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ORIGINAL ARTICLE

Carbon balance in the life cycle of wood: targeting a timber check dam

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Abstract Focusing on a timber check dam, this study evaluated the carbon balance in the life cycle of wood, taking into account both carbon emissions and reductions associated with fossil fuel use and carbon stocks in wood and forests. A significant difference can occur because the net carbon balance may be either on the emission side or on the reduction side, depending on the implementation of reforestation after harvesting, the use of forest-residue- and sawmill-residue-based energy, and the difference in the evaluation period. Thus, it is necessary to examine which framework should be used to conduct an evaluation. Post-harvesting reforestation is essential to achieve net carbon emission reduction effects by substituting the concrete check dam with the timber check dam. Then, with the energy use of forest and sawmill residues, the net carbon emission reduction effects per dam can be expected after an evaluation period of 35 years, and 28 t-C/dam of those can be obtained during an evaluation period of 100 years. From mid- to long-term perspectives, carbon emission will be reduced more if the carbon balance of wood and forests is taken into account rather than focusing only on fossil fuel consumption.

Keywords Carbon stock · Life cycle assessment (LCA) · Reforestation · Energy use · Time horizon

Introduction

The use of biomass has been attracting attention as a way to counter global warming. In particular, it is believed that wood plays a role in mitigating global warming since it continues to store carbon absorbed by a tree during its growth process for a certain period of time. In addition, wood can reduce CO_2 emissions due to fossil fuel consumption by substituting for steel and concrete materials, and by replacing energy from fossil fuels such as petroleum and coal [1]. Therefore, the use of wood has been encouraged in various areas including construction, furniture, paper, civil engineering, and energy fields, and the greenhouse gas (GHG) (primarily represented by CO_2) emission reduction effects have been examined based on the Life Cycle Assessment method (LCA) [2–7]. LCA is a comprehensive method to assess various environmental impacts on the atmosphere, soil, and water by considering the entire life cycle, from raw material extraction, which produces a target product or service, to product use and disposal stages, and by calculating the volume of resource consumption and environmental load emissions. The authors have also focused on wood use to date in the forest civil engineering field, in which almost no prior

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studies have been conducted, and they examined the CO_2 emission reduction effects of timber check dams using the LCA method [8]. The popularization of measuring carbon footprints (CFs) that only target GHGs has been promoted in recent years as an environmental load item of LCA.

To evaluate the carbon (CO_2) balance of biomass-derived materials such as wood, many prior studies [4, 8–11] claimed to be carbon–neutral, meaning they had no impact on the concentrations of CO_2 in the atmosphere, thus the carbon balance was considered to be zero. This is based on the idea that the carbon emitted by biomass incineration or biodegradation in the final process was originally absorbed by means of photosynthesis during the biomass growth process [12]. Another way of seeing this is that after biomass incineration or biodegradation, carbon emissions are absorbed by the growth of next-generation biomass [13]. Moreover, similar logic is used in the Global Warming Potential (GWP), which assesses the degree of impact caused by each GHG on global warming [14] and the standards of the LCA and CFs (ISO 14067, Section 6.4.9.2 of the standard, Note) [15] set forth by the International Organization for Standardization (ISO). As a result, it has been agreed that the carbon balance of biomass-derived materials were consequently omitted.

However, they have ignored that there is a significant time lag between carbon emissions and absorption [12, 13]. With regard to the time change, wood continues to store carbon for a certain period of time, and the timing of harvesting and regrowth in forests varies. Therefore, to comprehend precisely how wood use mitigates global warming, it is imperative to consider the carbon balance of both wood and forests in conjunction with time changes, and to discuss CO_2 emission reduction effects within the evaluation framework of the LCA and the CF.

Accordingly, this study used the application of wood to the check dam in Akita Prefecture discussed in a previous study [8] as a case study, and an evaluation of the carbon balance in the life cycle of wood was performed, taking into account changes in carbon stocks in the wood and forest over time. This study focused on an all-wood timber check dam since it uses a high volume of wood and it has been built many times as a standard type in the past. Moreover, we focus on a concrete dam as a typical non-timber check dam, compare it to the timber dam, and then examine the carbon emission reduction effects by substituting the concrete dam with the timber dam. To avoid confusing the terms carbon dioxide (CO_2) and carbon (C), both terms will be described hereafter as “carbon” in this study, and evaluation results will also be expressed by the amount of carbon (e.g., t-C).

The framework of carbon balance evaluations

Overview of the check dams covered by the study

Based on a previous study [8], we focused on both timber (all-wood type) and concrete check dams, which can prevent the same volume of sediment runoff to ensure the consistency of functional units. The structure of an all-wood timber check dam (Fig. 1) is such that the squared timbers (width: 0.30 m, height: 0.25 m, length: 0.60–3.60 m) are stacked parallel to the length and width of the dam alternately. Then, they are connected with one another toward the vertical direction in a staggered arrangement using connectors (0.46 m in length) to establish the dam body. Since the dam body is constructed only with squared timbers and connectors, the wood utilization rate in the volume per dam reaches more than 90 %. This type of dam is a forestry civil engineering structure that can contribute to the effective utilization of mature trees producing large-diameter logs in Japanese forests. Squared timbers of 60-year-old sugi (*Cryptomeria japonica* D. Don) are used for the dam in this study. With regard to the connectors, metal fittings called lag screws are used for the areas where the tensile load acts on the dam body, while steel bars are used for the other areas. Furthermore, when an all-wood timber check dam is constructed in Akita Prefecture, a front apron is set up to prevent the scouring of the downstream side of the structure caused by the water flowing from the upstream area.

On the other hand, a concrete check dam is the most common structural type of check dam. There are two types of dam forms (such as steel and wood) for which concrete is cast and cured: that for which the forms are removed (without forms) and that for which the forms are left in place (with forms) [8]. In this study, we examined the type without forms.

Scope of the carbon balance evaluation

Figure 2 presents the scope of the evaluation of the carbon balance in the timber check dam (a) and the concrete check dam (b). It covers the wood- and forest-related carbon balance and the fossil-fuel-related carbon balance.

With regard to the wood- and forest-related carbon balance for the timber check dam, we evaluated the carbon stock in the squared timbers used to build the dam and the carbon stock in the forest where harvesting of the wood actually took place. While the carbon stock in the forest declines due to harvesting, the subsequent implementation of reforestation after the harvesting influences whether the carbon stock will go up again. Therefore, we assumed scenarios of reforestation and no reforestation in the forest upon the wood harvesting and the dam construction, and

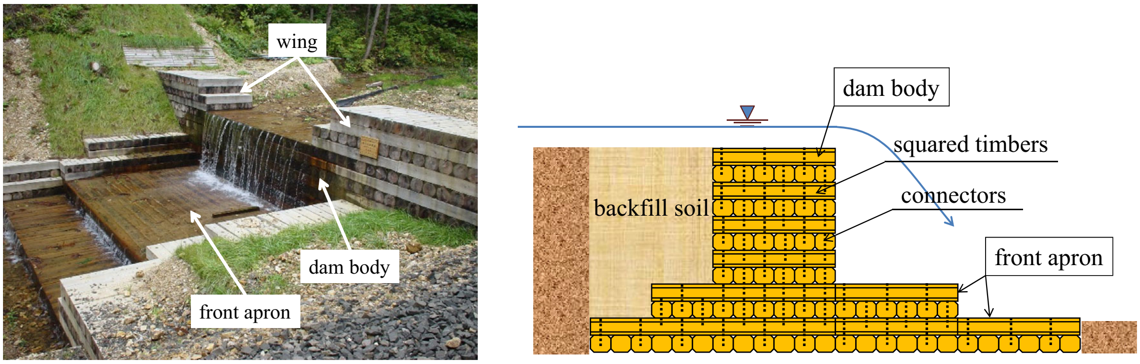
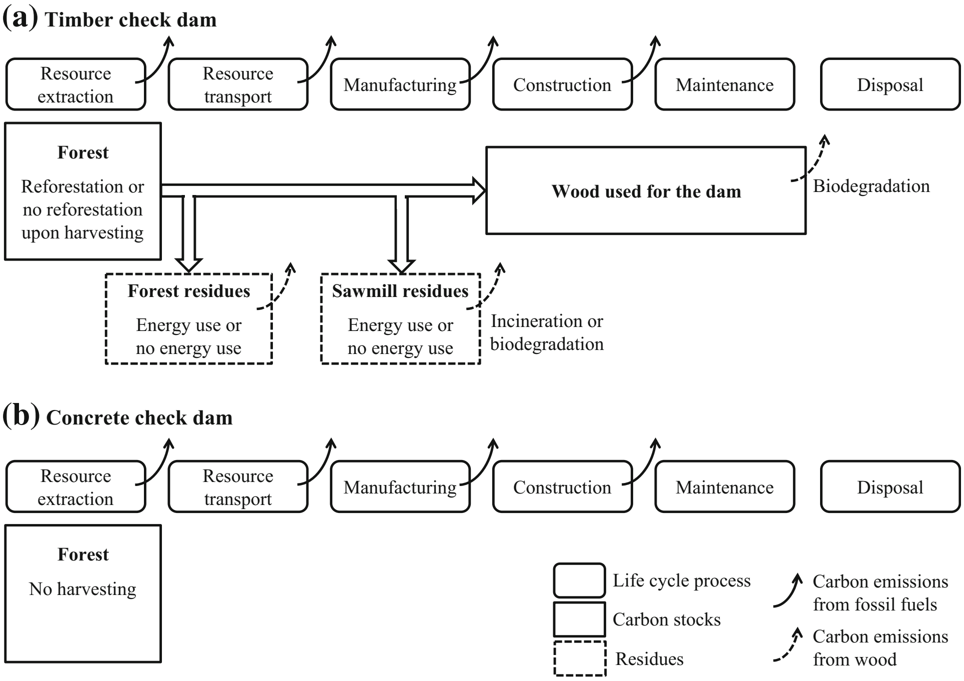


Fig. 1 Appearance of the timber check dam (all-wood type) (*left*) and cross-section diagram of the dam (*right*) [8]

Fig. 2 Scope of evaluation of the carbon balance



we used the differences in those scenarios to investigate the impact on the results of the entire carbon balance. For the concrete check dam, the carbon stock from forest growth following no harvesting was included in the evaluation.

For the fossil-fuel-related carbon balance, we evaluated the amount of carbon emissions derived from fossil fuel consumption in the life cycle of the timber dam or concrete dam. For the timber dam, we determined that harvesting in currently existing forests is the initial (resource extraction) process of the life cycle.

In both the resource extraction and the manufacturing processes, the use of energy from forest residues and sawmill residues affects whether carbon emissions derived from fossil fuel will be reduced by replacing fossil fuels with forest residues and sawmill residues. Hence, we also assumed scenarios of energy use and no energy use from forest residues and sawmill residues upon the wood harvesting and the dam construction.

In the maintenance process, the previous study [8] assumed that some of the squared timbers are changed to new timbers after construction. However, the interval of the repair work and replaced areas were set hypothetically because there have been no prior studies available. The hypothetically set conditions have a significant impact on the outcome when evaluating changes in the carbon stock of the squared timbers, and they also complicate the evaluation process. Therefore, this study did not take this maintenance process into consideration.

In the disposal process, it is not realistic to reuse the squared timbers used for the dam as a fuel after their disposal because the squared timbers are actually left in the forest without being disposed of or removed. Therefore,

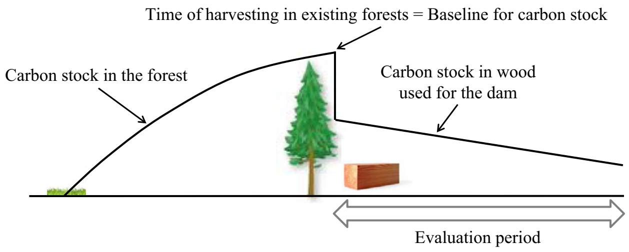


Fig. 3 Baseline for carbon stock in the carbon balance evaluation

this study did not set up scenarios in which the energy from wood after disposal was used.

The baseline for carbon stocks

Upon evaluating the carbon balance, it is necessary to decide what standard (in other words, the baseline) should be used for the carbon stock in the forest or the wood. As Fig. 3 described, an evaluation of this study was conducted on the carbon balance using a baseline for carbon stocks at the time of wood harvesting in forests (that is, the carbon stock level of the existing forests) based on Kayo et al. [16]. The baseline is consistent with the initial process of the life cycle.

Evaluation period

Regarding the LCA and CF, it is imperative to answer the question of how long an evaluation period should be postulated. While the evaluation period was set to be 50 years in the previous study [8], as that is the service life of timber dams, evaluation results on carbon balance vary if a period shorter or longer than the 50 year evaluation period is considered. Brandão et al. [12] mentioned that using a different evaluation period can significantly change the evaluation results on the carbon balance of wood in the LCA and CF. Therefore, in this study the evaluation period was set to be a maximum of 100 years, and then an examination was done to determine how using different evaluation periods (e.g., 30, 50, and 100 years) would affect the results.

We supposed that a stable vegetation environment, such as riparian trees, would form around the check dam 100 years after the dam was constructed, regardless of the type of dam. One of the ultimate goals of constructing a check dam is to enable the formation of such an environment so that water current will be stabilized and sediment runoff will be prevented. Therefore, the function of preventing sediment runoff, equal to that at the time of dam construction, can be maintained for 100 years.

Materials and methods

Carbon balance evaluation equations

The carbon balance equations for each scenario (refer to "Scope of the carbon balance evaluation") are described as follows:

$$\mathrm{CBT}_{\mathrm{r,e}}(t) = \mathrm{CEF}(1) - \mathrm{CRR}(1) + \mathrm{CSF}(60) - \mathrm{CSF}(t) - \mathrm{CSW}(t) \tag{1}$$

$$\mathrm{CBT}_{\mathrm{r,ne}}(t) = \mathrm{CEF}(1) + \mathrm{CSF}(60) - \mathrm{CSF}(t) - \mathrm{CSW}(t) \tag{2}$$

$$\mathrm{CBT}_{\mathrm{nr,e}}(t) = \mathrm{CEF}(1) - \mathrm{CRR}(1) + \mathrm{CSF}(60) - \mathrm{CSW}(t) \tag{3}$$

$$\mathrm{CBT}_{\mathrm{nr,ne}}(t) = \mathrm{CEF}(1) + \mathrm{CSF}(60) - \mathrm{CSW}(t) \tag{4}$$

$$\mathrm{CBC}(t) = \mathrm{CEFc}(1) + \mathrm{CSF}(60) - \mathrm{CSF}(60+t) \tag{5}$$

Here, CBT(t) denotes the net carbon balance (t-C/dam) in the timber check dam during the evaluation period for t year(s). r, nr, e, and ne describe a scenario of reforestation, no reforestation, energy use, and no energy use, respectively. CBC(t) denotes the net carbon balance (t-C/dam) in the concrete check dam during the evaluation period for t year(s). CEF(1) represents the amount of carbon emissions (t-C/dam) derived from fossil fuel consumption in the life cycle of the timber dam at the time of dam construction, while CEFc(1) represents that of the concrete dam (t-C/dam). CRR(1) indicates the amount of carbon emission reductions (t-C/dam) associated with replacing fossil fuels with forest-residue- and sawmill-residue-based energy use. CSF(t) denotes the carbon stock (t-C/dam) in the forest t year(s) after reforestation. CSF(60) expresses the carbon stock (t-C/dam) in the forest consisting of 60-year-old trees at the time of harvesting, indicating a baseline for carbon stock. CSF($60 + t$) denotes the subsequent carbon stock (t-C/dam) in the forest t year(s) after the harvesting of 60-year-old trees did not take place. CSW(t) shows the carbon stock (t-C/dam) in the wood (squared timber) t year(s) after the dam was built.

We assumed that harvesting, reforestation, and dam construction will be conducted in the first year ($t = 1$) of the evaluation period because the harvesting process was the first (resource extraction) process of the life cycle, and the baseline for carbon stocks was set at the time of harvesting in this study. In addition, it is possible to conduct harvesting, reforestation, and dam construction in the same year. The use of forest-residue- and sawmill-residue-based energy was also set to start in the first year ($t = 1$) of the evaluation when harvesting takes place. The following sections explain the details of the calculation methods for each variable.

Carbon stocks in wood

The calculation equations for the carbon stock in wood (t-C/dam) are described in the following equations:

$$\mathrm{CSW}(t) = \mathrm{SW}(t) \times d \times c \tag{6}$$

$$\mathrm{SW}(t) = [w(t-1) - b \times 2] \times [h(t-1) - b \times 2] \times l \times n \tag{7}$$

Here, SW(t) denotes the wood stock (m^3/dam) t years after the dam construction, d represents the bulk density (t/m^3), c indicates the carbon content rate (t-C/t), $w(t-1)$ describes the width of one squared timber (m) found at each area (dam body, wing, front apron areas) $t-1$ years after the dam construction, b represents the thickness of annual biodegradation (m) in one squared timber found at each area, $h(t-1)$ means the height of one squared timber (m) found at each area $t-1$ years after the dam construction, l expresses the length of one squared timber found at each area (m), and n denotes the number of squared timbers found at each area.

As coefficients of sugi, 0.314 t/m^3 and 0.500 t-C/t [17] were adapted for the bulk density (d) and the carbon content rate (c), respectively. The width [$w(1)$] and the height [$h(1)$] of the squared timber at the time of the dam construction ($t = 1$) are 0.300 and 0.250 m [8], respectively, at all areas, while the length (l) of the wood ranges from 0.600 to 3.600 m [8] depending on each area. The total number of squared timbers (n) is 1083 [8] when combining each area. A total of 189.90 m^3 of squared timbers per dam [SW(1)] was used in the construction of the timber check dams in this study.

The information contained in Dang et al. [18], who surveyed the decayed rates of sugi at four timber dams, was used for the thickness of the annual biodegradation in wood—the rate of biodegradation (b). It was set at 0.001 and 0.002 m, respectively, for the squared timber at the dam body, which is considered to be constantly affected by running water, and the squared timber at the wing and the front apron of the dam, which is considered to be either completely unaffected or affected occasionally by running water. With regard to the rate of biodegradation of wood, methods using the weight loss rate are generally used in the research fields of wood preservation. For civil engineering structures such as timber dams, a survey of weight loss for wood used on the site requires destruction of the structures, meaning it is not realistic. Some results of experiments using the weight loss rate were reported [19, 20]. However, because the wood elements for the samples used in those studies were much smaller than the squared timbers used in the timber dams, the weight loss rate in those studies could be overestimated. Moreover, because the experiments were based on a compulsive decay method, environmental conditions were considerably different from those for the timber dams. For these reasons, we decided that it was undesirable to apply the results of those experiments to this study. Therefore, we applied the results from Dang et al. [18], who used a "Resistograph®" apparatus that is commonly used as a practical survey device to measure wood decay on the site. In the study [18], the Resistograph® was used to drill directly into the timbers, and measure the drilling resistance (torque) of a fine needle as it penetrates the timbers with constant rotational speed and constant advance. The drilling resistance value was used to judge the depth of the decayed part [21]. Relatively high resistance values indicate soundwood, while low values suggest decay or other defects [22].

Moreover, for the reason mentioned in "Scope of the carbon balance evaluation", this study did not take the replacement of squared timbers in the maintenance process into consideration, and the subsequent changes in the wood stock were evaluated at the time of dam construction.

Additionally, it was assumed that forest residues such as branches and leaves generated from harvesting, and sawmill residues such as saw dust produced upon sawing, are pyrolyzed immediately by energy use or waste disposal. Therefore, these residues will not be considered part of the carbon stocks.

Carbon stocks in the forest

The calculation equations for the carbon stock in the forest (t-C/dam) are described in the following equations:

$$\mathrm{CSF}(t) = \mathrm{SF}(t) \times \mathrm{bef} \times d \times c \tag{8}$$

$$\mathrm{SF}(t) = A \times \mathrm{sf}(t) \tag{9}$$

$$A = \mathrm{SW}(1)/y_\mathrm{r}/y_\mathrm{s}/\mathrm{sf}(60) \tag{10}$$

Here, SF(t) denotes the forest growing stock (stem volume) (m^3/dam) t years after reforestation, bef represents a biomass expansion factor, A indicates the area of reforestation (=the area of tree harvesting) (ha/dam), sf(t) describes the forest growing stock (stem volume) (m^3/ha) per unit area t years after reforestation, y_r denotes the yield of sawing a log to the squared timber used for the dam, while y_s denotes the yield from a tree stem to a log, and sf(60) represents the forest growing stock (stem volume) (m^3/dam) per unit area of 60-year-old trees at the time of harvesting.

It was assumed that the type of trees used for reforestation is sugi, since it is the same type as the trees that are harvested. Since a biomass expansion factor (bef) is a coefficient used to expand the volume of tree stems to the volume of the entire tree, including branches and leaves (above-ground biomass), this study referred to the numerical value of 1.230 [17] used for sugi trees. Additionally, tree roots are not included in the above-ground biomass.

The forest growing stock [sf(t)] per unit area is adapted from the numerical value based on the sugi yield tables (which show the relationship between tree age and the standing tree volume per unit area) for the Tohoku region (on the Sea of Japan side), which includes Akita Prefecture [23]. The yield of sawing a log to the squared timber used for the dam (y_r) is set at 0.640, as calculated from the previous study [8], while the yield of processing the tree stem to a log (y_s) is set at 0.856 [16]. The forest growing stock per unit area of 60-year-old trees [sf(60)] is defined as 501 m^3/ha, adapted from the sugi yield tables [23].

Carbon emission reductions associated with replacing fossil fuels by forest-residue- and sawmill-residue-based fuel use

The calculation equations for the amount of carbon emission reduced by forest-residue- and sawmill-residue-based energy use (t-C/dam) are described in Eqs. (11–13). Additionally, in this study it was assumed that heavy crude oil is the fossil fuel to be replaced by forest-residue- and sawmill-residue-based energy use.

$$\mathrm{CRR}(1) = \mathrm{RR}(1) \times e_h \tag{11}$$

$$\mathrm{RR}(1) = \mathrm{GR}(1) \times d \times \mathrm{cal}_w/\mathrm{cal}_h \tag{12}$$

$$\mathrm{GR}(1) = \mathrm{SW}(1)/\,y_r/\,y_s \times \mathrm{bef} - \mathrm{SW}(1) \tag{13}$$

Here, RR(1) denotes the quantity of fossil fuels (l/dam) replaced by forest-residue- and sawmill-residue-based fuels at the time of harvesting, e_h represents a carbon emission coefficient (t-C/l) associated with the combustion of heavy crude oil, GR(1) describes the quantity of forest residues and sawmill residues generated by harvesting and sawing (m^3/dam), cal_w expresses the caloric value of wood (GJ/t), and cal_h denotes the caloric value of heavy crude oil (GJ/l).

The carbon emission coefficient (e_h) associated with the combustion of heavy crude oil was set at 0.000739 (t-C/l) [24]. The caloric value of the wood (cal_w) and the caloric value of the heavy crude oil (cal_h) were set at 14.400 (GJ/t) and 0.039 (GJ/l) [24], respectively. We assumed that forest and sawmill residues are used for heat generation, and heat generated from heavy crude oil is displaced with that from the residues. Differences in heat conversion efficiency between wood and heavy crude oil were not included in this study.

Carbon emissions derived from fossil fuel consumption in the life cycle of a timber check dam and a concrete check dam

The amount of carbon emissions in the life cycle of a timber check dam [CEF(1)] (t-C/dam) and a concrete check dam [CEFc(1)] (t-C/dam) was adapted from the amount of carbon emissions derived from fossil fuel consumption in the material production process (the process ranging from resource extraction to manufacturing in Fig. 2) and the construction process (the construction process in Fig. 2) mentioned in the previous study [8]. Additionally, the maintenance process was excluded from the target of evaluation on the amount of carbon emissions since this study does not take repairs into consideration due to the reasons mentioned previously. The disposal process was also not considered for the target of evaluation since the check dams are usually not removed or disposed of, as discussed previously. Therefore, this study adapted 20 t-CO_2/dam (material production process: 16 and construction process: 4) for the timber check dam and 45 t-CO_2/dam (material production process: 44 and construction process: 1) for the concrete check dam, and then converted it to the carbon content by multiplying the figure obtained from dividing the atomic weight of carbon by the molecular weight of carbon dioxide (=12/44).

Regarding silviculture along with reforestation after wood harvesting, the carbon emissions from fossil fuel consumption (due to site preparation, planting, weeding, cleaning, pruning, and thinning) were negligibly small (less than 3 % of total emissions in the life cycle of round wood production) [25], therefore emissions from the silviculture process were not included.

Results and discussion

Carbon stocks in the wood and the forest

Figure 4 shows the evaluation results on carbon stocks in the wood and the forest [CSW(t), CSF(t), CSF(60 + t)]. The quantitative relationship between the carbon stock in the wood used for the dam [CSW(t): "Wood (used for the dam)" in Fig. 4] and the forest carbon stock due to reforestation after harvesting [CSF(t): "Forest (reforestation after harvesting)" in Fig. 4] became reversed when the evaluation period reached 22 years or beyond. Additionally, the area of harvesting and reforestation in the forest is 0.681 ha/dam. This study also revealed that most of the carbon stock in the wood disappears around 100 years after the dam construction. The carbon stock in the wood used in both the dam wings and the front apron became zero after 63 years. However, this result is based on the average wood biodegradation speed (refer to "Carbon stocks in wood") at check dams in Japan. Therefore, it is important to note that the result varies depending on the characteristics (such as variations in durability) of each wood, and various environmental conditions (such as the extent of the impact from running water, and periods of temperature under which wood-rotting fungi can act). Moreover, the concept of decayed thickness, based on the assumption that

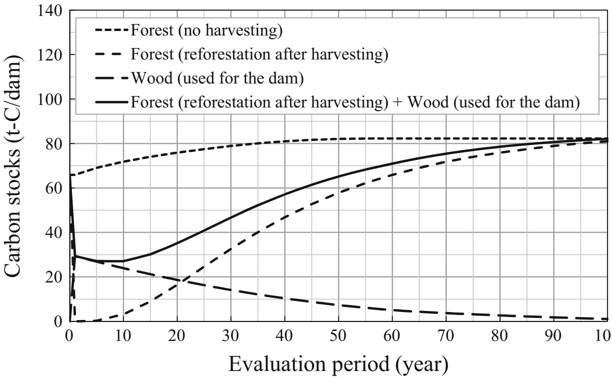


Fig. 4 Carbon stocks in the wood and the forest

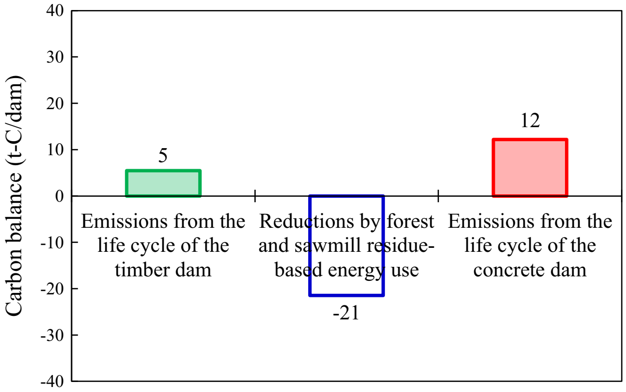


Fig. 5 Fossil-fuel-derived carbon balance (+value: emissions, −value: reductions)

the decay proceeds equally from the surface toward the inside of the squared timber, cannot explain clearly the mechanism of wood biodegradation. Because there have been no prior studies focused on biodegradation for a timber dam from a long-term perspective, an important challenge in the near future will be to investigate a more detailed biodegradation rate for the timber dam.

Focusing on the implementation of reforestation revealed that the carbon stock for the scenario with reforestation [“Forest (reforestation after harvesting) + Wood (used for the dam)” in Fig. 4] progresses at a greater level than that for the scenario without reforestation [“Wood (used for the dam)” in Fig. 4], and that the difference in the carbon stock between the two scenarios widened as the evaluation period was extended. However, both scenarios never exceeded the carbon stock in the forest without harvesting for 100 years [CSF(60 + t): “Forest (no harvesting)” in Fig. 4]. Yet, for the scenario with reforestation, the gap with the scenario without harvesting in the forest becomes narrower as time passes. When the evaluation period exceeds 100 years, the carbon stock for both scenarios reaches an almost identical level and remains in a saturated state.

The baseline level for the carbon stock was set 66 t-C/dam at the time of harvesting in the existing forests (refer to “The baseline for carbon stocks”). The carbon stock with reforestation scenario exceeded the baseline when the evaluation period reached 52 years or longer, while that without reforestation scenario was smaller than the baseline level throughout the entire evaluation period. The carbon stock without harvesting exceeded the baseline over the entire period.

Fossil-fuel-derived carbon emissions and carbon emission reductions

Figure 5 shows the evaluation results of the fossil-fuel-derived carbon balance [CEF(1), CRR(1), CEFc(1)]. The carbon emissions from the life cycle of the timber check dam [CEF(1)] are about 5 t-C/dam, which are less than half of those from the concrete check dam [CEFc(1)]. On the other hand, approximately 21 t-C/dam of carbon emission reductions [CRR(1)] can be expected from substituting fossil fuels with the forest-residue- and sawmill-residue-based energy use, resulting in reductions about four times greater than the carbon emissions. Approximately, 16 (=21–5) t-C/dam of net reductions can be expected upon offsetting the carbon emissions. While forest-residue- and sawmill-residue-based energy use are assumed to substitute for heavy crude oil in this study, the carbon emission reductions would increase to approximately 26 t-C/dam if coal was assumed to be substituted, making it possible to achieve a net reduction of about 21 (=26–5) t-C/dam. However, it should be noted that the results might vary when considering the differences in heat conversion efficiency between wood and fossil fuels, and nitrous oxide (N_2O) emissions from the combustion of wood [16].

Carbon balance

Figure 6 shows net carbon balance evaluation results [Eqs. (1–5)] for each reforestation scenario and energy use scenario (more detailed results were shown in Table 1). The

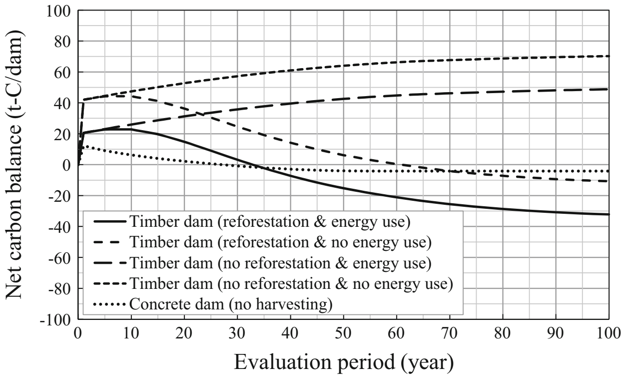


Fig. 6 Net carbon balance (+value: emissions, −value: reductions)

Table 1 The evaluation results of the carbon balance

Evaluation period (year)	Timber dam (reforestation and energy use) (t-C/dam)					Timber dam (reforestation and no energy use) (t-C/dam)				
	Stocks in the wood[a]	Stocks in the forest[b]	Emissions[c]	Emission reductions[d]	Net carbon balance[e]	Stocks in the wood[a]	Stocks in the forest[b]	Emissions[c]	Emission reductions[d]	Net carbon balance[e]
1	−29.341	65.889	5.463	−21.463	20.547	−29.341	65.889	5.463	–	42.011
5	−26.861	65.626	5.463	−21.463	22.765	−26.861	65.626	5.463	–	44.228
10	−23.931	62.732	5.463	−21.463	22.801	−23.931	62.732	5.463	–	44.264
15	−21.192	56.946	5.463	−21.463	19.754	−21.192	56.946	5.463	–	41.217
20	−18.642	49.449	5.463	−21.463	14.807	−18.642	49.449	5.463	–	36.270
25	−16.283	41.296	5.463	−21.463	9.012	−16.283	41.296	5.463	–	30.475
30	−14.114	33.273	5.463	−21.463	3.159	−14.114	33.273	5.463	–	24.622
35	−12.135	25.777	5.463	−21.463	−2.358	−12.135	25.777	5.463	–	19.105
40	−10.345	19.070	5.463	−21.463	−7.276	−10.345	19.070	5.463	–	14.187
45	−8.746	13.151	5.463	−21.463	−11.595	−8.746	13.151	5.463	–	9.868
50	−7.337	8.022	5.463	−21.463	−15.315	−7.337	8.022	5.463	–	6.148
55	−6.118	3.682	5.463	−21.463	−18.436	−6.118	3.682	5.463	–	3.027
60	−5.089	0.000	5.463	−21.463	−21.090	−5.089	0.000	5.463	–	0.374
65	−4.299	−3.156	5.463	−21.463	−23.456	−4.299	−3.156	5.463	–	−1.993
70	−3.717	−5.918	5.463	−21.463	−25.636	−3.717	−5.918	5.463	–	−4.173
75	−3.177	−8.154	5.463	−21.463	−27.331	−3.177	−8.154	5.463	–	−5.867
80	−2.677	−9.995	5.463	−21.463	−28.672	−2.677	−9.995	5.463	–	−7.209
85	−2.218	−11.573	5.463	−21.463	−29.791	−2.218	−11.573	5.463	–	−8.328
90	−1.800	−13.020	5.463	−21.463	−30.820	−1.800	−13.020	5.463	–	−9.357
95	−1.423	−14.204	5.463	−21.463	−31.627	−1.423	−14.204	5.463	–	−10.163
100	−1.087	−15.111	5.463	−21.463	−32.198	−1.087	−15.111	5.463	–	−10.735

Evaluation period (year)	Timber dam (no reforestation and energy use) (t-C/dam)					Timber dam (no reforestation & no energy use) (t-C/dam)				
	Stocks in the wood[a]	Stocks in the forest[b]	Emissions[c]	Emission reductions[d]	Net carbon balance[e]	Stocks in the wood[a]	Stocks in the forest[b]	Emissions[c]	Emission reductions[d]	Net carbon balance[e]
1	−29.341	65.889	5.463	−21.463	20.547	−29.341	65.889	5.463	–	42.011
5	−26.861	65.889	5.463	−21.463	23.028	−26.861	65.889	5.463	–	44.491
10	−23.931	65.889	5.463	−21.463	25.957	−23.931	65.889	5.463	–	47.421
15	−21.192	65.889	5.463	−21.463	28.696	−21.192	65.889	5.463	–	50.160
20	−18.642	65.889	5.463	−21.463	31.246	−18.642	65.889	5.463	–	52.709
25	−16.283	65.889	5.463	−21.463	33.605	−16.283	65.889	5.463	–	55.069
30	−14.114	65.889	5.463	−21.463	35.774	−14.114	65.889	5.463	–	57.238
35	−12.135	65.889	5.463	−21.463	37.754	−12.135	65.889	5.463	–	59.217
40	−10.345	65.889	5.463	−21.463	39.543	−10.345	65.889	5.463	–	61.006
45	−8.746	65.889	5.463	−21.463	41.142	−8.746	65.889	5.463	–	62.605
50	−7.337	65.889	5.463	−21.463	42.551	−7.337	65.889	5.463	–	64.015
55	−6.118	65.889	5.463	−21.463	43.770	−6.118	65.889	5.463	–	65.234
60	−5.089	65.889	5.463	−21.463	44.799	−5.089	65.889	5.463	–	66.263
65	−4.299	65.889	5.463	−21.463	45.589	−4.299	65.889	5.463	–	67.052
70	−3.717	65.889	5.463	−21.463	46.171	−3.717	65.889	5.463	–	67.634
75	−3.177	65.889	5.463	−21.463	46.712	−3.177	65.889	5.463	–	68.175
80	−2.677	65.889	5.463	−21.463	47.212	−2.677	65.889	5.463	–	68.675
85	−2.218	65.889	5.463	−21.463	47.671	−2.218	65.889	5.463	–	69.134
90	−1.800	65.889	5.463	−21.463	48.089	−1.800	65.889	5.463	–	69.552
95	−1.423	65.889	5.463	−21.463	48.466	−1.423	65.889	5.463	–	69.929
100	−1.087	65.889	5.463	−21.463	48.802	−1.087	65.889	5.463	–	70.265

Table 1 continued

Evaluation period (year)	Concrete dam (no harvesting) (t-C/dam)		
	Stocks in the forest[f]	Emissions[g]	Net carbon balance[e]
1	0.000	12.178	12.178
5	−3.156	12.178	9.022
10	−5.918	12.178	6.260
15	−8.154	12.178	4.024
20	−9.995	12.178	2.183
25	−11.573	12.178	0.605
30	−13.020	12.178	−0.842
35	−14.204	12.178	−2.025
40	−15.111	12.178	−2.933
45	−15.769	12.178	−3.590
50	−16.176	12.178	−3.998
55	−16.334	12.178	−4.156
60	−16.334	12.178	−4.156
65	−16.334	12.178	−4.156
70	−16.334	12.178	−4.156
75	−16.334	12.178	−4.156
80	−16.334	12.178	−4.156
85	−16.334	12.178	−4.156
90	−16.334	12.178	−4.156
95	−16.334	12.178	−4.156
100	−16.334	12.178	−4.156

[a] Carbon stocks in the wood {[−CSW(t)] in Eqs. (1–4))}

[b] Carbon stocks in the forest {[CSF(60) − CSF(t)] in Eqs. (1–4)}

[c] Carbon emissions derived from fossil fuel consumption in the life cycle of the timber check dam {[CEF(1)] in Eqs. (1–4)}

[d] Carbon emission reductions from substituting fossil fuels with the forest-residue- and sawmill-residue-based energy use {[−CRR(1)] in Eqs. (1–4)}

[e] Net carbon balance {Eqs. (1–5)}

[f] Carbon stocks in the forest {[CSF(60) − CSF(60 + t)] in Eq. (5)}

[g] Carbon emissions derived from fossil fuel consumption in the life cycle of the concrete check dam {[CEFc(1)] in Eq. (5)}

results revealed that the net carbon balance would be either on the emission side (+value) or the reduction side (–value), depending on the implementation of reforestation and the use of forest-residue- and sawmill-residue-based energy, causing a significant difference ranging from the carbon emissions of 70 t-C/dam ["Timber dam (no reforestation and no energy use)" in Fig. 6] to the carbon reductions of 32 t-C/dam ["Timber dam (reforestation and energy use)" in Fig. 6] at most in the evaluation period of 100 years.

Examining the reforestation scenario showed that the carbon emission reductions become greater for the scenario with reforestation as the evaluation period is extended, while no carbon emission reductions were realized for the scenario without reforestation throughout the evaluation period of 100 years, and carbon emissions occurred instead. Reforestation in the forest after harvesting is essential despite the differences in the energy use scenarios in to achieve carbon emission reductions. Reviewing the energy use scenario revealed that the starting time of carbon emission reduction effects varies depending on whether the energy use is actually implemented, even though it does not have as strong an impact on the results as the reforestation scenario. Moreover, a comparison between the scenario with or without reforestation and the scenario with or without energy use revealed the characteristic that carbon emission reduction effects become greater for the scenario with reforestation as the evaluation period is extended, while a constant level of carbon emission effects can be expected in both short-term and long-term periods for the scenario with energy use.

The timber dam for each scenario is compared to the concrete dam ["Concrete dam (no harvesting)" in Fig. 6], and then we examined the carbon emission reduction effects by substituting the concrete dam with the timber dam. Reforestation after harvesting is essential to achieve carbon emission reduction effects by substituting with the timber dam. Then, with energy use, carbon emission reduction effects can be expected after an evaluation period of 35 years ["Timber dam (reforestation and energy use)" in Fig. 6]. On the other hand, the effects cannot be achieved until the evaluation period of 70 years ["Timber dam (reforestation and no energy use)" in Fig. 6] without the energy use.

For the scenario with reforestation and energy use, approximately 11 [=−4–(−15)] t-C/dam and 28 [=−4–(−32)] t-C/dam of carbon emission reduction effects can be expected for the evaluation periods of 50 and 100 years, respectively. These results demonstrated that the carbon emission reduction effects in these scenarios are greater than the carbon emission reductions of approximately 7 (=12–5) t-C/dam associated with substituting the concrete dam with the timber dam, which takes only fossil fuel consumption into consideration. In other words, from mid- to long-term perspectives, carbon emission reduction effects will be greater by taking the carbon balance of the wood into consideration based on the premise that reforestation and energy use will be implemented rather than targeting only fossil fuel consumption.

Conclusions

Targeting a timber check dam, this study evaluated the carbon balance of the life cycle of wood by considering the changes in the carbon stocks related to the wood and the forest over time. Moreover, we examined the carbon emission reduction effects by substituting a concrete check dam (a typical non-timber check dam) with the timber check dam. The following describes the main points obtained from the study:

(a) The carbon stock in the wood used for the dam disappears almost completely about 100 years after the dam construction. On the other hand, the carbon stock in the forest declines due to harvesting and then increases again due to subsequent reforestation. The quantitative relationship with the carbon stock in the wood becomes reversed after an evaluation period of 22 years.

(b) In the fossil-fuel-derived carbon balance, carbon emission reductions from using forest-residue- and sawmill-residue-based energy are approximately four times greater than carbon emissions from the life cycle of a timber dam. Additional reduction effects can be expected upon offsetting the carbon emissions.

(c) The net carbon balance can be either on the emission side or the reduction side, depending on the implementation of reforestation after harvesting, the use of forest-residue- and sawmill-residue-based energy, and the evaluation period, causing a significant difference ranging from 70 t-C/dam of emissions to 32 t-C/dam of reductions at most. The results would vary considerably depending on which framework is used to conduct an evaluation.

(d) Post-harvesting reforestation is essential to achieve net carbon emission reduction effects by substituting the concrete check dam with the timber check dam. The net carbon emission reduction effects become greater for the scenario with reforestation as the evaluation period is extended, while a constant level of carbon emission effects can be expected in both short-term and long-term periods for the scenario with energy use.

(e) Net carbon emission reductions per dam can be expected after an evaluation period of 35 years, and 28 t-C/dam of those can be obtained during an evaluation period of 100 years by substituting a concrete dam with a timber dam based on the premise that reforestation and energy use are implemented. From the mid- to long-term standpoints, carbon emission reduction effects are greater when considering the wood- and forest-related carbon balance compared to when targeting only fossil fuel consumption.

An important challenge in future study is to investigate the biodegradation speed of wood. Areas for future study include considering the differences in energy conversion efficiency between wood and fossil fuels, and GHGs (such as N_2O and CH_4) as a whole rather than CO_2 alone. A future task is to conduct a similar carbon balance evaluation for wooden-based structures other than timber check dams and then investigate the carbon emission reduction effects. Moreover, since this study was focused on Akita Prefecture as a target region, it is likely that regional characteristics are reflected in the study results. It is also an important task to examine other regions or the entire country of Japan in the future.

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