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ORIGINAL ARTICLE

**Chihiro Kayo · Seiji Hashimoto · Atsunori Numata
Masanori Hamada**

Reductions in greenhouse gas emissions by using wood to protect against soil liquefaction

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Abstract We compared the greenhouse gas (GHG) emissions from a log pile (LP) to those from a sand compaction pile (SCP) and from cement deep mixing (CDM) as measures against soil liquefaction, assuming that forest and waste management scenarios influence the GHG (CO_2, CH_4, and N_2O) balance of wood. We found little difference between the LP and SCP methods with respect to GHG emissions from fossil fuel and limestone consumption. However, GHG emissions from the CDM method were seven times higher than emissions from the LP method. In the GHG balance of wood, when the percentage of CH_4 emissions from carbon in underground wood was lower than 3.3%, permanent storage in the log achieved greater reductions in GHG emissions than using the waste log as fuel in place of coal or heavy oil. In order to obtain reductions in GHG emissions by replacing SCPs or CDM with LPs, sustainable forest management with reforestation and prevention of CH_4 emissions from the underground log are essential. Using reforestation, permanent storage of the log, no CH_4 emission from the log, and using logging residues instead of coal, the LP can achieve reductions in GHG emissions of 121 tonnes of CO_2 per 100 m^2 of improvement area by replacing CDM.

Key words Soil liquefaction · Greenhouse gas balance · Log pile · Sand compaction pile · Cement deep mixing

C. Kayo · (✉) S. Hashimoto
Research Center for Material Cycles and Waste Management, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
Tel. +81-29-850-2967; Fax +81-29-850-2917
e-mail: kayo.chihiro@nies.go.jp

A. Numata
Research Institute of Technology, Tobishima Corporation, Chiba 270-0222, Japan

M. Hamada
School of Creative Science and Engineering, Waseda University, Tokyo 169-8555, Japan

Introduction

Wood can contribute to climate change mitigation through carbon storage in which CO_2 absorbed by trees during their growth is fixed in harvested wood and through carbon substitution in which fossil fuel consumption is reduced by using wood as an energy source. Fossil fuel and limestone consumption in the production of woody materials is less than that in the production of other materials such as steel, concrete, and plastic, and therefore replacing nonwood materials with wood materials would result in CO_2 emission reductions. However, when we examine the effects of the use of wood on climate change mitigation, it is necessary to consider the greenhouse gas (GHG) balance in the life cycle of wood, which includes post-harvest forest management, the service life of wood products, recycling or the energy use of wood waste, nitrous oxide (N_2O) emissions from combustion of waste wood, and methane (CH_4) emissions from anaerobic degradation in landfills.

Reductions in GHG emissions by using wood materials have previously been investigated. Jönsson et al.[1] assessed the environmental impact of three flooring materials, linoleum, vinyl flooring, and solid wood flooring. Using a life-cycle and forest land-use perspective, Börjesson and Gustavsson[2] calculated primary energy use and CO_2 and CH_4 emissions from the construction of a multi-storey building with either a wood or a concrete frame. Petersen and Solberg[3] compared the use of glulam beams in the construction of Oslo airport with an alternative using steel in order to compare GHG emissions and energy use over the life cycle of these two materials, calculate the reduced GHG emissions and the cost of substitution, and analyze which factors had the strongest influence on the results. Dodoo et al.[4] investigated the effects of post-use material management on the life-cycle carbon balance of buildings by comparing a concrete-framed building with a wood-framed building.

In this study we focused on pile driving and storing wood underground as reinforcement for protection against soil liquefaction (a phenomenon in which the strength and stiffness of a saturated soil is reduced by earthquake movement or other rapid loadings) as another way to use wood in construction in Japan. A potential 1.5 million m^3 of wood (2.3% of the total wood demand in Japan in 2009) is available for ground improvement by log piling.[5] Numata et al.[6] compared CO_2 emissions from fossil fuel consumption during harvesting, processing, transporting, and log piling with the carbon storage in the log pile. We, however, evaluated the possibility of mitigating climate change by considering the GHG (CO_2, CH_4, and N_2O) balance through the life cycle of the wood with respect to forest and waste management practices. We compared the log pile (LP) method using wood with the sand compaction pile (SCP) method and the cement deep mixing (CDM) method as general measures against soil liquefaction. For the use of wood, we assumed various scenarios of forest and waste management influencing the GHG balance.

Material and methods

CO_2 and N_2O emissions from fossil fuel and limestone consumption

We interviewed practitioners in order to set equal foundation construction conditions for the LP, SCP, and CDM methods. The construction conditions and use of materials and fuel for each method are shown in Table 1. We evaluated CO_2 and N_2O emissions from fossil fuel and limestone consumption during the production of materials and the production and combustion of fuels for use in the construction machinery, electric generators, compressors, wheel loaders, and backhoes. CO_2 and N_2O emissions were calculated as follows:

$$EC = U_{(M)} \times ec_{(M)} + U_{(F)} \times ec_{(F)}, \tag{1}$$

$$EN = U_{(F)} \times en_{(F)} \times GWP_n \tag{2}$$

where EC [tonnes of CO_2 (t-CO_2)] is CO_2 emissions from fossil fuel and limestone consumption; $U_{(M)}$ (t, m^3) (Table 1) is use of materials (sand, blast-furnace cement, logs); $ec_{(M)}$ (t-CO_2/t, m^3) (Table 2) is CO_2 emissions from fossil fuel and limestone consumption per unit weight or volume of material; $U_{(F)}$ (l) (Table 1) is use of fuels (light oil); $ec_{(F)}$ (t-CO_2/l) (Table 2) is CO_2 emissions from fossil fuel and limestone consumption per unit volume of fuel (light oil); EN (t-CO_2) (CO_2 equivalent) is N_2O emissions from fossil fuel consumption; $en_{(F)}$ (kg-N_2O/kl) is N_2O emissions from fossil fuel combustion per unit volume of fuel (0.06494, light oil for a diesel engine);[9] and GWP_n (Table 3) is the global warming potential relative to CO_2 for N_2O in 100 years.

GHG balance of wood

The life cycle of wood, including forest and waste management, for the LP method is shown in Fig. 1. In this study, we

Table 2. CO_2 emissions from fossil fuel and limestone consumption per unit weight or volume for each material and fuel

	Unit	Production	Combustion
Sand	kg-CO_2/m^3	19[a]	–
Blast-furnace cement	kg-CO_2/t	481[b]	–
Log	kg-CO_2/m^3	28[a]	–
Logging residues	kg-CO_2/m^3	4[a]	–
Light oil	kg-CO_2/kl	312[a]	2620[c]
Heavy oil	kg-CO_2/kl	112[a]	2710[c]
Coal	kg-CO_2/t	68[a]	2410[c]

[a] Data for production stages of sand, logs, logging residues, light oil, heavy oil, and coal were obtained by an input–output analysis from Nansai and Moriguchi[7]

[b] Data for the production stage of blast-furnace cement was derived from 198 kg-CO_2/t from fossil fuel consumption (excluding fossil fuels from waste) and 283 kg-CO_2/t from limestone consumption, as reported by the Japan Environmental Management Association for Industry[8]

[c] Data for the combustion stages of light oil, heavy oil, and coal were obtained from the Ministry of the Environment of Japan[9]

Table 1. Construction conditions and use of material and fuel for each method to protect against soil liquefaction

		Unit	SCP	CDM	LP
Pile length		m	8	8	8
Improvement area		m^2	500	500	500
Placing pitch		m	1.60	1.34	0.50
Pile diameter		m	0.70	–	0.17
Placing cross-sectional area		m^2	–	1.50	–
Improvement rate		–	0.15	0.84	0.15
Cement content		t/m^3	–	0.10	–
Material use	Sand	m^3	848	–	–
	Blast-furnace cement	t	–	368	–
	Logs	m^3	–	–	586
Fuel use (light oil)	Construction machinery	l	417	1701	–
	Electric generator	l	3581	14732	–
	Compressor	l	1527	–	–
	Wheel loader	l	558	–	–
	Backhoe	l	–	3157	5865
	Total	l	6083	19590	5865

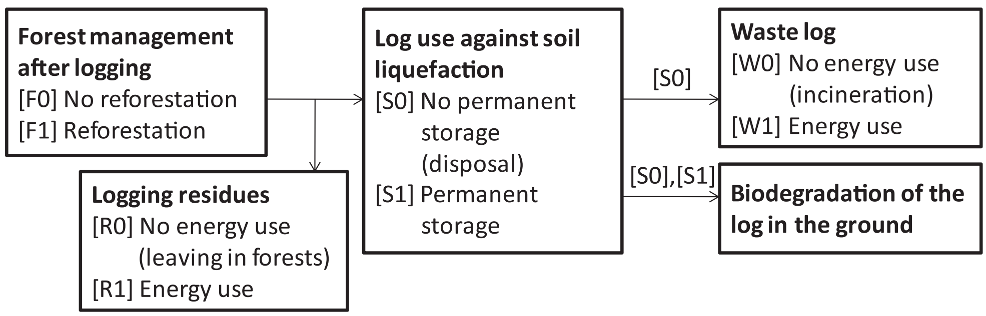
SCP, sand compaction pile; CDM, cement deep mixing; LP, log pile

Table 3. Coefficients for calculation of the GHG balance

	Parameter	Unit	Value
Y	Yield of the log	–	0.8559[a]
BEF	Biomass expansion factor	–	1.23[b]
R	Ratio of tree below ground	–	0.25[b]
D	Density of wood	t/m^3	0.314[b]
CC	Carbon content of wood	t-C/t	0.5[b]
GC(min)	Gasification from carbon in the wood	%	0.0[c]
GC(max)	Gasification from carbon in the wood	%	17.0[c]
MG	Methane ratio of the gas	–	0.50[d]
$cal_{(L)}$	Calorific value of wood	GJ/t	14.4[e]
$cal_{(F)}$ (coal)	Calorific value of coal	GJ/t	26.6[e]
$cal_{(F)}$ (oil)	Calorific value of oil	GJ/kl	39.1[e]
$en_{(L)}$	N_2O emissions from combustion of waste log	kg-N_2O/t	0.01[e]
GWP_m	Global warming potential of CH_4 relative to CO_2	–	21[f]
GWP_n	Global warming potential of N_2O relative to CO_2	–	310[f]

[a] Y is based on values of *Cryptomeria japonica* as reported by Nakayama[10]
[b] BEF, R, D, and CC are based on values of *Cryptomeria japonica* as reported by the Ministry of the Environment of Japan[11]
[c] GC is based on minimum and maximum values reported in previous studies.[12–17] GC (min) was obtained from Micales and Skog[12] and GC (max) was obtained from Ximenes et al.[13]
[d] MG was obtained from IPCC[18]
[e] $cal_{(L)}$, $cal_{(F)}$ (coal), and $cal_{(F)}$ (oil) were reported by the Ministry of the Environment of Japan[9]
[f] GWP_m and GWP_n were reported by the IPCC[19]

Fig. 1. Life cycle of wood in the LP method



assumed that the life cycle of wood begins not with planting trees but with harvesting them for log piles in existing forests, and therefore the system boundary of the life cycle includes reforestation after harvesting. The GHG balance of wood is influenced by whether sustainable forest management with reforestation occurs after logging, whether the log pile is sequestered permanently underground without log disposal, whether CH_4 and CO_2 are emitted from the logs in the ground as a result of biodegradation, and whether logging residues and waste logs are used for fuel. We examined eight wood scenarios [LP(a–h), as explained in Table 4] using a combination of reforestation (F1) or no reforestation (F0) (i.e., change to grassland after logging), permanent storage (S1) or no permanent storage (S0) of the log pile underground including biodegradation, and energy use (R1, W1) or no energy use (R0, W0) of logging residues and waste logs, and incineration of the waste logs. In Japan, when a waste log is not used for energy, it is usually incinerated, and when logging residues are not used for energy, they are normally left in the forests. The GHG balance, including CO_2, CH_4, and N_2O for each wood scenario is given in Table 5. The four scenarios LP(e–h) with reforestation after harvesting trees are equivalent to the case of planting trees at the beginning of the life cycle of wood.

Table 4. Wood scenarios in the LP method

	LP(a)	LP(b)	LP(c)	LP(d)	LP(e)	LP(f)	LP(g)	LP(h)
F	0	0	0	0	1	1	1	1
S	0	0	1	1	0	0	1	1
R, W	0	1	0	1	0	1	0	1

F indicates reforestation (F1) or no reforestation (F0) after logging in the forests, S indicates permanent storage (S1) or no permanent storage (S0) of the log pile underground, and R and W indicate energy use (R1, W1) or no energy use (R0, W0) of logging residues and waste log (Fig. 1)

The net GHG balance is defined by Eq. 3 and calculated using Eqs. 4–12 (see Table 3 for coefficients used) as follows:

$$GHG = \left(C_{dec(T)} + M_{emi(L)} + MC_{emi(L)} + N_{emi(L)}\right) - \left(C_{sto(L)} + C_{sub(L)} + C_{sub(R)}\right) \quad (3)$$

$$C_{dec(T)} = L/Y \times BEF \times (1+R) \times D \times CC \times 44/12 \quad (4)$$

$$C_{sto(L)} = L \times D \times CC \times 44/12 \quad (5)$$

$$M_{emi(L)} = L \times D \times CC \times GC \times MG \times 16/12 \times GWP_m \quad (6)$$

$$MC_{emi(L)} = M_{emi(L)} + C_{sto(L)} \times GC \times (1 - MG) \quad (7)$$

$$C_{sub(L)} = F_{sub(L)} \times ec_{(F)} \quad (8)$$

Table 5. Greenhouse gas (GHG) balance including CO_2, CH_4, and N_2O for each wood scenario

	LP(a)	LP(b)	LP(c)	LP(d)	LP(e)	LP(f)	LP(g)	LP(h)
F	$C_{dec(T)}$	$C_{dec(T)}$	$C_{dec(T)}$	$C_{dec(T)}$	–	–	–	–
S	$M_{emi(L)}$	$M_{emi(L)}$	$C_{sto(L)}$, $MC_{emi(L)}$	$C_{sto(L)}$, $MC_{emi(L)}$	$M_{emi(L)}$	$M_{emi(L)}$	$C_{sto(L)}$, $MC_{emi(L)}$	$C_{sto(L)}$, $MC_{emi(L)}$
R, W	$N_{emi(L)}$	$C_{sub(L)}$, $C_{sub(R)}$	–	$C_{sub(R)}$	$N_{emi(L)}$	$C_{sub(L)}$, $C_{sub(R)}$	–	$C_{sub(R)}$

F indicates reforestation or no reforestation after logging in the forests, S indicates permanent storage or no permanent storage of the log pile underground, and R and W indicate energy use or no energy use of logging residues and waste log (Fig. 1 and Table 3). See text for definitions

$$F_{sub(L)} = L \times D \times cal_{(L)} / cal_{(F)} \quad (9)$$

$$C_{sub(R)} = F_{sub(R)} \times ec_{(F)} - L/Y \times (BEF - 1) \times ec_{(R)} \quad (10)$$

$$F_{sub(R)} = L/Y \times (BEF - 1) \times D \times cal_{(L)} / cal_{(F)} \quad (11)$$

$$N_{emi(L)} = L \times D \times en_{(L)} \times GWP_n \quad (12)$$

where GHG (t-CO_2) (CO_2 equivalent) is the net GHG balance of wood; $C_{dec(T)}$ (t-CO_2) (CO_2 equivalent) is the decrease in carbon storage from above-ground and below-ground parts of the tree from log harvesting and logging residues (this study supposes that the base level of carbon storage is the existing forest, and therefore log harvesting represents a decrease of carbon storage in the forest); $M_{emi(L)}$ (t-CO_2) (CO_2 equivalent) is CH_4 emissions from the log from biodegradation underground; $MC_{emi(L)}$ (t-CO_2) (CO_2 equivalent) is CH_4 and CO_2 emissions from the log from biodegradation underground; $N_{emi(L)}$ (t-CO_2) (CO_2 equivalent) is N_2O emissions from combustion of the waste logs; $C_{sto(L)}$ (t-CO_2) (CO_2 equivalent) is carbon storage by the log underground; $C_{sub(L)}$ and $C_{sub(R)}$ (t-CO_2) (CO_2 equivalent) are carbon substitution from fossil fuels (coal or heavy oil) replaced with fuels from waste logs and logging residues, respectively; L (m^3) (Table 1) is the volume of log used for the pile; Y (Table 3) is the yield of the log from the trunk used for the pile; BEF (Table 3) is the biomass expansion factor for estimating the mass of the entire above-ground tree, including branches and leaves from the trunk; R (Table 3) is the ratio of the below-ground tree, including roots, relative to the above-ground tree; D (t/m^3) (Table 3) is the density of wood; CC (t-C/t) (Table 3) is the carbon content of wood; and GC (%) (Table 3) is the percentage of gasification from carbon in the wood. GC is based on minimum and maximum values reported in previous studies;[12–17] the minimum value of 0% is from Micales and Skog[12] and the maximum value of 17% is from Ximenes et al.[13] MG (Table 3) is the CH_4 ratio of the gas; GWP_m (Table 3) is the global warming potential relative to CO_2 for CH_4 in 100 years; $F_{sub(L)}$ and $F_{sub(R)}$ (t, kl) are fossil fuel (coal or heavy oil) substitutions by fuels from the waste log and logging residues, respectively; $ec_{(F)}$ (t-CO_2/t, kl) (Table 2) is the CO_2 emissions from fossil fuel and limestone consumption per unit weight or volume of fuel (coal or heavy oil); $cal_{(L)}$ (GJ/t) (Table 3) is the calorific value of the wood; $cal_{(F)}$ (GJ/t, kl) (Table 3) is the calorific value of fossil fuels (coal or heavy oil); $ec_{(R)}$ (t-CO_2/m^3) (Table 2) is the CO_2 emissions from fossil fuel and limestone consumption per unit volume of logging residues; and $en_{(L)}$ (t-N_2O/t) (Table 3) is N_2O emissions from combustion of waste log per unit weight of wood.

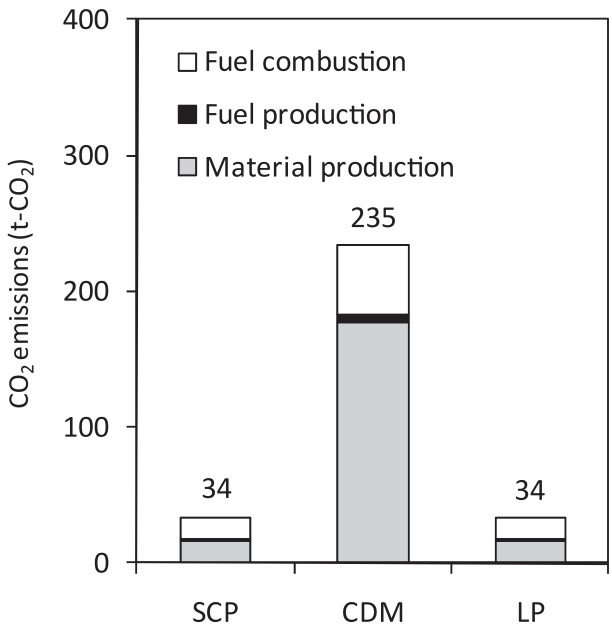


Fig. 2. Greenhouse gas (GHG) (CO_2 and N_2O) emissions from fossil fuel and limestone consumption for each measure to protect against soil liquefaction per 500 m^2 of improvement area. *SCP*, sand compaction pile; *CDM*, cement deep mixing; and *LP*, log pile

Results and discussion

GHG emissions from fossil fuel and limestone consumption

GHG (CO_2 and N_2O) emissions from fossil fuel and limestone consumption for the SCP, CDM, and LP methods are shown in Fig. 2. Total GHG emissions from the LP and SCP methods were similar; however, total GHG emissions from the CDM method were approximately seven times the emissions from the LP method. GHG emissions from the production of materials, production of fuels, and combustion of fuels were 48%, 6%, and 46%, respectively, of the total emissions in the LP method and 47%, 6%, and 47%,

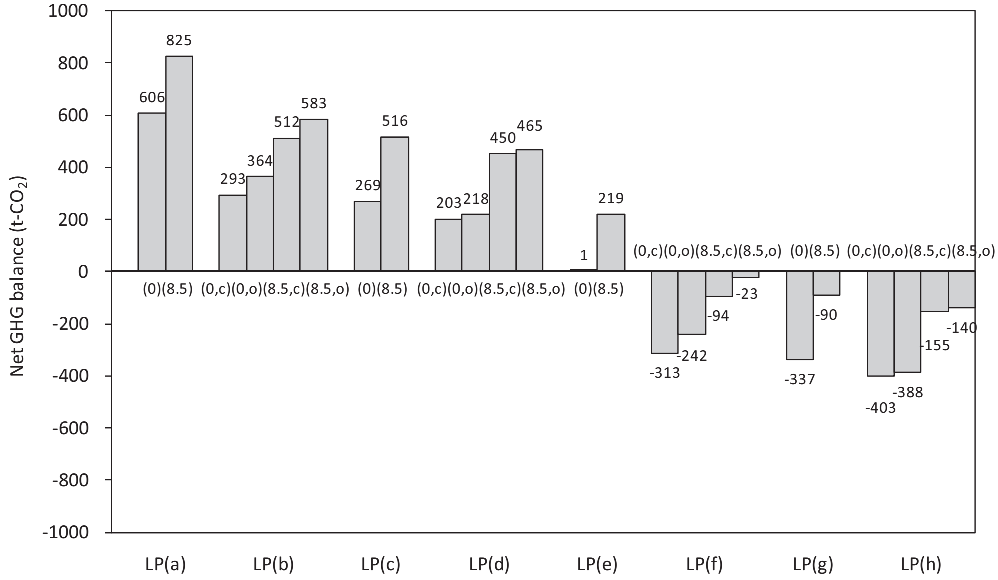


Fig. 3. Net GHG (CO_2, CH_4, and N_2O) balance of wood for the LP method. Positive values indicate carbon, CH_4, and N_2O emissions (CO_2 equivalent), whereas negative values indicate carbon storage and substitution (CO_2 equivalent). The net GHG balance is shown in Eq. 3. In the x axis labels, *LP(a)* to *LP(h)* indicate the wood scenarios in the LP method, as explained in Fig. 1 and Table 4. In the x axis labels, *(0)* and *(8.5)* indicate the percentage of CH_4 emissions from carbon in the wood (GC × MG in Eq. 6), i.e., 0% and 17% of the percentage of gasification from carbon in the wood (GC in Eqs. 6 and 7 and Table 3, with MG = 0.5). *(c)* and *(o)* are coal and heavy oil fuel substitution, respectively, from waste logs and logging residues

respectively, of the total emissions in the SCP method, indicating only slight differences between the two methods. GHG emissions from material production, fuel production, and fuel combustion were 75%, 3%, and 22%, respectively, of the total emissions in the CDM method. The largest amount of GHG is emitted during the material production stage as a result of both fossil fuel consumption and limestone calcination in the cement production process (Table 2).

GHG balance of wood

Results of the net GHG balance of wood in the LP method are shown in Fig. 3. In the four scenarios LP(a–d) in which there was no reforestation after logging, carbon, CH_4, and N_2O emissions were greater than carbon storage and substitution, with net emissions ranging from 203 t-CO_2 for LP(d)-(0,c), where 0 indicates no CH_4 emission from the wood and c means that waste log is used to replace coal, to 825 t-CO_2 for LP(a)-(8.5), where 8.5 indicates the maximum amount of CH_4 emission from the wood. This demonstrates that sustainable forest management with reforestation after harvesting is required to reduce GHG emissions when wood is used. The LP(e)-(8.5) scenario showed a net GHG emission of 219 t-CO_2 as a result of CH_4 emissions from the log underground, although this scenario included reforestation after logging. The LP(g) scenario included reforestation after logging and permanent storage of the log pile underground, and carbon storage in this scenario was 337 t-CO_2 without CH_4 emission from the wood and 90 t-CO_2 with CH_4 emission. The effect on GHG emissions through carbon storage in the log was a 73% change between the absence or presence of CH_4 emissions. Moreover, carbon storage for LP(g)-(0) was greater than carbon substitution for LP(f)-(0,c) (313 t-CO_2) or LP(f)-(0,o) (242 t-CO_2), indicating that when there is no CH_4 emission from wood underground, permanent storage of the log pile can reduce GHG emissions more than using fuel from the waste log instead of coal or heavy oil (o). However, carbon storage in LP(g)-(8.5) was less than the carbon substitution in LP(f)-(0,c) or LP(f)-(0,o), indicating that when the percentage of CH_4 emissions from carbon in the wood (GC × MG in Eq. 6) is lower than 0.8% (GC of 1.6%, MG of 0.50), permanent storage of the log underground can achieve greater reductions in GHG emissions than using fuel from the waste log instead of coal [if GC × MG is 0.8%, then the net GHG balance for LP(g) in Eq. 3 is 313 t-CO_2]. When the percentage of CH_4 emissions from carbon in wood (GC × MG) is lower than 3.3% (GC of 6.6%, MG of 0.50), permanent storage of the log can reduce GHG emissions to a greater extent than heavy oil substitution by the waste log [if GC × MG is 3.3%, then the net GHG balance in the LP(g) in Eq. 3 is 242 t-CO_2]. However, in order to use a waste log as fuel, pretreatment of the wood, such as seasoning, may be necessary because a log pile in the ground may contain water.

GHG balance of wood including fossil fuel and limestone consumption

The net GHG balance from the GHG emissions from fossil fuel and limestone consumption (Fig. 2) and the GHG balance of wood (Fig. 3) is shown in Fig. 4. The LP scenarios that assumed no reforestation after logging [LP(a–d)] showed a range in GHG emissions from 236 to 859 t-CO_2, which was greater than the 34 t-CO_2 obtained for the SCP method and the 235 t-CO_2 for the CDM method. Therefore, in order to achieve reductions in GHG emissions by replacing the SCP or CDM method with the LP method, sustainable forest management is essential. Moreover, the LP(e)-(8.5) scenario with CH_4 emission involved GHG emissions of 253 t-CO_2, which was more than that for the SCP or CDM method; even with sustainable forest

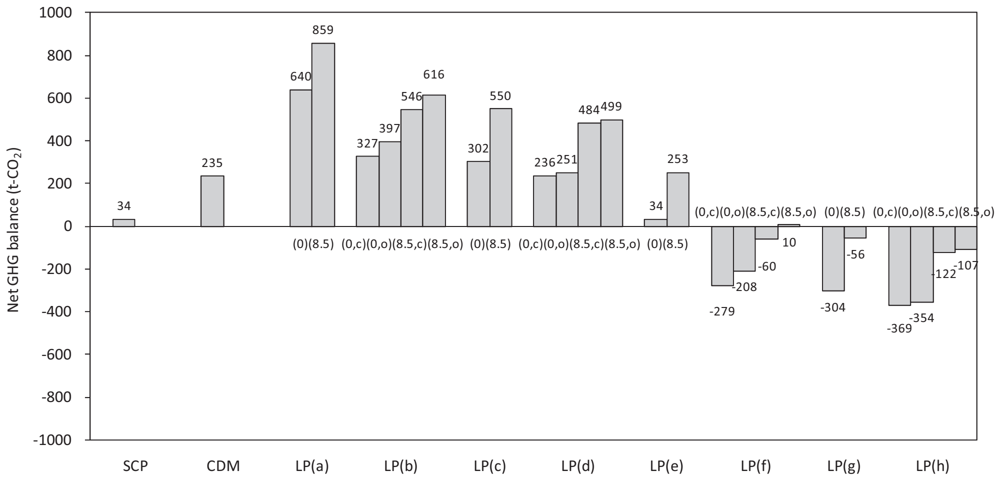


Fig. 4. Net GHG (CO_2, CH_4, and N_2O) balance for each method (i.e., the sum of Figs. 2 and 3). Positive values indicate carbon, CH_4, and N_2O emissions (CO_2 equivalent), whereas negative values indicate carbon storage and substitution (CO_2 equivalent). The net GHG balance is shown in Eq. 3

management, preventing CH_4 emissions from the log pile underground is required to reduce GHG emissions for the LP method in place of the SCP or CDM method. The LP(h)-(0,c) scenario resulted in 369 t-CO_2 of carbon storage and substitution, which was the largest reduction in GHG emissions of all the scenarios. Therefore, using sustainable forest management, permanent storage of the log pile, no CH_4 emission from the log underground, and using logging residues as fuel in place of coal, the LP method can achieve reductions in GHG emissions of 403 (= 34 + 369) t-CO_2, equivalent to 81 t-CO_2 per 100 m^2 of improvement area, by replacing the SCP method and 604 (= 235 + 369) t-CO_2, equivalent to 121 t-CO_2 per 100 m^2 of improvement area, by replacing the CDM method. If carbon storage decreases in forests as a result of land use change by extracting sand and limestone in the SCP and CDM method, GHG emissions from SCP and CDM may increase when this decrease in carbon storage is taken into consideration.

Conclusions

We compared the GHG balance for the LP method (using a log pile) to that for the SCP method (using a sand pile) and the CDM method (using cement stabilization) for soil reinforcement against soil liquefaction. When using wood, we assumed various scenarios of forest and waste management that influence the GHG (CO_2, CH_4, and N_2O) balance. The main findings are summarized as follows:

1. There was little difference between the LP method and the SCP method in terms of GHG emissions from fossil fuel and limestone consumption. GHG emissions for the CDM method were, however, seven times higher than that for the LP method.
2. When the percentage of CH_4 emissions from carbon in wood was less than 0.8%, permanent storage of the log in the ground achieved greater reductions in GHG emissions than using waste log after disposal as fuel in place of coal. When the percentage of CH_4 emissions from carbon in wood was less than 3.3%, permanent storage of the log reduced GHG emissions to a greater extent than using the waste log as fuel in place of heavy oil.
3. In order to obtain reductions in GHG emissions by replacing the SCP or CDM method with the LP method, sustainable forest management with reforestation after logging and prevention of CH_4 emissions from the log underground are essential.
4. Using sustainable forest management, permanent storage of the log pile, no CH_4 emissions from the log underground, and using logging residues as fuel instead of coal, the LP method can achieve reductions in GHG emissions of 81 t-CO_2 per 100 m^2 of improvement area by replacing the SCP method and 121 t-CO_2 per 100 m^2 of improvement area by replacing the CDM method.

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