J Wood Sci (2015) 61:620–629
DOI 10.1007/s10086-015-1502-y

ORIGINAL ARTICLE

Life cycle greenhouse gas emissions of woodchip-paved walkways using tsunami salt-damaged wood: examination in Otsuchi, Iwate Prefecture

Chihiro Kayo[1] · **Chiaki Watanabe**[2] · **Takanobu Sasaki**[2] · **Seiki Kumagai**[3] · **Ryu Noda**[4] · **Seiji Hashimoto**[5]

Received: 27 April 2015 / Accepted: 22 July 2015 / Published online: 5 August 2015

Abstract A life cycle assessment of greenhouse gas (GHG: CO_2, CH_4, N_2O) emissions for woodchip-paved walkways using tsunami salt-damaged wood was conducted in Otsuchi, Iwate Prefecture. The GHG emissions for woodchip-paved walkways from the raw material procurement process to the construction process were 2.62 kg-CO_2-eq/m^2/year. Of these, most were for the raw material procurement process (88 %), with the production process accounting for 7 %, the transportation process <1 %, and the construction process 4 %. In the raw material procurement process, almost all of the GHG emissions were related to raw materials for adhesive. On the other hand, in the disposal process, use of disposed chips as energy (heat supply) in place of heavy oil obtained GHG emission reductions of 2.42 kg-CO_2-eq/m^2/year. With these taken into account, the net GHG emissions of the woodchip-paved walkway were reduced to 0.20 kg-CO_2-eq/m^2/year. We found that using a woodchip-paved walkway to replace an asphalt-paved walkway could reduce GHG emissions by 1.45 kg-CO_2-eq/m^2/year, and replacing an artificial turf walkway could reduce GHG emissions by 1.61 kg-CO_2-eq/m^2/year. However, achieving these reductions depends upon maintaining the woodchip pavement for at least 2 years and using the disposed chips as energy.

Keywords Life cycle assessment (LCA) · Paving materials · Tsunami salt-damaged wood · Adhesive · Energy use

Introduction

In an effort to establish a sound material-cycle society, woodchip paving is garnering attention in the field of utilizing unused thinnings and waste wood, and work is underway to promote technological development and

✉ Chihiro Kayo
kayoc@cc.tuat.ac.jp

Chiaki Watanabe
chiaki@iwt.akita-pu.ac.jp

Takanobu Sasaki
taka@iwt.akita-pu.ac.jp

Seiki Kumagai
kumagai@woodyland.jp

Ryu Noda
noda.ryu.008@m.kyushu-u.ac.jp

Seiji Hashimoto
shashimo@fc.ritsumei.ac.jp

[1] Department of Environment Conservation, Graduate School of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan

[2] Institute of Wood Technology, Akita Prefectural University, 11-1 Kaieizaka, Noshiro, Akita 016-0876, Japan

[3] Woody Sannai Co., Ltd, 34-8 Komekurasawa, Sannaitsuchibuchi, Yokote, Akita 019-1108, Japan

[4] Faculty of Agriculture, Graduate School of Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

[5] Department of Environmental Systems Engineering, College of Science and Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan

popularization [1–3]. The estimated amount of wood material available for use as paving material for the whole of Japan has been reported to be 300,000 m^3 per year [4]. Moreover, an enormous quantity of salt-damaged wood and disaster waste wood was generated by the earthquake and tsunami in areas affected by the Great East Japan Earthquake of March 11, 2011 [5]. Effective use of this wood is currently an important issue for promoting recovery and regional revitalization in the disaster-affected areas, and a variety of wood material applications such as woodchip pavement is being promoted [6].

Moreover, use of wood material is considered to contribute to the establishment of a low-carbon society. There are numerous papers of prior research using the life cycle assessment (LCA) method to evaluate greenhouse gas (GHG) emissions and emission reductions of wood material use in various fields including buildings [7, 8], furniture [9], soil improvement materials [10], check dams [11, 12], and energy use [13, 14]. The LCA method evaluates the total amounts of resource consumption and environmental load for a target product or service to evaluate its environmental impact over the entire life cycle, from extraction of the resources used to produce it through to its usage and disposal. In particular, the LCA targeting only GHGs as an environmental load is referred to as the carbon footprint (CF). However, there is no prior research on the LCA or CF of woodchip paving, and the life cycle GHG emissions and GHG reduction effects compared with other paving material have not been clarified.

Against this background, in the present research we focused on the use of woodchip-paved walkways using tsunami salt-damaged wood in Otsuchi, Iwate Prefecture. This initiative had the potential to contribute to supporting the recovery of the disaster-affected area, effective utilization of unused wood and waste wood, and mitigation of global warming. We used the LCA method to assess the GHG (CO_2, CH_4, N_2O) emissions throughout the life cycle. Furthermore, we conducted a comparison with non-wood pavements to investigate the GHG emission reduction effects of woodchip-paved walkways.

Materials and methods

Overview of Otsuchi, Iwate Prefecture

The town of Otsuchi is located on the Pacific coast of Iwate Prefecture. It has a population of 12,531 and an area of 20,059 ha (as of February 23, 2015) [15]. The Great East Japan Earthquake and ensuing tsunami, which occurred on March 11, 2011, caused the deaths of 1232 people, with two people missing and 50 earthquake-related deaths (as of February 1, 2015). The forestry industry damage included 301 ha of forest areas and six forestry roads, with the total amount of damage reaching ¥69.24 million [16]. Forest areas in Otsuchi are total 17,816 ha, or approximately 89 % of the town area, with 788 ha owned by the town, 8010 ha owned privately, and 9018 ha owned nationally [16]. Moreover, the cedar, red pine, and other major tree species planted after the Second World War are now nearing an age suitable for harvesting. The urban areas are surrounded by mountainous areas, with an industrial history divided between fishing and forestry. In recreating the fishing industry after the disaster, the importance of revitalizing the forestry industry and using wood material has been recognized [6].

Overview of target woodchip-paved walkways

Many of the temporary houses and shopping districts in Otsuchi have been erected on school grounds or paddy fields. In the case of buildings on paddy fields in particular, there are issues with drainage with puddles forming easily, since the soil originally had high water content. However, since these sites must be returned to their original condition after use, ordinary road paving has not been used and many areas suffered from poor drainage and walkability during rain and snow. To address this issue, a collaborative initiative between an educational research institution (Institute of Wood Technology, Akita Prefectural University), a private-sector company (Woody Sannai Co. Ltd.), and a non-profit organization (NPO: Kirikiri Koku) resulted in construction of a woodchip-paved walkway (width 1.2 m, length approx. 100 m, thickness 4 cm) in September 2012 to provide a comfortable walkway in the shopping district adjacent to Koduchi Temporary Housing Lot No. 4. This site was originally a paddy field and was later covered with gravel for use as a parking lot. Since the Great East Japan Earthquake, it has been used as a temporary shopping district. Figure 1 shows photographs before and after construction of the woodchip-paved walkway. The woodchip material was tsunami salt-damaged wood (standing cedar trees soaked with seawater by tsunami), and sawmill residues after sawing of the salt-damaged wood from within Otsuchi. The salt-damaged wood (standing trees) and sawmill residues are shown in Fig. 2. From regular interview surveys of people involved with the shopping district over a period of 2 years and 6 months (till March 2015), starting from 1 month after completion of the walkway, their assessment indicated that it suffered no seepage at all during rain, presented no signs of frost damage during cold periods, and that it improved the atmosphere and walkability of the shopping district [6].

Fig. 1 Construction of the woodchip-paved walkway, before (*left*) and after (*right*)

Fig. 2 Main steps from raw material procurement to construction of the woodchip-paved walkway

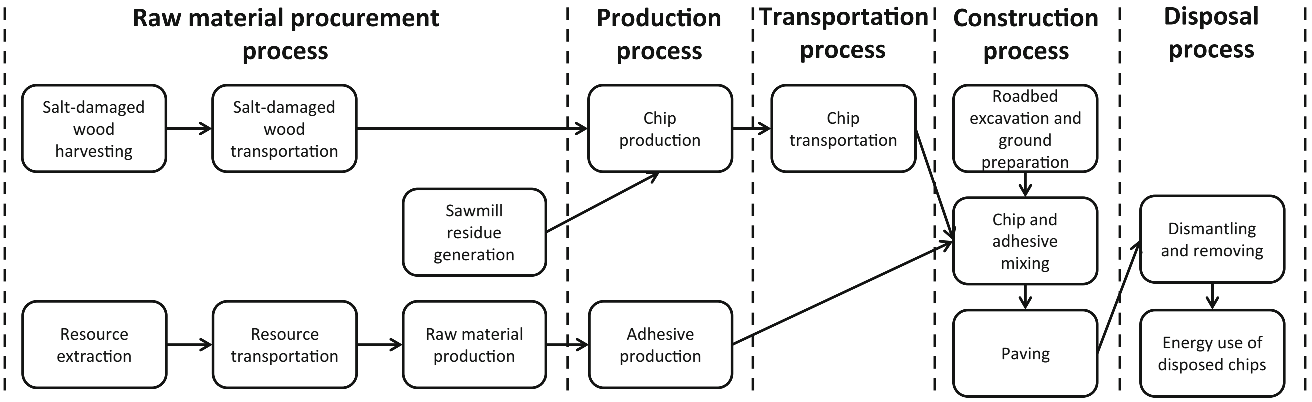

Fig. 3 Processes in the life cycle of a woodchip-paved walkway

Scope of assessment

The life cycle of the assessed woodchip-paved walkway is presented in Figs. 2 and 3, including the processes of raw material procurement, production, and transportation, as well as construction and disposal. With regard to the service life of the walkway, it was confirmed through an interview survey with Woody Sannai Co., Ltd., which has a track record of manufacturing and constructing woodchip-paved walkways, that there are actual examples in Akita

Prefecture that have been maintained in good condition for 12 years after construction. At the site of this research also, we confirmed that as of March 2015, 2 years and 6 months after construction, the target walkway has been maintained in good condition. We, therefore, estimated the usable life at 10 years, making reference to the abovementioned examples.

Method of assessing life cycle GHG emissions

Table 1 shows the total amount of actual material and energy consumption used as foreground data along with the construction conditions when assessing the GHG emissions. Furthermore, Table 2 shows the GHG emission intensities used as background data. GHGs were assessed on the basis of emissions of CO_2, CH_4, and N_2O originating in fossil fuels. With regard to the balance of CO_2 in terms of carbon stored and emitted from wood, we have assumed carbon neutrality based on the assumption of reforestation after wood harvesting, and omitted this item from the assessment; however, the CH_4 and N_2O emitted through combustion of the wood are included in the assessment pursuant to ISO provisions [17]. Moreover, each GHG has been presented in terms of a CO_2 equivalent (kg-CO_2-eq) using its 100-year global warming potential (GWP_{100}) (CO_2 1, CH_4 34, N_2O 298) [18]. The following section discusses the assessment method for each life cycle process in detail.

Raw material procurement process

For the raw material procurement process for the woodchips, we considered the stages of harvesting the salt-damaged wood and transporting it from the harvesting site to the chip production site. The sawmill residues, which made up part of the raw materials for the chips, were generated as waste wood (by-product) from sawing. Therefore, we did not consider the stage of production (sawing) for sawmill residues. The chip production site was onsite at a saw mill. Therefore, we did not consider transportation for the sawmill residues since these were generated on the same site (the chip production site). With regard to the raw material procurement process for the adhesive that was mixed with the woodchips, we considered the stages of resource extraction, resource transportation, and raw material production (Fig. 3).

The GHG emissions (kg-CO_2-eq) of salt-damaged wood at the harvesting stage were calculated by multiplying the amount of salt-damaged wood harvested (m^3) (Table 1) by the GHG emission intensity (kg-CO_2-eq/m^3) for harvesting wood (Table 2). Since the method for harvesting salt-damaged wood is the same as for thinning it, we used the figure used for thinning with wood use [19] for the GHG emission intensity. To estimate the GHG emissions (kg-CO_2-eq) for the transportation stage of salt-damaged wood, we multiplied the harvested amount (m^3) by the bulk density of cedar (0.314 t/m^3) [10, 12], by the transportation

Table 1 Construction conditions and amounts of material and energy consumed

	Unit	Value	Note
Construction condition			
Paving width	m	1.20	
Paving area	m^2	110.00	
Paving thickness	cm	4.00	
Raw material procurement process			
Salt-damaged wood harvesting	m^3	1.51	Unit: roundwood conversion volume, tree species: cedar
Transportation distance of salt-damaged wood	km	0.50	From the harvesting site to the chip production site, two-ton truck
Sawmill residue generation	m^3	4.28	Unit: residue conversion volume, tree species: cedar
Adhesive production	kg	702.00	6.38 kg/m^2, product name: KS Binder
Production process			
Chip production	m^3	6.20	Unit: chip conversion volume, chip size: 1–10 mm
Light oil consumption by the chipper	L	10.46	
Transportation process			
Transportation distance of chips	km	11.30	From the chip production site to the construction site, two-ton truck
Construction process			
Light oil consumption by the heavy machinery	L	20.00	For roadbed excavation and ground preparation
Electric power consumption by the mixer	kWh	20.00	For chip and adhesive mixing
Electric power consumption by the road roller	kWh	62.00	To compact the paving

Table 2 GHG emission intensities

	Unit	CO_2	CH_4	N_2O	GHG total	Scope of assessment	References
Wood harvesting	kg-CO_2-eq/m^3	5.5500	0.2278	0.0480	5.8258	Thinning with wood use	[19]
Transportation by two-ton truck	kg-CO_2-eq/t·km	0.2193	0.0083	0.0011	0.2287	Resource extraction ~ fuel production ~ fuel combustion	[20]
Raw material production for adhesive	kg-CO_2-eq/kg	3.6232	0.0017	0.0002	3.6252	Resource extraction ~ transportation ~ raw material production	[20]
Adhesive production	kg-CO_2-eq/kg	0.2500	–	–	0.2500	Adhesive production (synthesis of raw materials)	–[a]
Electric power consumption	kg-CO_2-eq/kWh	0.5826	0.0064	0.0192	0.6082	Resource extraction ~ electric power generation	[20][b]
Light oil combustion	kg-CO_2-eq/L	2.8207	0.1073	0.0140	2.9420	Resource extraction ~ light oil production ~ light oil combustion	[20]
A-type heavy oil combustion	kg-CO_2-eq/L	2.9891	0.1137	0.0148	3.1176	Resource extraction ~ heavy oil production ~ heavy oil combustion	[20]
Woodchip combustion	kg-CO_2-eq/m^3	–	0.0025	0.0002	0.0027	Woodchip combustion	[20]

[a] An interview survey with the adhesive manufacturer

[b] The value of Tohoku Electric Power Co., Inc

distance (km) (Table 1), by two for a two-way trip, and by the GHG emission intensity for transportation by a two-ton truck (kg-CO_2-eq/t·km) (Table 2). Since the woodchip raw material used in this research was unused wood and waste wood such as tsunami salt-damaged trees and sawmill residues, the GHG emissions did not consider silviculture stages such as ground preparation, planting, weeding, cleaning, pruning, and thinning without wood use. On the other hand, if logs harvested from ordinary trees were used as the raw material for woodchips, the emissions from these silviculture stages would need to be considered. However, the emissions from such stages are small, at around 5 % [19] of the emissions from the wood harvesting stage. Therefore, even if the silviculture stages were considered, there would be little change in the assessment result of GHG emissions.

To calculate the GHG emissions (kg-CO_2-eq) for the resource extraction, resource transportation, and raw material production stages for the adhesive, we used the respective GHG emission intensities (kg-CO_2-eq/kg) [20] for the main raw materials: polyetherpolyol (composition ratio of 75 % of the adhesive), methylene diphenyl diisocyanate (MDI) (20 %), tolylene diisocyanate (TDI) (2 %), and toluene (1 %). We multiplied these intensities for each raw material by their respective composition ratio within the adhesive and added them up to calculate the GHG emission intensity by adhesive volume (kg-CO_2-eq/kg) ("Raw material production for adhesive" in Table 2). This was then multiplied by the adhesive production volume (kg) (Table 1) to calculate the GHG emissions (kg-CO_2-eq).

Production process

We considered the chip production stage and the adhesive production stage for the production process. The GHG emissions (kg-CO_2-eq) in the chip production stage were calculated by multiplying the amount of light oil consumed by the chipper (L) (Table 1) by the GHG intensity (kg-CO_2-eq/L) for light oil combustion (Table 2). The GHG emissions (kg-CO_2-eq) in the adhesive production stage were calculated by multiplying the adhesive production amount (kg) (Table 1) by the GHG intensity (kg-CO_2-eq/kg) for adhesive production (synthesis of raw materials) (Table 2). This intensity was obtained by an interview survey with the adhesive manufacturer.

Transportation process

The GHG emissions (kg-CO_2-eq) for the transportation process were calculated by multiplying the chip production amount (m^3) (Table 1) by the bulk density of cedar (0.314 t/m^3) [10, 12], by the transportation distance from the chip production site to the walkway construction site (km) (Table 1), by two for a two-way trip, and by the GHG emission intensity for transportation by a two-ton truck (kg-CO_2-eq/t·km) (Table 2).

Construction process

The construction process was classified into three stages: the roadbed excavation and ground preparation stage, the chip and adhesive mixing stage, and the paving stage

(Figs. 2, 3). The GHG emissions (kg-CO_2-eq) for the roadbed excavation and ground preparation stage were calculated by multiplying the light oil consumption amount (L) of the heavy machinery (Table 1) by the GHG emission intensity for light oil combustion (kg-CO_2-eq/L) (Table 2). The GHG emissions (kg-CO_2-eq) for the chip and adhesive mixing stage were calculated by multiplying the amount of electric power consumed (kWh) by the mixer (Table 1) by the GHG emission intensity (kg-CO_2-eq/kWh) for electric power consumption (Table 2). For this intensity, we used the figures of Tohoku Electric Power Co., Inc. [20], in whose operation area the town of Otsuchi lies. The GHG emissions (kg-CO_2-eq) for the paving stage were calculated by multiplying the amount of electric power consumed (kWh) by the road roller used to compact the paving (Table 1), and by the GHG emission intensity (kg-CO_2-eq/kWh) for electric power consumption (Table 2).

Disposal process

We envisaged that after the woodchip-paved walkway was dismantled and removed, the disposed woodchips would be used for heat supply by a chip boiler, and decided to investigate the GHG emission reductions associated with their use as a substitute form of heat supply by an A-type heavy oil boiler. Woodchips containing adhesive, high moisture and some salt (not exceeding 0.4 % of salinity concentration) could be used in an incineration boiler [21].

We did not consider the GHG emissions from the dismantling and removing stage (Fig. 3), since only manpower without heavy machinery is generally used for the task. Furthermore, the woodchip volume could conceivably diminish due to decay with the passage of time. However, since the speed of the decay in the woodchip-paved walkway is not scientifically clear, this study did not consider the change of the woodchip volume.

For the energy use of disposed chips stage (Fig. 3), supposing no change in the woodchip volume with the passage of time as mentioned above, the chip production volume (volume used) (Table 1) was assumed to be the volume of disposed chips generated (m^3), and it was multiplied by a chip bulk density of 0.55 t/m^3 [22] and the calorific value of 10.5 GJ/t [22] assuming 40 % water content, and by the average chip boiler energy usage efficiency of 77.5 % [22] to calculate the heat supply amount (GJ). By dividing this amount by the A-type heavy oil calorific value of 0.0367 GJ/L [22] and by the average heavy oil boiler energy usage efficiency of 88.5 % [22], we calculated the A-type heavy oil substitution amount (L).

Meanwhile, the GHG emissions (kg-CO_2-eq) from combustion of the disposed chips were calculated by multiplying the amount of disposed chips generated (m^3) by the GHG emission intensity for woodchip combustion (kg-CO_2-eq/m^3) (Table 2). However, as mentioned above, this intensity is used for CH_4 and N_2O, and not for CO_2. Moreover, the GHG emissions (kg-CO_2-eq) from combustion of A-type heavy oil were calculated by multiplying the A-type heavy oil substitution amount (L) found previously by the GHG emission intensity (kg-CO_2-eq/L) for A-type heavy oil combustion (Table 2). The GHG emission reductions (kg-CO_2-eq) from using the disposed woodchips to substitute for A-type heavy oil were found by subtracting the GHG emissions from disposed woodchip combustion, from the GHG emissions for A-type heavy oil combustion.

Results and discussion

Life cycle GHG emissions of the woodchip-paved walkway

The result of assessing the annual life cycle GHG emissions for the woodchip-paved walkway is shown in Table 3. The total GHG emissions from the raw material procurement process to the construction process were 288.64 kg-CO_2-eq/year for 110 m^2 of woodchip-paved walkway, or 2.62 kg-CO_2-eq/year per m^2. In the breakdown of each GHG, CO_2 accounted for more than 99 % of the total, with CH_4 and N_2O <1 %. Looking at the processes in the life cycle, of the total emissions the raw material procurement process accounted for the largest share at 88 %, while the production process accounted for 7 %, the transportation process less than 1 %, and the construction process 4 %.

In the raw material procurement process, almost all of the emissions were due to resource extraction, resource transportation, and raw material production relating to the adhesive. The emissions due to harvesting and transportation of the salt-damaged wood for the chips were less than 1 % of the total. Since the emissions relating to the raw material for the adhesive were significant, the potential for reducing the amount of adhesive used should be considered in the further promotion of woodchip-paved walkways going forward. According to an interview survey with Woody Sannai, the operator who manufactured and constructed the abovementioned woodchip-paved walkway, the usual amount of adhesive used per 1 m^2 of woodchip-paved walkway is 6.16 kg (in several actual examples within Akita Prefecture), which is 3 % less than the 6.38 kg used in this research. The target site of this research was originally a paddy field, with a high level of water content in the soil. Moreover, it was subject to low temperature and frequent snowfall in winter. Therefore, to prevent the surface of the walkway detaching or cracking due to freezing in winter, the amount of adhesive used was

Table 3 Assessment result for annual life cycle GHG emissions for the woodchip-paved walkway (+: emission, −: reduction)

Life cycle process/stage		GHG emissions ($kg-CO_2-eq/year$)	
		Per 110 m^2	Per 1 m^2
Raw material procurement	Salt-damaged wood harvesting	0.88	0.01
	Salt-damaged wood transportation	0.02	2.E-04
	Raw material production for adhesive	254.49	2.31
Production	Chip production	3.08	0.03
	Adhesive production	17.55	0.16
Transportation	Chip transportation	1.76	2.E-02
Construction	Roadbed excavation and ground preparation	5.88	0.05
	Chip and adhesive mixing	1.22	0.01
	Paving	3.77	0.03
Disposal	Energy use of disposed chips	−266.35	−2.42
Total	Raw material procurement to construction	288.64	2.62
	Raw material procurement to disposal	22.29	0.20

increased slightly to enhance the adhesion of the woodchips. Therefore, in areas where the winter temperature is relatively higher and the water content of the soil lower, the GHG emissions related to adhesive can be reduced by 3 % due to reduction in the amount of adhesive used. Moreover, to improve the adhesion of the woodchips for the above-mentioned reasons, fine woodchips of 1–10 mm in size were used to reduce the porosity. However, in regions or sites that have different temperatures and soil conditions, the chip diameter could be enlarged to 10–30 mm, increasing the porosity and reducing the amount of adhesive used per 1 m^2 of paved surface by 25 % to 4.80 kg (actual examples existing in Akita, Akita Prefecture). Through such means, the GHG emissions relating to the adhesive could be reduced by 25 %.

Meanwhile, the GHG emissions from the transportation process of the salt-damaged wood and chips account for an extremely small portion of the total emissions, each less than 1 %. In this research, the transportation distance of the salt-damaged wood was 0.5 km and the transportation distance of the chips was 11.3 km—both relatively short distances. The overall trend in Japan is not to carry logs and chips over long distances as this increases the transportation cost while their added value is relatively low compared to wood products such as sawn wood or plywood [23, 24]. For this reason, even in different regions and at sites other than the site of this research, the transportation distances for logs and chips are unlikely to increase much, and the GHG emissions from the transportation process can be estimated to have a low impact over the entire life cycle.

Now we turn to the disposal process. Using disposed woodchips to replace heavy oil used for heat supply can be expected to reduce GHG emissions by 266.35 $kg-CO_2-eq/year$ over the woodchip-paved walkway area of 110 m^2, or 2.42 $kg-CO_2-eq/year$ per m^2. Considering these emission reductions, the total GHG emissions of the woodchip-paved walkway can be reduced to 22.29 $kg-CO_2-eq/year$ over the entire 110 m^2, or 0.20 $kg-CO_2-eq/year$ per m^2. This shows that the overall life cycle GHG emissions are dependent to a large degree on whether the woodchips are used for energy in the disposal process.

Comparison of woodchip-paved walkways and non-wooden walkways

Here, we will compare the life cycle GHG emissions of woodchip-paved walkways and non-wooden walkways. We compared the woodchip-paved walkway against an ordinary asphalt walkway and an artificial turf walkway. The asphalt walkway was a walkway paved with a water-permeable asphalt mixture with a typical paving thickness of 4 cm, the same thickness as the woodchip-paved walkway. The GHG emissions, considering all processes in the life cycle including raw material procurement, production, transportation, and construction (roadbed excavation, roadbed construction, pavement construction), are reported to be 16.48 $kg-CO_2-eq$ per m^2 [25]. Moreover, we compared an artificial turf walkway because we considered that it has a similar level of functionality to a woodchip-paved walkway in terms of comfort while walking. The GHG emissions considering the raw material procurement, production, transportation, and construction are 18.08 $kg-CO_2-eq$ per m^2 [25]. We used ten years as the service life of asphalt-paved and artificial turf walkways, which is the legal service life [26], because the actual service life of asphalt-paved and artificial turf walkways has not yet been scientifically studied and reported. We calculated the annual GHG emissions by dividing the total GHG emissions by the number of years in the legal service life.

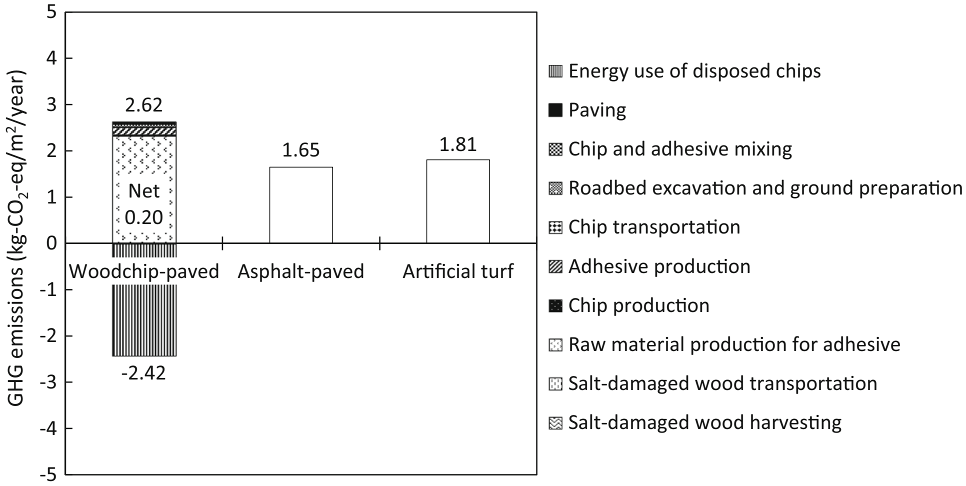

Fig. 4 Comparison of annual life cycle GHG emissions per m^2 of woodchip-paved, asphalt-paved, and artificial turf walkways (+: emission, −: reduction)

Figure 4 shows a comparison of the annual GHG emissions per m^2 for woodchip-paved walkways, asphalt-paved walkways, and artificial turf walkways. The GHG emissions for woodchip-paved walkways from the raw material procurement process to the construction process were significantly higher than non-wooden walkways at 159 % of the emissions of asphalt-paved walkways and 145 % of the emissions of artificial turf walkways. However, the net emissions after deducting the GHG emission reductions from using the disposed chips in the disposal process for heat were less than the non-wooded type, at 12 % of the emissions of asphalt-paved walkways and 11 % of the emissions of artificial turf walkways. This shows that using woodchip-paved walkways to replace asphalt-paved and artificial turf walkways can reduce GHG emissions by 1.45 kg-CO$_2$-eq/m^2/year and 1.61 kg-CO$_2$-eq/m^2/year, respectively, providing the disposed chips are used for energy.

Moreover, looking at service life, in the present research we assumed a service life of 10 years for the woodchip-paved walkway; however, if the woodchip-paved walkway was to be dismantled and disposed of in a single year, even taking into consideration the use of the disposed chips as energy, the net emissions would be large (2.03 kg-CO$_2$-eq/m^2/year), 123 % of the emissions of an asphalt-paved walkway and 112 % of the emissions of an artificial turf walkway. When the service life becomes 2 years or longer, the net emissions became less than those of the non-wooden walkways. In other words, we found that if woodchip-paved walkways are not maintained for at least 2 years, the GHG emission reduction effects of using them to replace asphalt-paved or artificial turf walkways cannot be achieved.

Incidentally, there is an option to landfill disposed woodchips rather than to use them for energy. Some previous researches [27, 28] have reported that there was little or no decay in wood in landfills, and carbon could be stored in the wood for the long term. Therefore, we evaluated the volume of carbon storage in the disposed woodchips, using the chip bulk density of 0.55 t/m^3 [22] and the carbon content of 0.50 t-C/t. The results showed that the disposed chips in landfills would store a large volume of carbon at 56.83 kg-CO$_2$-eq/m^2 for the long term in the case of no decay in the chips.

Conclusions

We evaluated the life cycle GHG (CO$_2$, CH$_4$, N$_2$O) emissions of a woodchip-paved walkway using tsunami salt-damaged wood in Otsuchi, Iwate Prefecture. Moreover, by comparing these with an asphalt-paved walkway and an artificial turf walkway, we investigated the GHG emission reduction effects of woodchip-paved walkways. The main points we obtained are as follows.

(a) The GHG emissions of the woodchip-paved walkway from the raw material procurement process to the construction process were 2.62 kg-CO$_2$-eq/m^2/year. In a breakdown by process, the raw material procurement process accounted for 88 %, the production process 7 %, the transportation process <1 %, and the construction process 4 %. Almost all of the emissions from the raw material procurement process were accounted for by the emissions relating to the raw materials for the adhesive.

(b) In the disposal process, using the disposed woodchips as heat supply to substitute for heavy oil yielded emission reductions of 2.42 kg-CO$_2$-eq/m^2/year. Considering these, the life cycle GHG emissions could be reduced to 0.20 kg-CO$_2$-eq/m^2/year.

(c) Using a woodchip-paved walkway could achieve GHG emission reduction effects of 1.45 kg-CO$_2$-eq/

m^2/year when replacing an asphalt-paved walkway and 1.61 kg-CO_2-eq/m^2/year when replacing an artificial turf walkway. However, to achieve the emission reduction effects, the service life of the woodchip-paved walkway must be maintained for at least 2 years, and the disposed chips must be used as energy.

The woodchip-paved walkway that was studied in this research contributed to effective use of tsunami salt-damaged trees and waste wood in the town of Otsuchi, which was heavily damaged in the Great East Japan Earthquake. It is an important initiative for supporting the improvement of the living environment for people affected by the disaster [16]. This research led to the effective use of 5.79 m^3 of tsunami salt-damaged trees and sawmill residues in a pavement area of 110 m^2. Furthermore, it was also demonstrated that the woodchip-paved walkway is an effective way to use wood material from a perspective of mitigating global warming. However, to promote GHG emission reductions through the future spread of woodchip-paved walkways, it is important to promote reductions in the amount of adhesive mixed with the woodchips, use of an adhesive with a lower environmental load, maintenance management to ensure long-term use of the woodchip-paved walkways, and reuse of the chips after disposal. Moreover, an important future consideration is the CO_2 balance in the wood itself.

Acknowledgments In conducting this research, the authors were assisted greatly by the people of the Otsuchi Town Hall, the NPO Kirikiri Koku, Ikarigawaseikan Co., Ltd., and the Warabikko Shopping District. The authors would like to express heartfelt gratitude for their assistance. This work was supported by the Toyota Foundation, MEXT KAKENHI Grant No. 25282115 and No. 15H02863, and JSPS KAKENHI Grant No. 26870181.

References

1. Aoyama T (2007) Test construction of woodchip pavement using broken wood generated by the eruption in Miyakejima (in Japanese). Constr Recycl 38:13–15
2. Takeda T, Ouki H, Hiyama R (2009) Woodchip pavement construction examples using various wood materials generated locally through thinning etc. (in Japanese). Pavement 44(11):11–15
3. Kubo H, Mitamura F, Ogata N, Yonemura T (2008) Studies and development of the waste wood chip pavement which used recycling resources (Part 4) (in Japanese). Constr Tech Res Center Fukui Prefect Annu Rep Reg Tech 21:66–73
4. Inter-disciplinary committee on the increased use of wood in civil engineering (2010) 2009 report on inter-disciplinary study on the increased use of wood in civil engineering (in Japanese): 73
5. Kayo C, Ishigaki T, Yamada M, Osako M, Tachio K (2012) Consideration relating to wide area treatment of disaster waste from the Great East Japan Earthquake (part 1) (in Japanese). Life Environ 1:36–42
6. Watanabe C, Sasaki T, Yamauchi H, Gotoh F, Kumagai S, Abe R (2013) Study on regional regeneration through the utilization of wooden disaster waste and timber in Otsuchi town, Iwate (in Japanese). Proc Annu Conf Inst Soc Saf Sci 32:59–60
7. Upton B, Miner R, Spinney M, Heath LS (2008) The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass Bioenerg 32:1–10
8. Petersen AK, Solberg B (2005) Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. For Policy Econ 7:249–259
9. García SG, Gasol CM, Lozano RG, Moreira MT, Gabarrell X, Pons JR, Feijoo G (2011) Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. Sci Total Environ 410–411:16–25
10. 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
11. 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
12. Kayo C, Noda R, Sasaki T, Takaoku S (2015) Carbon balance in the life cycle of wood: targeting a timber check dam. J Wood Sci 61:70–80
13. Kayo C, Aramaki T, Hanaki K (2011) Effect of change of forest carbon storage on net carbon dioxide balance of wood use for energy in Japan. J Ind Ecol 15(1):122–136
14. Whittaker C, Mortimer N, Murphy R, Matthews R (2011) Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass Bioenergy 35:4581–4594
15. Otsuchi town (2015) Otsuchi town web site. http://www.town.otsuchi.iwate.jp. Accessed 10 Mar 2015
16. Otsuchi town (2014) 2014 Otsuchi town directory (in Japanese)
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. IPCC (2013) IPCC Fifth assessment report: climate change 2013 (AR5)
19. 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
20. Japan Environmental Management Association for Industry (2014) MiLCA
21. The Task Team on Disaster Waste Management and Reconstruction in Japan Society of Material Cycles and Waste Management (2012) Strategy of separation and treatment of disaster waste: Focusing on the Great East Japan Earthquake 2011
22. Japan Wood Energy Co., Ltd. (2012) Wood biomass boiler installation guide (in Japanese)
23. Forestry Agency of Japan (2014) 2012 wood material demand and supply report, main sector material exchange table (for sawn wood, plywood, and chips) (in Japanese)
24. Ministry of Land, Infrastructure, Transport and Tourism, Japan (2012) 2010 national net flow of cargo (9th logistics census), flow volume between prefectures (forestry products) (in Japanese)
25. National Institute for Land and Infrastructure Management Ministry of Land, Infrastructure, Transport and Tourism, Japan (2012) Life cycle assessment of social capital, environmental load units corresponding to construction type system tree subdivisions (Level 4), 2010 preliminary version
26. Ministry of Finance, Japan (2015) Ministerial ordinance concerning the useful life, etc. of Depreciable Assets (in Japanese)

http://law.e-gov.go.jp/htmldata/S40/S40F03401000015.html. Accessed 25 Jan 2015

27. Micales JA, Skog KE (1997) The decomposition of forest products in landfills. Int Biodeterior Biodegrad 39(2–3):145–158
28. Ximenes F, Bjordal C, Cowie A, Barlaz M (2015) The decay of wood in landfills in contrasting climates in Australia. Waste Manag 41:101–110