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ORIGINAL ARTICLE

Life cycle greenhouse gas emission of wooden guardrails: a study in Nagano Prefecture

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Abstract Greenhouse gas (GHG: specifically CO_2, CH_4, and N_2O) emissions over the life cycles of type no. 1 and no. 3 wooden guardrails widely used in Nagano Prefecture were evaluated. A comparison with steel (guardrail and guard pipe) types was conducted to investigate the GHG emission reduction effect of wooden guardrails. It was shown that the greatest GHG emissions for all types of guardrails occur during the raw material procurement and production process. The amount of total (life cycle) GHG emissions for pressure-injected wooden type no. 3 guardrails (92 % of steel guardrails and 72 % of steel guard pipes) shows that replacing steel with this type of wooden guardrail can reduce GHG emissions. On the other hand, comparison of the GHG emissions for pressure-injected type no. 1 guardrails with steel (175 % of guardrail; 138 % of guard pipe) shows that no reduction is achieved. When the disposed wooden beams (painted type no. 1; painted and pressure-injected type no. 3) are chipped and used for energy as a substitute for Type-A heavy oil, the volume of the GHG emission reduction significantly exceeds the GHG emission volume, and GHG emissions can be reduced by up to a maximum of 117.67 kg-CO_2-eq/m.

Keywords Life cycle assessment (LCA) · Traffic barrier · Preservative treatment · Energy use · Material use

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Introduction

Recently, there have been efforts to find effective uses for wood from the perspectives of addressing the issue of global warming, and of making effective use of trees that were planted in Japan after the Second World War and are now at an appropriate age for harvest. Recent initiatives have involved promoting the use of wood for civil engineering, and one such use that has been the subject of focus is wooden guardrails. There have been efforts to promote technological development for wooden guardrails, and to popularize them [1–3]. The total potential amount of wood that could be used for making Class C roadside earth embedded guardrails (available for wooden ones) in Japan is estimated at approximately 730,000 m^3 (log conversion volume) per year [4].

Wood can mitigate global warming via a carbon stock effect, a material substitution effect, and an energy substitution effect [5]. Focusing on the material substitution effect, and compared to other materials such as steel and aluminum, the production process for wood consumes less energy and emits less CO_2 [5]. The use of wood can therefore contributes to easing of global warming. When examining the easing effect on global warming of substituting wood for other materials, it is necessary to use a life cycle assessment (LCA) approach that takes into account the environmental burden across the entire life cycle from collection of raw material through to manufacture and disposal of the product.

Research projects using the LCA approach have already been undertaken to investigate the reductive effect on greenhouse gas (GHG) emissions due to use of wood. In prior research that has focused on civil engineering in particular, Kayo et al. [6] compared the life cycle GHG emissions of construction methods used as countermeasures against liquefaction of the ground, namely the sand compaction pile method, the cement deep mixing method, and the log pile method. Noda et al. [7] and Kayo et al. [8] compared the life cycle balance of CO_2 and economic effectiveness of check dams made of concrete, steel, and wood. All of these previous studies confirmed the GHG or CO_2 emission reducing effect of using wood as a substitute for other materials.

However, in our reading, we found no instances of peer-reviewed research papers on the LCA of the use of wood for guardrails, which is the topic of this research. Although there have been academic presentations by Kayo et al. [9] and Ohkata et al. [10], these did not consider the entire life cycle and did not conduct a sufficient comparison with non-wooden guardrails. Therefore, there has not yet to be a sufficient quantitative evaluation of the GHG emission reduction effect of the use of wood for guardrails.

In this study, we focused on Nagano Prefecture [11], which is a local government leading the field in development and spread of wooden guardrails in Japan. The objective of this study is to evaluate the life cycle GHG emissions of wooden and non-wooden guardrails in Nagano Prefecture. Moreover, we examined the GHG emission reduction effect of wooden guardrails compared to non-wooden ones. We looked at two types of wooden guardrail developed in Nagano Prefecture (type no. 1 and type no. 3) [12]; a steel guardrail, which has an extensive record of use; and a steel guard pipe, which is recently seeing increased use as a surrounding scenery considerate model.

Materials and methods

Overview of guardrails examined in this study

The wooden guardrails in this study were Class C roadside earth embedded guardrails (design speed 50 km/h). We targeted two types because their data were available on the interview surveys with the manufacture and construction operators: (1) Shinshu type no. 1 wooden guardrails (hereafter "wooden type no. 1", Fig. 1a), which are used not only in Nagano Prefecture, but nationwide; (2) Shinshu type no. 3 wooden guardrails (hereafter "wooden type no. 3", Fig. 1b), the majority of which have been used in Nagano Prefecture. We compared these wooden guardrails with an ordinary steel guardrail (Fig. 2a), and steel guard pipe (Fig. 2b) which is being increasingly used recently and is more considerate of the surrounding scenery. The steel guardrail and guard pipe were Class C roadside earth embedded, as were the wooden guardrails.

The wooden type no. 1 has supporting posts made of the steel pipe used for Class C steel guardrails, and a 4 m span. The beams were made from Japanese cedar wood (including the pith) grown in Nagano Prefecture, machined into φ 180 mm round poles, and split in half. These are attached in two horizontal tiers to a 3.2-mm-thick steel plate, beneath which a steel supporting pipe is provided. The wooden type no. 3 has square supporting posts of steel reinforced concrete, with a 2 m span. The beams are Japanese larch wood (including the pith) grown in Nagano Prefecture, machined into φ 180 mm round poles, and arranged in two horizontal tiers. Twelve types of wooden guardrails, made from either Japanese cedar wood or Japanese larch wood, have been developed and installed in Japan [13]. They can be broadly classified into two types. In one type, the beam is made of wood and steel materials, and the supporting posts are made of steel materials (e.g., the wooden type no. 1 in this study). In the second type, the beam is made only of wood and the supporting posts are made of steel reinforced concrete (e.g., the wooden type no. 3 in this study). Therefore, the two types evaluated in this study can be considered representative of all 12 types of wooden guardrails used in Japan.

The preservation method employed for the wooden beams was a surface coating (type no. 1: water-based synthetic resin paint; type no. 3: oil-based paint) when they were initially developed; however, due to occurrence of carpophores and splintering, there were concerns about injury to pedestrians who touched the guardrails. Therefore, more recently newly installed or renewed guardrails are pressure injected with a preservative (ACQ) rather than a surface coating. As of April 2015, both surface-coated and pressure-injected cases are in existence. For wooden guardrails, we therefore investigated both the surface-coated case (hereafter "painted") and the pressure-injected case (hereafter "pressure-injected").

Method of evaluating life cycle GHG emissions

The life cycle processes that were evaluated (the system boundary) are shown in Fig. 3. The processes were raw material procurement and production, construction, maintenance and management, and disposal. For each process, we evaluated the emissions and reduction of GHGs (CO_2, CH_4, N_2O) originating from consumption of fossil fuels. A

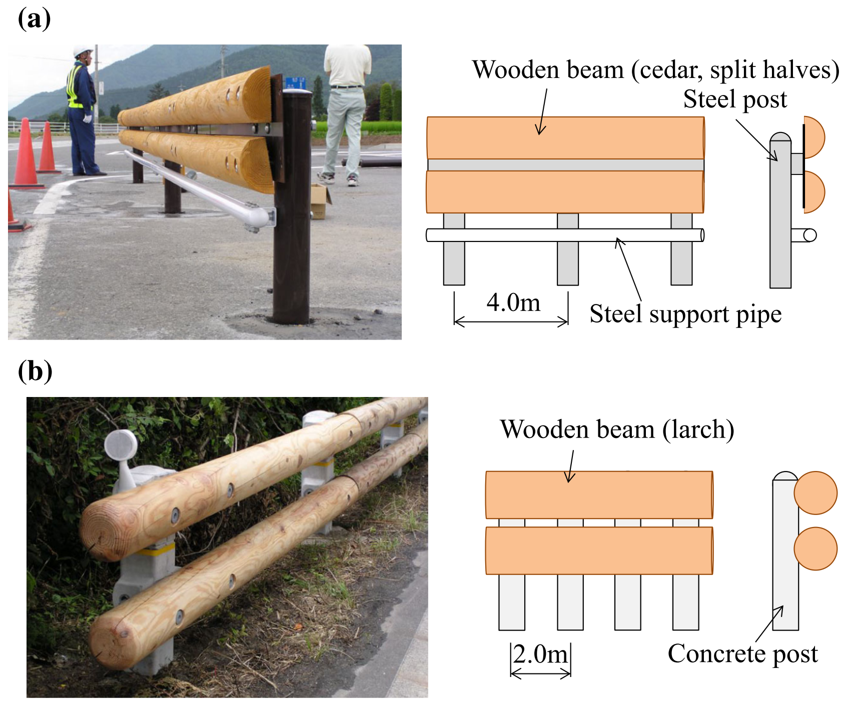

Fig. 1 Types of wooden guardrail. **a** Wooden type no. 1. **b** Wooden type no. 3

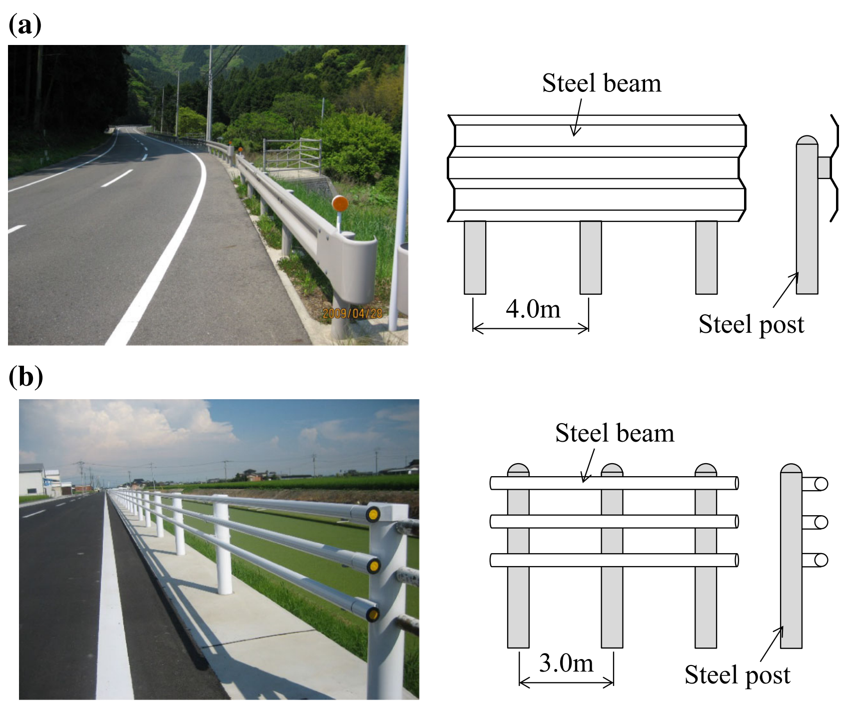

Fig. 2 Types of steel guardrail. **a** Steel guardrail. **b** Steel guard pipe

functional unit was consistent with a Class C roadside earth embedded 1 m-long guardrail, with an evaluation period of 40 years. This is true for all guardrails examined.

Table 1 shows the construction conditions of each guardrail along with the material and fuel usage amounts that were measured as foreground data when evaluating the GHG emissions. Table 2 shows the GHG emission intensities that were used as background data. Furthermore, in terms of GHGs, we approached the CO_2 balances from internal carbon reserves and emissions of wood, by treating them as being carbon neutral and excluding them from the evaluation. However, the amounts of CH_4 and N_2O emitted from the combustion of wood were included in the evaluation in accordance with ISO rules [17]. Each GHG was

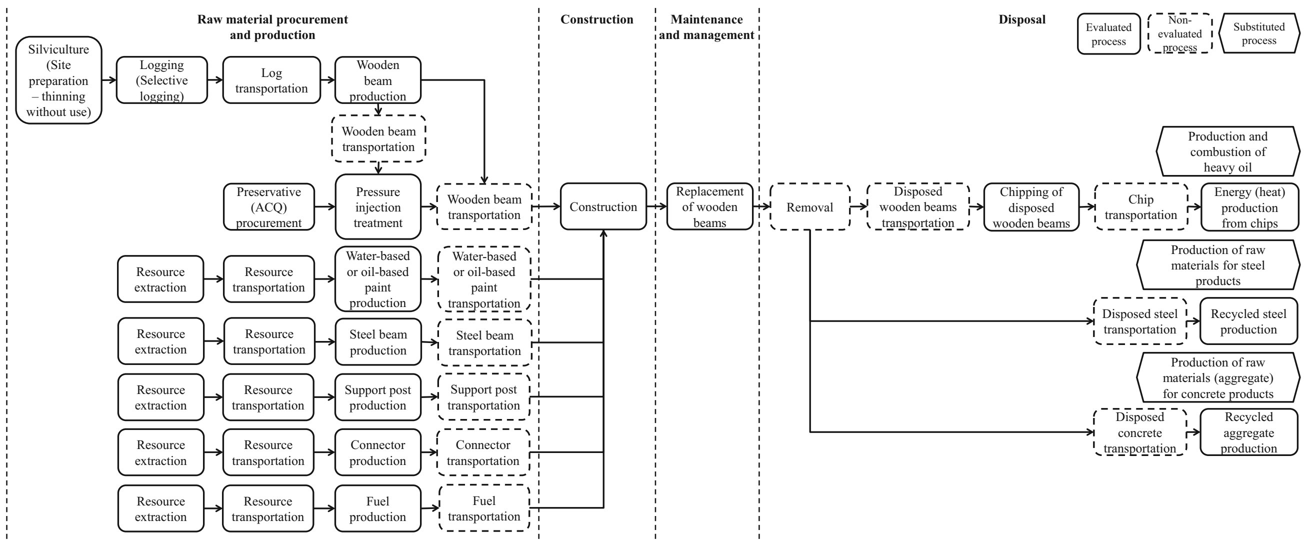

Fig. 3 Life cycle process (system boundary)

displayed as a CO_2 equivalent (kg-CO_2-eq) using their 100-year time-horizon global-warming potentials (GWP_{100}) (CO_2: 1, CH_4: 34, N_2O: 298) [5]. In the next section, we describe the evaluation method for each process of the life cycle.

Raw material procurement and production process

The raw material procurement and production process covers the steps from resource extraction, resource transportation and manufacturing for raw materials and fuels used for guardrails. To calculate the GHG emissions from the process, we multiplied the amounts of raw materials and fuels used (Table 1) by the GHG emission intensities (Table 2).

The raw material usage of the wooden guardrail was obtained from the Nagano Prefectural Forestry Research Center, and that of the steel guardrail and guard pipe from Nippon Steel & Sumikin Metal Products Co. Ltd. We referred to an interview survey with Kiso Kensetsu Sangyo Co. Ltd. for the amount of electric power used in producing wooden beams from logs, and to an interview survey with Lumbertech Co. Ltd. for the amount of electric power used for the pressure injection treatment on the wooden beams. In working out the emission intensities, we referred to Hitoe et al. [15] for the GHG emissions from procurement of logs, to the reported values [16] from Koshii Preserving Co. Ltd. for procurement of raw materials for the preservative for wood, and to the MiLCA Data Base [14] for information about the other raw materials and fuels.

For the transportation of logs from the logging site to the wooden beam production site, we multiplied the log production amount (m^3) by the density of green wood (cedar: 0.628 t/m^3, larch: 0.808 t/m^3) [18] assuming 100 % green moisture content [19], by the transportation distance (30 km) obtained from the Nagano Prefectural Forestry Research Center, by two for a two-way trip, and by the GHG emission intensity [kg-CO_2-eq/(t km)] for transportation by a four-ton truck (Table 2). Because we lacked reliable data for the transportation of wooden beams, other raw materials and fuels, we did not include the GHG emissions from such transportation in this study.

Construction process

For all of the guardrails, the only machinery use in the construction operation was for setting up the support posts. Other steps in the operations, such as attaching the beams, were carried out by manual labor. The evaluation therefore included the GHG emissions from combustion of machine fuel (light oil) when setting up the support posts during the construction process.

Based on the results of the interview surveys with the manufacture and construction operators (EMC Co. Ltd. for the wooden type no. 1 guardrail, the steel guardrail and guard pipe, and Kiso Kensetsu Sangyo Co. Ltd. for the wooden type no. 3 guardrail), we determined the amount of light oil used from the length of time the machinery was used, and calculated the GHG emissions by multiplying the amount of light oil used (Table 1) by the GHG emission intensity associated with the production and combustion of light oil (Table 2).

Maintenance and management process

The service life of the guardrails is 10 years, according to the statutory number of years for depreciation of assets [20]. This service life is thought to reflect the high

Table 1 Construction conditions and amounts of material and energy used and substituted

	Unit	Wooden type no. 1		Wooden type no. 3		Steel	
		Painting treatment	Pressure injection	Painting treatment	Pressure injection	Guardrail	Guard pipe
Construction conditions							
Support post spacing	m	4.000	4.000	2.000	2.000	4.000	3.000
Beam material		Japanese cedar wood (split halves)		Japanese larch wood		Steel	Steel
Beam diameter	m	0.180	0.180	0.180	0.180	–	0.049
Materials and fuels used in the raw material procurement and production process (per 1 m)							
Support post							
Carbon steel post	kg	6.760	6.760	–	–	6.719	9.295
Concrete	kg	–	–	59.271	59.271	–	–
Steel bar	kg	–	–	7.695	7.695	–	–
Resin powdered paint	kg	0.049	0.049	–	–	0.049	0.069
Zinc galvanizing	kg	0.109	0.109	–	–	0.108	0.151
Connector							
Bolt (steel)	kg	1.334	1.334	1.367	1.367	0.322	0.739
Inner sleeve (steel)	kg	0.414	0.414	–	–	–	1.028
Bracket (steel)	kg	0.640	0.640	–	–	0.239	0.430
Connection plate (steel)	kg	–	–	0.656	0.656	–	–
Resin powdered paint	kg	0.008	0.008	–	–	0.004	0.128
Steel beam							
Steel beam	kg	13.245[a]	13.245[a]	–	–	8.273	8.409
Resin powdered paint	kg	0.221	0.221	–	–	0.190	0.115
Wooden beam							
Wooden beam	m^3	0.025	0.025	0.053	0.053	–	–
Electric power for wooden beam production from logs	kWh	0.462	0.462	0.962	0.962	–	–
Electric power for pressure injection into wooden beams	kWh	–	0.843	–	1.755	–	–
Preservative (ACQ)	kg	–	0.607	–	0.474	–	–
Water-based synthetic resin paint	kg	0.093	–	–	–	–	–
Oil-based paint	kg	–	–	0.122	–	–	–
Fuels used in the construction process (per 1 m)							
Light oil	L	0.202	0.202	0.960	0.960	0.202	0.271
Fuels used in the disposal process (per 1 m)							
Light oil for chip processing	L	0.038	0.038	0.079	0.079	–	–
Materials and fuels substituted in the disposal process (per 1 m)							
Steel products[b]	kg	22.394	22.394	9.719	9.719	15.553	19.901
Aggregate[b]	kg	–	–	59.271	59.271	–	–
Heavy oil[c]	L	3.624	3.624	9.707	9.707	–	–

[a] The values include the amount of steel support pipe (Fig. 1)

[b] The values indicate the amount of materials substituted with recycled materials from disposed steel or concrete

[c] The values represent the amount of fossil fuels substituted with fuel from the disposed wooden beams

performance required of guardrails with regard to safety, since they are an important structural item for separating the vehicle road from the sidewalk for traffic safety, and the relatively short time frame for infrastructure upgrades in line with social development. The actual service life of steel guardrails has not yet been scientifically studied and reported. On the other hand, according to the results of an interview survey of Nippon Steel & Sumikin Metal Products Co. Ltd., there are some cases of steel guardrails that have been in place for over 40 years since their installation. In the case of wooden guardrails, their history is relatively shorter and has not been long enough to clearly establish

Table 2 Greenhouse gas (GHG) emission intensities

	Unit	CO_2	CH_4	N_2O	GHG total	Scope of assessment	Sources
Raw material procurement and production process							
Resource extraction—support post							
Structural carbon steel production	kg-CO_{2eq}/kg	1.8040	0.0324	0.0104	1.8468	Resource extraction—structural carbon steel production	[14]
Freshly mixed concrete production	kg-CO_{2eq}/m^3	289.5000	2.8155	1.0609	293.3764	Resource extraction—freshly mixed concrete production	[14]
Steel bolt production	kg-CO_{2eq}/kg	0.8604	0.0089	0.0079	0.8772	Resource extraction—steel bolt production	[14]
Resin powdered paint production	kg-CO_{2eq}/kg	5.2540	0.1687	0.2992	5.7219	Resource extraction—resin powdered paint production	[14]
Zinc galvanizing production	kg-CO_{2eq}/kg	2.3200	0.0376	0.0444	2.4020	Resource extraction—zinc galvanizing production	[14]
Resource extraction—connector production							
Steel bolt production	kg-CO_{2eq}/kg	2.3210	0.0390	0.0205	2.3804	Resource extraction—steel bolt production	[14]
Inner sleeve (steel) production	kg-CO_{2eq}/kg	2.3200	0.0376	0.0444	2.4020	Resource extraction—steel plate production	[14]
Bracket (steel) production	kg-CO_{2eq}/kg	2.3200	0.0376	0.0444	2.4020	Resource extraction—steel plate production	[14]
Connection plate (steel) production	kg-CO_{2eq}/kg	2.3200	0.0376	0.0444	2.4020	Resource extraction—steel plate production	[14]
Resin powdered paint production	kg-CO_{2eq}/kg	5.2540	0.1687	0.2992	5.7219	Resource extraction—paint production	[14]
Resource extraction—steel beam production							
Steel beam production	kg-CO_{2eq}/kg	2.3200	0.0376	0.0444	2.4020	Resource extraction—steel plate production	[14]
Resin powdered paint production	kg-CO_{2eq}/kg	5.2540	0.1687	0.2992	5.7219	Resource extraction—paint production	[14]
Silviculture—wooden beam production							
Log procurement	kg-CO_{2eq}/m^3	5.8300	0.2390	0.0498	6.1188	Silviculture—selective logging (thinning for use)	[15]
Log transportation by four-ton truck	kg-CO_{2eq}/(t km)	0.1502	0.0057	0.0007	0.1566	Resource extraction—light oil production—light oil combustion	[14]
Electric power consumption for wooden beam production	kg-CO_{2eq}/kWh	0.5915	0.0044	0.0175	0.6134	Resource extraction—electric power generation	[14][a]
Pressure injection							
Preservative (ACQ) procurement	kg-CO_{2eq}/kg	–	–	–	6.3077	Preservative (ACQ) procurement	[16]
Electric power consumption for pressure injection	kg-CO_{2eq}/kWh	0.5915	0.0044	0.0175	0.6134	Resource extraction—electric power generation	[14][a]
Painting treatment							
Water-based synthetic resin paint production	kg-CO_{2eq}/kg	3.6400	0.2281	0.1112	3.9793	Resource extraction—paint production	[14]
Oil-based paint production	kg-CO_{2eq}/kg	3.5100	0.2275	0.1043	3.8418	Resource extraction—paint production	[14]
Construction process							
Light oil combustion	kg-$CO_{2\text{-}eq}$/L	2.8207	0.1073	0.0140	2.9420	Resource extraction—light oil production—light oil combustion	[14]
Disposal process							
Energy use of disposed wooden beams							
Light oil combustion for chip processing	kg-$CO_{2\text{-}eq}$/L	2.8207	0.1073	0.0140	2.9420	Resource extraction—light oil production—light oil combustion	[14]

Table 2 continued

	Unit	CO_2	CH_4	N_2O	GHG total	Scope of assessment	Sources
Chip combustion	kg-$CO_{2\text{-eq}}$/GJ	–	2.5160	0.1728	2.6888	Chip combustion (CO_2 not evaluated)	[14]
A-type heavy oil combustion	kg-$CO_{2\text{-eq}}$/L	2.9891	0.1137	0.0148	3.1176	Resource extraction—heavy oil production—heavy oil combustion	[14]
Material use of disposed steel and concrete							
Recycled aggregate production	kg-CO_{2eq}/kg	0.0037	0.0001	0.0001	0.0039	Recycled aggregate production	[14]
Aggregate production	kg-CO_{2eq}/kg	0.0043	0.0001	0.0000	0.0044	Resource extraction—aggregate production	[14]
Steel scrap processing	kg-CO_{2eq}/kg	0.0167	0.0003	0.0003	0.0172	Steel scrap processing	[14]
Average of steel bolts, bars, plates and wire production	kg-CO_{2eq}/kg	1.3497	0.0223	0.0072	1.3791	Resource extraction—each steel product production	[14]

[a] The value of Chubu Electric Power Co., Inc.

their service life. On the other hand, it was confirmed that in Kumamoto Prefecture, there are some wooden guardrails that are still maintaining sufficient function after being in place for more than 15 years. Furthermore, the wooden beams of wooden guardrails that had been in place for 10 years in Miyazaki Prefecture were recovered and subjected to strength tests. The result showed that they still retained plenty of function [21]. All of the wood used in these examples was treated with preservatives by pressure injection. Furthermore, the efficacy of pressure injection is influenced by the amount of preservatives inside the wood, and it is known that pressure injection treatment results in a larger amount of chemical agent absorption compared with surface coating treatment [22].

As a result of the above findings, for this study, we assumed a service life of 10 years for painted wooden beams, 20 years for pressure-injected wooden beams, 40 years for the steel beam and support posts of the wooden guardrails, and 40 years for all components of the steel guardrails and guard pipes. Therefore, we set the maintenance and management period at 40 years, and assumed replacement of wooden beams (wooden beam material procurement, production, and construction) in the wooden guardrails after their service lives of 10 or 20 years. In addition, since it was reported that there was no difference between Japanese cedar and larch in terms of service life of wooden materials [23], we did not consider the difference of tree species for service life in this study.

Disposal process

During the disposal process, we did not consider the GHG emissions from the removal of guardrails and the transportation of disposed materials because we lacked reliable data. We evaluated the GHG emissions and reductions achieved by recycling the disposed materials (wood, steel, and concrete).

Because more than 80 % of the amount of wood disposed of from construction is currently being used for energy in Japan [24]. Moreover, according to the quality standard of recycled wood chips [25], wood materials mixed with preservatives or paints are considered inappropriate for material recycling (e.g., particleboard, paper). Therefore, in this study we assumed that the disposed wooden beams were used for energy. After replacement, the disposed wooden beams were assumed to be converted into chips and used as fuel in a chip boiler in place of a heavy oil boiler.

Assuming that the entire volume of the wooden beams used were disposed of, we estimated the reduction of GHG emissions from substituting for Type-A heavy oil with chips using Eqs. (1–4).

$$\mathrm{RGE} = \mathrm{GEO} - \mathrm{GEW} \tag{1}$$

$$\mathrm{GEO} = \mathrm{DWB} \times \mathrm{CW} \times \mathrm{EW/CH/EH} \times \mathrm{GO} \tag{2}$$

$$\mathrm{GEW} = \mathrm{DWB} \times \mathrm{LC} \times \mathrm{GL} + \mathrm{DWB} \times \mathrm{CW} \times \mathrm{GW} \tag{3}$$

$$\mathrm{CW} = \mathrm{DW} \times \{H_{h0} - 2.512 \times (9 \times h_0 + U)\} \tag{4}$$

Here, RGE (kg-CO_2-eq/m) represents the reduction of GHG emissions from substituting Type-A heavy oil with chips, and GEO (kg-CO_2-eq/m) indicates the GHG emissions from production and combustion of Type-A heavy oil. GEW (kg-CO_2-eq/m) denotes the GHG emissions from production and combustion of chips. DWB (m^3/m) describes the volume of disposed wooden beams, CW (GJ/m^3) describes the net calorific value of disposed wooden beams obtained using Eq. (4) [26]. The moisture content of disposed wooden beams was assumed to be 0.2 [27–29]. EW represents average energy usage efficiency for chip boilers (0.775 [30]). CH (GJ/L) represents the net calorific value of Type-A heavy oil (0.0367 [31]), and EH represents the average energy efficiency for heavy oil boilers (0.885 [30]). GO (kg-CO_2-eq/L) indicates the GHG emission intensity for production and combustion of Type-A heavy oil (Table 2). LC (L/m^3) represents light oil consumption due to chip processing from disposed wooden beams (1.500, this value was obtained from an interview survey with agricultural public corporations that have a chip plant) (Table 1). GL (kg-CO_2-eq/L) denotes the GHG emission intensity for production and combustion of light oil (Table 2), whereas GW (kg-CO_2-eq/GJ) indicates the GHG emission intensity for combustion of chips (Table 2). However, as stated above, this intensity is for CH_4 and N_2O, and not for CO_2. DW (t/m^3) represents the density of oven-dried wood (cedar: 0.314, larch: 0.404) [18], H_{h0} (GJ/t) represents the gross calorific value of oven-dried wood (21 for both cedar and larch) [32], h_0 (t/t) represents the hydrogen content of oven-dried wood (0.06 [32]), and U (t/t) indicates the moisture content of disposed wooden beams (0.2 [27–29]).

As mentioned above, we did not consider GHG emissions from the transportation of disposed wooden beams to chip production sites or to heat production sites because the transportation distance of the disposed beams was hard to determine from assumptions made about their future (Fig. 3). Furthermore, the amount of use of wooden beam materials could conceivably diminish due to deterioration or rot with the passage of time; however, since the speed of rot is not scientifically clear, the change in GHG emissions due to reduction in the amount of material in use was not considered.

With regard to disposed steel (beams, pipes, support posts, and connectors) and concrete (support posts), over 95 % of the amount of disposed steel and concrete is currently recycled to other steel and concrete materials in Japan [33, 34]. Therefore, we estimated the reduction of GHG emissions from substituting for raw materials with recycled materials from the disposed steel and concrete after 40 years of the service life, using Eqs. (5–7).

$$\mathrm{RGM} = \mathrm{GEM} - \mathrm{GER} \tag{5}$$

$$\mathrm{GEM} = \mathrm{DST} \times \mathrm{GS} + \mathrm{DCO} \times \mathrm{GC} \tag{6}$$

$$\mathrm{GER} = \mathrm{DST} \times \mathrm{RS} + \mathrm{DCO} \times \mathrm{RC} \tag{7}$$

Here, RGM (kg-CO_2-eq/m) indicates the reduction of GHG emissions from substituting raw materials for steel and concrete products with disposed steel and concrete, GEM (kg-CO_2-eq/m) represents the GHG emissions from production of raw materials for steel and concrete products, and GER (kg-CO_2-eq/m) denotes the GHG emissions from production of recycled materials from disposed steel and concrete. DST (kg/m) and DCO (kg/m) represent the amount of disposed steel and concrete, respectively. GS (kg-CO_2-eq/kg) describes the GHG emission intensity for production of raw materials for steel products (the average value of steel bolts, bars, plates, and wire in Table 2), and GC (kg-CO_2-eq/kg) represents the GHG emission intensity of raw materials for concrete products (the value of aggregate in Table 2). RS (kg-CO_2-eq/kg) indicates the GHG emission intensity for recycling of disposed steel (the value of processed steel scrap in Table 2), and RC (kg-CO_2-eq/kg) denotes the GHG emission intensity for recycling of disposed concrete (the value of recycled aggregate in Table 2).

We did not consider the GHG emissions from transportation of both disposed steel and concrete to recycled material production sites, as with the case of disposed wooden beams.

Results and discussion

The result of evaluating GHG emissions over a period of 40 years is shown in Table 3 and Fig. 4. Looking at each life cycle process, the total GHG emissions for the three processes of raw material procurement and production, construction, and maintenance and management (positive values in Table 3; Fig. 4), were, for the pressure-injected (or painted) wooden type no. 1: 91 (93) %, 1 (1) %, and 8 (6) %; for the pressure-injected (or painted) wooden type no. 3: 74 (70) %, 9 (10) %, and 17 (20) %; and for both the steel guardrail and steel guard pipe: 98, 2, and less than 1 %. The amount of emissions was therefore greatest in the raw material procurement and production process.

Comparing the two kinds of wooden guardrail, the GHG emissions of type no. 3 were less than those of type no. 1, being 52 % for the painted case and 53 % for the pressure-injected case. The main reason for such a difference occurring between the wooden types is that type no. 1 has steel beams along with the wooden beams, while type no. 3 has wooden beams alone. The GHG emissions from the raw material procurement and production process for the steel beams used in type no. 1 were 33.08 kg-CO_2-eq/m, accounting for more than 50 % of the total GHG emissions of type no. 1 (59 % for the painted case, 53 % for the pressure-injected case). This process is the predominant source of emissions.

Comparing the painted and pressure-injected wooden guardrails of both type no. 1 and type no. 3, the GHG emissions of the pressure-injected cases were 110 and 111 % of the GHG emissions of the painted cases, respectively. This reflects the fact that GHG emissions involved with pressure injection treatment are around ten times those involved with surface coating treatment.

Comparing the steel guardrail and the steel guard pipe, the GHG emissions of the steel guard pipe were 127 % of

Table 3 Evaluation result for greenhouse gas (GHG) emissions over a 40-year evaluation period

	Wooden type no. 1		Wooden type no. 3		Steel	
	Painting treatment	Pressure injection	Painting treatment	Pressure injection	Guardrail	Guard pipe
Service life (year)	10	20	10	20	40	40
Raw material procurement and production process						
Resource extraction—support post production	12.80	12.80	14.00	14.00	12.72	17.61
Resource extraction—steel beam production	33.08	33.08	–	–	20.96	20.86
Resource extraction—connector production	5.75	5.75	4.83	4.83	1.36	6.00
Silviculture—wooden beam production	0.66	0.66	1.49	1.49	–	–
Preservative procurement—pressure injection	–	4.35	–	4.07	–	–
Resource extraction—paint production	0.37	–	0.47	–	–	–
Construction process	0.59	0.59	2.82	2.82	0.59	0.80
Maintenance and management process						
Replacement of wooden beams (the 10th year)	1.03	–	1.96	–	–	–
Replacement of wooden beams (the 20th year)	1.03	5.01	1.96	5.56	–	–
Replacement of wooden beams (the 30th year)	1.03	–	1.96	–	–	–
Disposal process						
Energy use of disposed wooden beams	−43.11	−21.55	−115.75	−57.87	–	–
Material use of disposed steel and concrete	−21.29	−21.29	−13.27	−13.27	−21.18	−27.10
Total						
Greenhouse gas (GHG) emissions (raw material procurement and production—maintenance and management process)	56.36	62.24	29.50	32.77	35.64	45.26
Net GHG emissions (raw material procurement and production—disposal process)	−8.03	19.40	−99.52	−38.38	14.46	18.15

+, emissions; −, reductions

Unit: kg-CO_2-eq/m

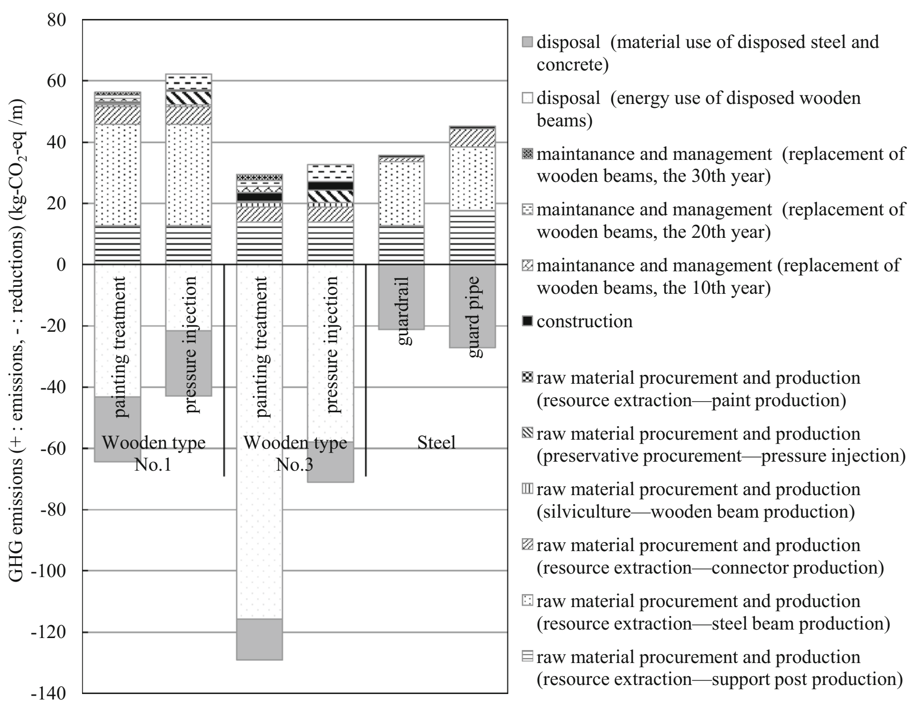

Fig. 4 Evaluation result for greenhouse gas (GHG) emissions over a 40-year evaluation period

the GHG emissions of the steel guardrail, which was significantly higher. There are two likely reasons for this. First, the guard pipe has a narrower support post spacing (3 m), and therefore uses a larger number of support posts with an attendant increase in the emissions associated with the raw material procurement and production of support posts, as well as their construction. Second, the guard pipe is installed in three tiers of beams, which increases the number of attachment fittings. While the GHG emissions from raw material procurement and production of attachment fittings for the steel guardrail were 1.36 kg-CO_2-eq/m, the equivalent emissions for the steel guard pipe were 6.00 kg-CO_2-eq/m.

Comparing the wooden guardrails with the steel guardrail and guard pipe, the GHG emissions of the wooden type no. 1 were significantly higher than the emissions of the steel guardrail and steel guard pipe (158 and 125 %, respectively, for the painted case; 175 and 138 %, respectively for the pressure-injected case). Looking at the wooden type no. 3, the emissions were much smaller than the emissions of the steel guardrail and steel guard pipe (83 and 65 %, respectively, for the painted case; 92 and 72 %, respectively for the pressure-injected case). Incidentally, there have recently been examples of the wooden type no. 3 being installed with support post spacing extended from 2 to 3 m, and these have passed the vehicle collision test [35]. There are no such installations within Nagano Prefecture yet; however, the GHG emissions of the pressure-injected case in the example of a 3 m installation with a 20-year service life are calculated to be 28.34 kg-CO_2-eq/m, which correspond to about 86 % of the current 2 m example. A further GHG emission reduction effect is therefore achievable.

Now we will examine the net GHG emissions, taking into consideration the emission reduction due to the use of disposed wooden beams, steel and concrete in the disposal process (negative values in Table 3; Fig. 4). In each case, the GHG reduction amount exceeds the GHG emission amount for the painted wooden type no. 1 (−8.03 kg-CO_2-eq/m), the painted wooden type no. 3 (−99.52 kg-CO_2-eq/m), and the pressure-injected wooden type no. 3 (−38.38 kg-CO_2-eq/m), resulting in a negative net GHG emission. This shows that the life cycle GHG emissions overall are greatly influenced by whether or not the wood is used as an energy source in the disposal process. On the other hand, there is a possibility that the disposed wooden beams might be used as fuel for electricity, not for heat. Prior studies [36–38] reported that power generation from woody biomass could result in less GHG emission reduction than heat generation. Therefore, when considering power generation from disposed wooden beams in this study, we anticipated that the amount of GHG reduction decreased more than for the current process of heat generation. Material use of disposed steel and concrete could also be important for reducing the life cycle emissions of both the wooden and steel types. Because disposed steel can be recycled many times, further reduction of life cycle emissions can be obtained by considering the number of times it has been recycled.

Looking at the painted and pressure-injected wooden guardrails, the replacement of the wooden beams at shorter intervals than that of the pressure-injected case (e.g., the interval of the painted case), with use of the disposed wood as fuels, resulted in a greater GHG emission reduction effect. However, as explained in the “Overview of guardrails examined in this study”, there are concerns with painted cases over a reduction in the service life due to splintering at the end sections, the detrimental effect on the scenery, and the potential for injury of people passing by. Furthermore, it is also necessary to bear in mind the increase in material and construction costs, as well as administrative expenses and so forth.

Comparing the wooden guardrails with the steel guardrail and guard pipe, we found that the GHG emission reduction effect of replacing the steel items with wooden ones could be a maximum of 117.67 kg-CO_2-eq/m when replacing steel guard pipe with painted wooden type no. 3. However, there would not be any reduction if replacing steel guardrail with pressure-injected wooden type no. 1. On the other hand, as explained in “Method of evaluating life cycle GHG emissions” in this study, the target for evaluation is the emission and reduction of GHGs originating from fossil fuel consumption, and the carbon reserve and CO_2 (other than CH_4 and N_2O) emissions of the wood itself are not evaluated. Therefore, considering the CO_2 balance of the wood itself could change the GHG balance in wooden type no. 1 and No. 3 guardrails, and the GHG emission reduction amount due from substitution of steel types. Examination of this possibility is a topic for future study.

With respect to service life for wooden guardrails, their history is relatively shorter and their service life is not scientifically clear. In addition, their service life could be changed by environmental conditions, the quality of preservative treatment, and so on. Accordingly, we conducted a sensitivity analysis to see whether a difference in the assumption of service life for the wooden guardrails influences the results for GHG emissions and reductions. The results, assuming a difference of 5 years from the stated service life of wooden beams for each type of wooden guardrail, are shown in Table 4. Little difference was noted between the GHG emissions of the painted wooden type no. 1 and those of the steel guardrail if the service life of wooden beams were extended 5 years longer than the current service life (10 years). The GHG emissions of pressure-injected wooden type no. 1 were higher

Table 4 Sensitivity analysis for service life of wooden beams for each type of wooden guardrail over a 40-year evaluation period

	Wooden type no. 1						Wooden type no. 3					
	Painting treatment			Pressure injection			Painting treatment			Pressure injection		
	Actual condition	−5 year	+5 year	Actual condition	−5 year	+5 year	Actual condition	−5 year	+5 year	Actual condition	−5 year	+5 year
Raw material procurement and production process												
Resource extraction—support post production	12.80	12.80	12.80	12.80	12.80	12.80	14.00	14.00	14.00	14.00	14.00	14.00
Resource extraction—steel beam production	33.08	33.08	33.08	33.08	33.08	33.08	–	–	–	–	–	–
Resource extraction—connector production	5.75	5.75	5.75	5.75	5.75	5.75	4.83	4.83	4.83	4.83	4.83	4.83
Silviculture—wooden beam production	0.66	0.66	0.66	0.66	0.66	0.66	1.49	1.49	1.49	1.49	1.49	1.49
Preservative procurement—pressure injection	–	–	–	4.35	4.35	4.35	–	–	–	4.07	4.07	4.07
Resource extraction—paint production	0.37	0.37	0.37	–	–	–	0.47	0.47	0.47	–	–	–
Construction process	0.59	0.59	0.59	0.59	0.59	0.59	2.82	2.82	2.82	2.82	2.82	2.82
Maintenance and management process												
Replacement of wooden beams (the 5th year)	–	1.03	–	–	–	–	–	1.96	–	–	–	–
Replacement of wooden beams (the 10th year)	1.03	1.03	–	–	–	–	1.96	1.96	–	–	–	–
Replacement of wooden beams (the 15th year)	–	1.03	1.03	–	5.01	–	–	1.96	1.96	–	5.56	–
Replacement of wooden beams (the 20th year)	1.03	1.03	–	5.01	–	–	1.96	1.96	–	5.56	–	–
Replacement of wooden beams (the 25th year)	–	1.03	–	–	–	5.01	–	1.96	–	–	–	5.56
Replacement of wooden beams (the 30th year)	1.03	1.03	1.03	–	5.01	–	1.96	1.96	1.96	–	5.56	–
Replacement of wooden beams (the 35th year)	–	1.03	–	–	–	–	–	1.96	–	–	–	–
Disposal process												
Energy use of disposed wooden beams	−43.11	−86.21	−21.55	−21.55	−21.55	−10.78	−115.75	−231.49	−57.87	−57.87	−57.87	−28.94
Material use of disposed steel and concrete	−21.29	−21.29	−21.29	−21.29	−21.29	−21.29	−13.27	−13.27	−13.27	−13.27	−13.27	−13.27
Total												
Greenhouse gas (GHG) emissions (raw material procurement and production—maintenance and management process)	56.36	60.50	55.33	62.24	67.25	62.24	29.50	37.35	27.54	32.77	38.33	32.77
Net GHG emissions (raw material procurement and production—disposal process)	−8.03	−47.00	12.48	19.40	24.41	30.17	−99.52	−207.42	−43.61	-38.38	−32.82	−9.44

+, emissions; −, reductions

Unit: kg-CO_2-eq/m

than for steel types, even if the service life of the wooden beams was extended or shortened. However, looking at wooden type no. 3, the emissions for both the painted case and pressure-injected case were much less than the emissions of steel ones, and the GHG reductions significantly exceeded emissions for wooden type no. 3.

Conclusions

We evaluated the life cycle GHG emissions (CO_2, CH_4, N_2O) of two types of wooden guardrails developed in Nagano Prefecture (types no. 1 and no. 3), a steel guardrail, and a steel guard pipe; and examined the GHG emission reduction effect of wooden guardrails compared to non-wooden ones. The main findings of the study were as follows.

1. For total GHG emissions evaluated over a period of 40 years, the amount of emissions for each process was greatest for raw material procurement and production process for all types of guardrails examined.
2. The GHG emissions from the wooden type no. 3, which uses only wood for its beam materials, are less than from the wooden type no. 1, which uses both wood and steel. GHG emissions from the no. 3 type are 52 % of those of the no. 1 type for the painted case, and 53 % for the pressure-injected case.
3. The steel guard pipe, which was recently developed as a type that is more considerate of the surrounding scenery, has more support posts and beams than the steel guardrail, and accordingly its GHG emissions are greater (127 % of those of the steel guardrail).
4. When the wooden beams, steel and concrete discarded in the disposal process are not used as fuel and recycled material, the GHG emissions of the pressure-injected (painted) wooden type no. 3 guardrails are 92 % (83 %) and 72 % (65 %) of those of the steel guardrail and steel guard pipe, respectively. A GHG emission reduction effect can be obtained by replacing the steel types with this wooden type. However, the GHG emissions of the pressure-injected (or painted) wooden type no. 1 are 175 % (158 %) and 138 % (125 %) of those of the steel types, respectively, and a GHG emission reduction effect cannot be obtained.
5. When the wooden beams and non-wooden materials (steel and concrete) discarded in the disposal process are used as fuel and recycled material, respectively, for the painted case of the wooden type no. 1, and the painted and pressure-injected cases of wooden type no. 3, the GHG emission reduction was significantly greater than the GHG emissions. As a result, a GHG emission reduction effect from substituting steel types with wooden types of up to 117.67 kg-CO_2-eq/m can be obtained (replacing steel guard pipe with painted wooden type no. 3). Whether or not the wood is used as an energy source in the disposal process, it has an extremely large effect on the overall life cycle GHG emissions.
6. In a sensitivity analysis, the GHG emissions of the painted wooden type no. 1 may not differ significantly from those of the steel guardrails if the service life of wooden beams was extended to 5 years longer than the current service life. However, the emissions for both the painted and the pressure-injected cases of wooden type no. 3 were much less than the emissions of steel ones even if the service life of the wooden beams was extended or shortened by 5 years.

Potential topics for further investigation include consideration of the process for material removal and transport and the CO_2 balance in the wood itself, and in the forests that are the wood supply source, the appropriate wood supply volume for the region, and the balance with wood demand volume including wooden guardrails, and so forth.

This study revealed that GHG emissions from the wooden guardrails varied with the type: the wooden type no. 3 generated less GHG emissions than did wooden type no. 1. As mentioned in "Overview of guardrails examined in this study", the findings and tendencies obtained from this study can be applied to all varieties of wooden guardrails in Japan because the two types in this study can be considered representative of all the wooden guardrails used in Japan. Therefore, the findings of this study can contribute to promote selection and design of wooden types with lower GHG emissions.

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References

1. Forestry Agency of Japan (2013) Annual report on trends in forests and forestry fiscal year 2012. Forestry Agency of Japan, Tokyo, Japan
2. Kanemaru K, Zhang R, Iimura Y (2013) Survey on the spread of wooden guardrails (in Japanese). In: Proceedings of the 12th symposium on use of wood for civil engineering, 29 Aug–30 Aug 2013, Tokyo, Japan, pp 31–34

3. Matsui H, Machida H (2011) Development of wooden vehicle safety barriers in Gunma (in Japanese). Wood Preserv 37(2):89–94
4. JSCE Wood Engineering Committee (2010) Cross-sector research report on expanding use of wood for civil engineering in fiscal 2009 (in Japanese). JSCE Wood Engineering Committee, Tokyo, Japan, p 73
5. IPCC (2014) Climate change 2014, fifth assessment report, mitigation of climate change. Cambridge University Press, New York, USA
6. Kayo C, Hashimoto S, Numata A, Hamada M (2011) Reductions in greenhouse gas emissions by using wood to protect against soil liquefaction. J Wood Sci 57:234–240
7. Noda R, Kayo C, Sasaki T, Takaoku S (2014) Evaluation of CO_2 emissions reductions by timber check dams and their economic effectiveness. J Wood Sci 60:461–472
8. Kayo C, Noda R, Sasaki T, Takaoku S (2015) Carbon balance on life cycle of wood: targeting a timber check dam. J Wood Sci 61:70–80
9. Kayo C, Hashimoto S, Shibata N, Yamanouchi M, Numata A, Sakazaki T, Ikeda Y (2011) LCA for wood in the field of civil engineering—balance of CO_2 exchange in wooden guardrails (in Japanese). In: The 66th annual meeting of the JSCE, 7 Sep–9 Sep 2011, Ehime, Japan
10. Ohkata I, Daigo I, Matsuno Y, Adachi Y (2011) Evaluation method for assessing reduction potential of CO_2 emissions by promotion of wood consumption (substituting other materials) (in Japanese). In: The 6th meeting of the institute of life cycle assessment, 2 Mar–4 Mar 2011, Sendai, Japan
11. Nagano prefectural government (2015) Nagano prefecture website. http://www.pref.nagano.lg.jp/michikanri/infra/doro/hashi/guardrail/index.html. Accessed Mar 19 2015
12. Shibata N (2004) Development of Shinshu type wooden guardrail (in Japanese). Wood Preserv 30:168–173
13. Wako Concrete Co., Ltd. (2012) Implementation report on fiscal 2011 regional material supply increase project (Ministry of Agriculture, Forestry and Fisheries assisted project), regional timber industry and related supporting projects (development of markets for cultural items). Wako Concrete Co. Ltd., Miyazaki, Japan
14. Japan Environmental Management Association for Industry (2014) MiLCA. Japan Environmental Management Association for Industry, Tokyo, Japan
15. Hitoe K, Hasegawa T, Hasegawa K, Terazawa K, Yamanaka K, Hattori N (2013) Case study of life cycle assessment of domestic logs (in Japanese). Mokuzai Gakkaishi 59:269–277
16. Sainoki (2013) Report on technology support in displaying the environmental contribution of wood (in Japanese). Sainoki, Tokyo, Japan, pp 14–17
17. ISO/TS 14067 (2013) Greenhouse gases—carbon footprint of products—requirements and guidelines for quantification and communication. The International Organization for Standardization, Geneva,, Switzerland, p 52
18. Ministry of the Environment of Japan (2006) Results of greenhouse gas emission calculations. Report No. 5 of subcommittee meetings on forest sinks (in Japanese). Ministry of the Environment of Japan, Tokyo, Japan
19. Forestry and Forest Products Research Institute (1982) Wood industry handbook, 3rd edn. Maruzen Publishing Co., Ltd., Tokyo, Japan, p 103
20. Ministry of Finance Japan (2014) Ministerial ordinance concerning the useful life, etc. of depreciable assets (in Japanese). Ministry of Finance Japan, Tokyo, Japan. http://law.e-gov.go.jp/htmldata/S40/S40F03401000015.html. Accessed Mar 4 2015
21. Wako Concrete Co., Ltd. (2013) Implementation report on fiscal 2012 regional material supply increase project (Ministry of Agriculture, Forestry and Fisheries assisted project), regional timber industry and related supporting projects (development of markets for cultural items). Wako Concrete Co. Ltd, Miyazaki, Japan
22. Forestry and Forest Products Research Institute (2004) Wood industry handbook, 4th edn. Maruzen Publishing Co., Ltd., Tokyo, Japan, p 829
23. Forestry and Forest Products Research Institute (2004) Wood industry handbook, 4th edn. Maruzen Publishing Co., Ltd., Tokyo, Japan, p 787
24. Ministry of the Environment of Japan (2013) The current situation as regards reduction of wood generated by construction (in Japanese). Ministry of the Environment of Japan, Tokyo, Japan, p 57
25. All Japan Wood-recycle Association (2010) Quality standard of recycled wood chips (in Japanese). All Japan Wood-recycle Association, Tokyo, Japan
26. Forestry and Forest Products Research Institute (2004) Wood industry handbook, 4th edn. Maruzen Publishing Co., Ltd., Tokyo, Japan, p 1037
27. Yamanouchi M, Shibata N, Yoshino A (2011) Bending strength of round poles of Japanese larch of wooden guardrails over a period of 5 years after installation (in Japanese). Abstracts of the 61st annual meeting of the Japan Wood Research Society, 18 Mar–20 Mar 2011, Kyoto, Japan, D19-P-AM06 (CD-ROM)
28. Yamanouchi M, Shibata N (2012) Bending strength of round poles of Japanese larch of wooden guardrails over a period between 4 and 6 years after installation (in Japanese). Abstracts of the 62nd annual meeting of the Japan Wood Research Society, 15 Mar–17 Mar 2012, Sapporo, Japan, D15-P-AM11(CD-ROM)
29. Yamanouchi M, Shibata N, Imai M (2013) Resonance frequency of the flexural vibration and bending strength of round poles of Japanese larch of wooden guardrails over a period of 7 years after installation (in Japanese). Abstracts of the 63rd annual meeting of the Japan Wood Research Society, 27 Mar–29 Mar 2013, Morioka, Japan, D28-P-AM02 (CD-ROM)
30. Japan Wood Energy Co., Ltd. (2012) Wood biomass boiler installation guide (in Japanese). Japan Wood Energy Co., Ltd., Tokyo, Japan, p 7
31. Research Institute of Economy, Trade and Industry (2014) RIETI discussion paper series 14-J-047 (in Japanese). Research Institute of Economy, Trade and Industry, Tokyo, Japan
32. Abe F (1986) Calorific value of Japanese coniferous wood. Bull For For Prod Res Inst 338:91–100
33. Ministry of the Environment of Japan (2015) State of discharge and treatment of industrial waste. Ministry of the Environment of Japan, Tokyo, Japan. http://www.env.go.jp/recycle/waste/sangyo.html/. Accessed Mar 12 2015
34. Ministry of Land, Infrastructure, Transport and Tourism of Japan (2015) Survey of the current situation of construction by-products, Ministry of Land, Infrastructure, Transport and Tourism of Japan, Tokyo, Japan. http://www.mlit.go.jp/sogoseisaku/region/recycle/fukusanbutsu/jittaichousa/index01.htm/. Accessed Mar 12 2015
35. Wako Concrete Co., Ltd. (2014) What's new (in Japanese). http://www.wakocon.co.jp/. Accessed Mar 10 2015
36. Hitoe K, Hattori N (2011) Evaluation of green house gas emissions from sawmill residues usage for energy (in Japanese). Mokuzai Gakkaishi 57:63–71
37. Puettmann ME, Lippke B (2012) Woody biomass substitution for thermal energy at softwood lumber mills in the US inland North West. For Prod J 62:273–279
38. Komata H, Sakai S, Yasaka M, Ishikawa Y, Hattori N (2013) An application of life cycle assessment for electric power generated by forest residues: discussion of reduction of greenhouse gas emission (in Japanese). Mokuzai Gakkaishi 59:22–28