawmills can produce lumber with much lower GHG emissions by using electricity from these renewable energy sources in their own sawmills. Thus, introducing incentives for lumber with lower GHG emissions is recommended to promote such activities. Furthermore, there was no significant difference in GHG emissions associated with

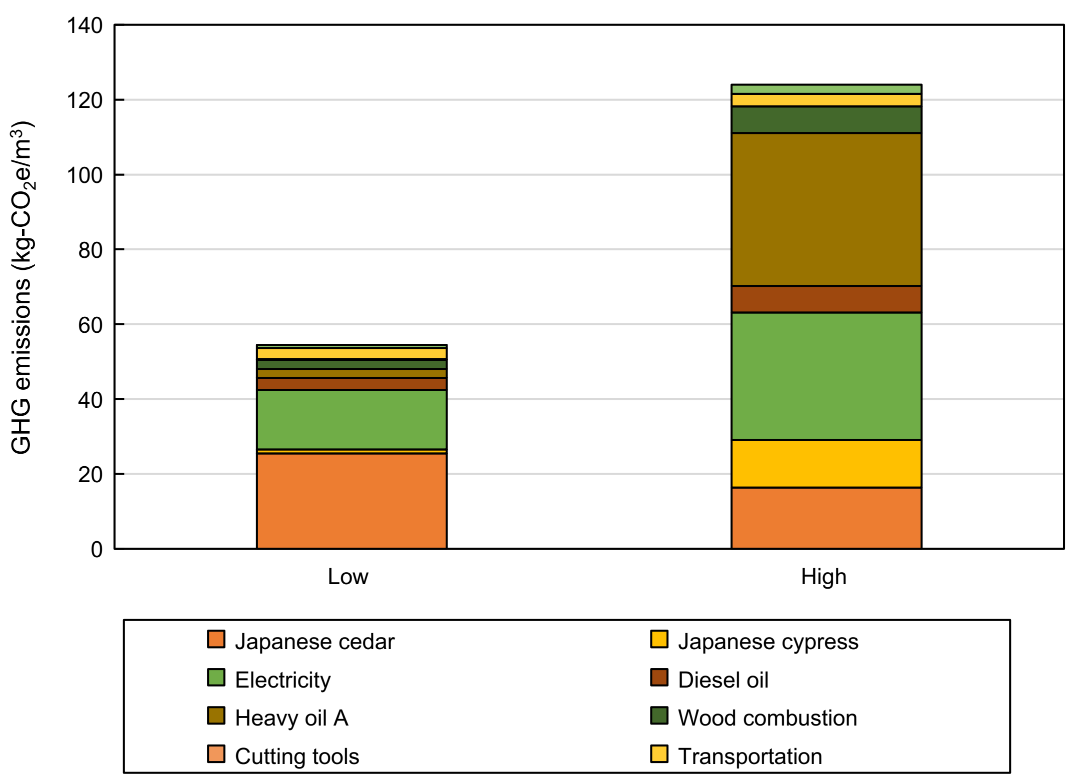

Fig. 6 Comparison of sawmills with high and low Greenhouse gas (GHG) emissions

roundwood consumption. This is because the rate of product conversion from roundwood did not differ significantly among the sawmills.

Comparison with other studies

We compared GHG emissions in this study with those in other Japanese cases (Fig. 7) [15–20]; as these studies considered allocating all GHG emissions to lumber, the no-allocation values in this study were added. The results of this study using mass-based allocation resulted in lower GHG emissions than those of the other cases. The Akita Prefecture case study of Kawanabe et al. [17] showed a similar result, but was for natural drying, and thus, the impact during drying was smaller. In other cases, fossil fuels, such as heavy oil or kerosene, are used during drying. In recent years, sawmills have rapidly converted heavy oil boilers to biomass boilers, which may have affected the results of this study.

Temporary storage of biogenic carbon

Assuming a carbon content of 0.50 for wood, 1.00 m^3 of lumber contains 162 kg of carbon. This is equivalent to 595 kg-CO_2e. The carbon contained in lumber is released into the atmosphere during the disposal phase and is, therefore, temporarily stored.

Since biomass fixes CO_2 in the atmosphere, the CO_2 released into the atmosphere after incineration at the end-of-life is considered as carbon neutral. However, since CO_2 in the atmosphere is temporarily fixed during the use of biomass products, biomass products contribute to the prevention of global warming during the period of their fixation.

Several methods have been proposed to assess the temporary storage of biogenic carbon in LCA; however, there is no internationally agreed upon scientific method [38, 39]. ISO 14067 [40] allows claiming impacts due to temporary carbon storage, an effect of delayed GHG emissions, as supplementary information. An impact of biogenic carbon storage is not negligible in LCA studies of wood products [39, 41–43]. For example, in a Japanese cross-laminated timber (CLT) case study, assuming a building half-life of 30 years, it was calculated that GHG emissions during manufacturing would be offset [44]. In that case study, the calculation was performed using a method of the Joint Research Centre (JRC) of the European Commission [45], presenting a characterization factor of -0.01 kg-CO_2e/(kg*year) for bio-derived carbon storage. For the remaining ratio, the Japanese GHG inventory report [46] adopted a lumber half-life of 35 years under the first-order decay method. Therefore, the same method was adopted to calculate the temporary storage of biogenic carbon in structural lumber. The results of varying the half-life are shown in Fig. 8. When the half-life was 35 years, the effect was equivalent to GHG emissions of -2.91×10^2 kg-CO_2e/m^3. Kayo and Tonosaki [47] estimated a half-life of 63 years using a log-normal distribution for wooden buildings in 2020. Under this condition, the negative effect increased further to -3.85×10^2 kg-CO_2e/m^3. The calculation of this figure is just an example, but the harvest wood products stocked in Japan was estimated to be 231 million t-C in 2019 [48];

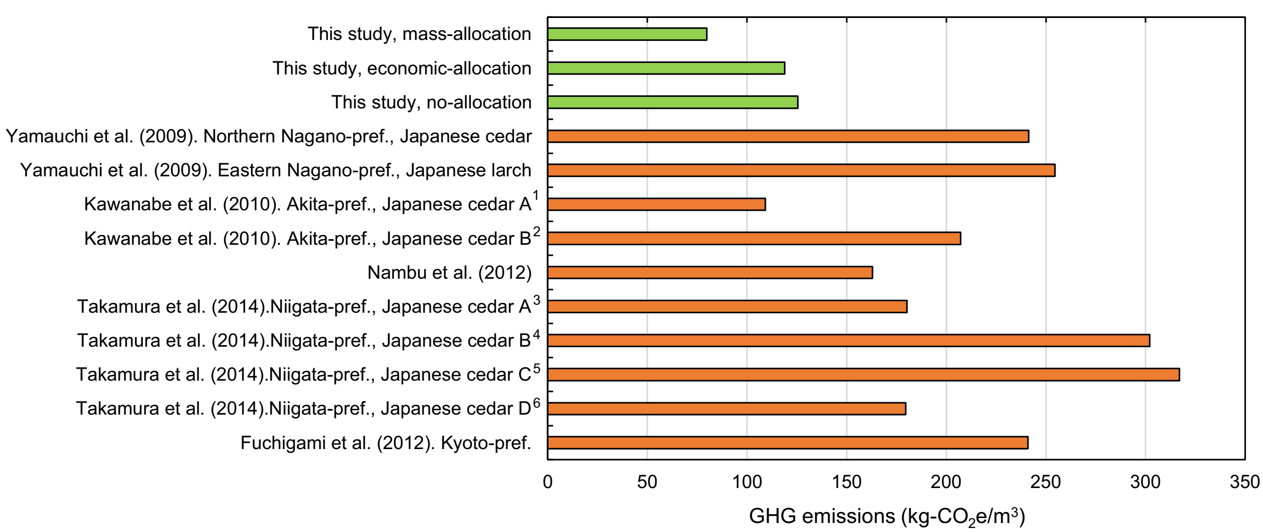

Fig. 7 Comparison of greenhouse gas (GHG) emissions with other cases. 1: medium temperature drying; 2: high temperature drying; 3: Kaetsu region; 4: Chuetsu region; 5: Chuetsu and Joetsu region; 6: Joetsu region

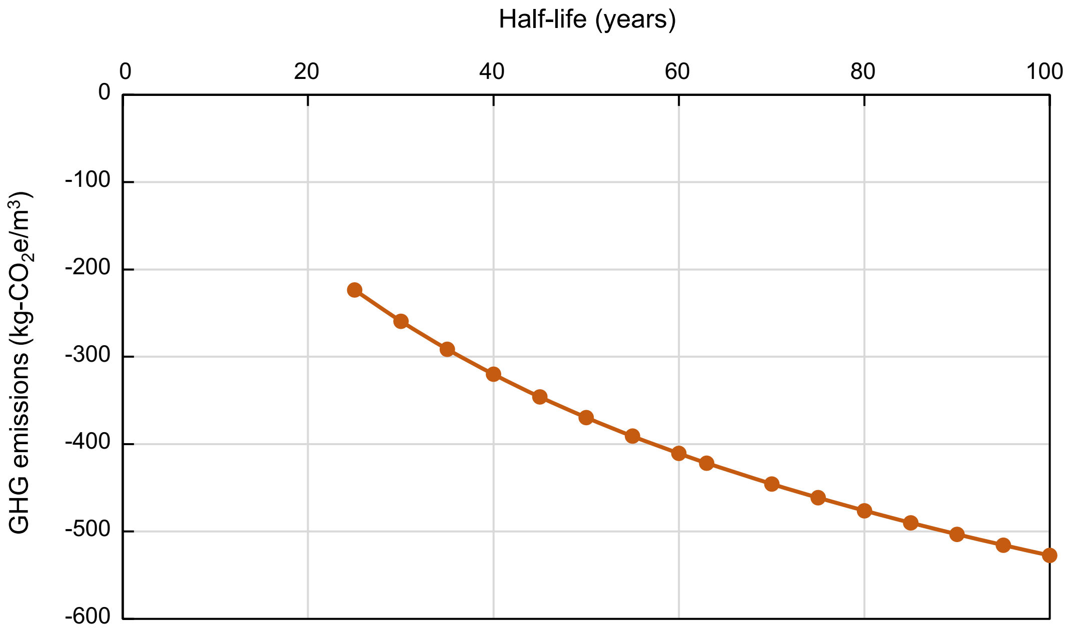

Fig. 8 Estimation of impact on greenhouse emissions due to temporary carbon storage. According to the National Greenhouse Gas Inventory Report of Japan, the default half-life of sawn wood in the use stage is 35 years

as such, the long-term fixation of biogenic carbon in wood is important for tackling climate change.

The sawmill consumed 4.49×10^3 MJ/m^3 of biomass fuel. This resulted in the emission of 3.96×10^2 kg of biomass-derived CO_2 to the atmosphere. Forest resources are renewable, and biomass-derived CO_2 emissions were evaluated as carbon–neutral. However, if forests are not managed sustainably, the emitted CO_2 remains in the atmosphere and cannot be treated as carbon–neutral. The amount of biomass-derived CO_2 emissions is more than three times higher than the fossil fuel-derived GHG emissions calculated in this study. Therefore, sustainable management of forests, including appropriate treatment after cutting, such as reforestation or conversion to natural forests, is essential.

Uncertainty

To generate accurate data, it is crucial to correctly understand the material balance in sawmills. However, data collected within the factory, even if in the same units, may not have the same meaning. For example, when the lumber produced is rectangular, the reported production volume (m^3) is highly reliable. However, the JAS rule for log volume [49] is used to measure the volume of roundwood. The rule for estimating roundwood volume (roundwood < 6 m in length) is as follows:

$$A = D^2 \times L \times \frac{1}{10000} \quad (1)$$

where A is the roundwood volume (m^3), D is the roundwood diameter at the tip end (cm), and L is the roundwood length (m). When the roundwood is a perfect circle, the area of the circle with diameter D is $\pi\times(D/2)^2$. The rules for JAS 1052 (Eq. 1) indicate the area of a square with a side length D. If the roundwood is a perfect circle, then the actual roundwood volume is $\pi/4 = 0.785$ of the volume calculated using this rule. In this case, the product volume is reduced by a maximum of approximately 21.5% relative to the volume of the purchased roundwood. However, in reality, the roundwood cross section is not a perfect circle. In addition, the diameter of the bottom end (cut surface closer to the root of the roundwood) tends to be larger than that of the tip end. The product volume is not expected to decrease to 78.5% of the recorded volume of the roundwood. Furthermore, wood shrinks during drying, making it difficult to balance inputs and outputs by volume. The wood mass contains large amounts of moisture. In this study, the data were organized based on the carbon content of the wood to avoid the effects of water and volume changes. However, the amount of biomass fuel used in the sawmills was estimated from the material balance, because the amount of biomass fuel used in some sawmills was not measured. To obtain more accurate results, it is necessary to measure the amount of biomass fuel used in biomass boilers in sawmills.

Conclusions

In Japan, as many as 45 million m^2 of wooden houses were constructed in 2022. Wood is a renewable resource and raw material that captures and stores CO_2 from the atmosphere; therefore, the Japanese government promotes the use of wood to tackle climate change. To assess the impacts of climate change, the environmental impacts of wood products must be quantified. In this study, GHG emissions and resource consumption of structural lumber production were evaluated using LCA. To ensure representativeness, data were collected from 15 companies and 15 sawmills, covering more than 70% of Japan's production. The results show that the GHG emissions and resource consumption of Japanese structural lumber are 7.99×10 kg-CO_2e/m^3 and 1.77×10^{-3} kg-Sb eq., respectively. Electricity (39%) and roundwood (33%) are major sources of GHG emissions. Roundwood and tools account for 42% of resource consumption. Recycling tools such as iron scrap fail to effectively utilize the rare metal components. Thus, there is a pressing need for a recycling method that enables the efficient utilization of these rare metal constituents.

If the heat source of the boiler is changed back from biomass fuel to fossil fuel, GHG emissions and resource consumption increase by 5.3 times and 1.6 times, respectively. Policies supporting the introduction of biomass boilers have been demonstrated to be highly effective. However, fossil fuel boilers remain in small-scale sawmills; therefore, it is recommended to support their replacement with biomass boilers, the establishment of communal drying plants, and outsourcing the drying process to facilities using biomass boilers. To further reduce the environmental impact of lumber, it is necessary to convert electricity generated by renewable energy sources.

Structural lumber has been used to store carbon for decades. Assuming a half-life of 35 years for lumber, the effect is estimated to be -2.91×10^2 kg-CO_2e/m^3. This indicates that long-term use of lumber is an important measure of global warming. In this study, CO_2 emissions from biomass were evaluated as carbon neutral. However, achieving carbon neutrality requires appropriate forest-management practices. Sustainable forest management, such as reforestation after logging, should be continued.

Abbreviations

BDt Bone dry tonne
CLT Cross-laminated timber
FIT Feed-in-tariff
GHG Greenhouse gas
HHV Higher heating value
JAS Japanese agricultural standard
LCA Life cycle assessment
LHV Lower heating value
MAFF Ministry of Agriculture, Forestry and Fisheries
ZEB Zero energy building
ZEH Zero energy house

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Author contributions

Conceptualization: NH; methodology and formal analysis: KN; investigation: MK, YY, and TO; writing—original draft preparation: KN; writing—review and editing: NH; funding acquisition and supervision: NH.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request, except for companies' proprietary data and data licensed by third parties.

Declarations

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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