J Wood Sci (2014) 60:461–472
DOI 10.1007/s10086-014-1423-1

ORIGINAL ARTICLE

Evaluation of CO_2 emissions reductions by timber check dams and their economic effectiveness

Ryu Noda · Chihiro Kayo · Takanobu Sasaki · Shinya Takaoku

Received: 6 March 2014 / Accepted: 7 July 2014 / Published online: 7 August 2014

Abstract We calculated the life cycle CO_2 emissions and direct installation costs for two types of timber check dams (all-wood timber and hybrid timber) developed in Akita Prefecture and non-timber check dams (concrete and steel). Additionally, we evaluated the effect of timber check dams in reducing CO_2 emissions and their economic efficiency compared with non-timber check dams. We found that switching from concrete to all-wood timber and hybrid timber check dams reduced CO_2 emissions by 54 and 43 %, respectively. Switching from steel to all-wood timber and hybrid timber check dams reduced CO_2 emissions by 28 and 11 %, respectively. In terms of direct installation costs, all-wood timber check dams were 241 % that of concrete check dams and 179 % that of steel check dams, but hybrid timber check dams were only 132 and 98 %, confirming that they could be competitive in terms of price. From the perspective of reducing CO_2 emissions costs, we found that a policy for switching from concrete to all-wood or hybrid timber check dams did not constitute a low-cost means of reducing CO_2 emissions, compared with other policies for reducing CO_2 emissions.

Keywords Check dam · Life cycle assessment (LCA) · Carbon dioxide emissions · Economic efficiency · Akita Prefecture

R. Noda
Faculty of Agriculture, Graduate School of Kyushu University,
6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
e-mail: noda.ryu.008@m.kyushu-u.ac.jp

C. Kayo (✉)
Department of Environment Conservation, Graduate School of
Agriculture, Tokyo University of Agriculture and Technology,
3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan
e-mail: kayoc@cc.tuat.ac.jp

T. Sasaki
Institute of Wood Technology, Akita Prefectural University,
11-1 Kaieizaka, Noshiro, Akita 016-0876, Japan
e-mail: taka@iwt.akita-pu.ac.jp

S. Takaoku
Kyoto Prefectural Government Forest Conservation Division,
Shimotachiuri-dori Shinmachi-nishiiru Yabunouchi-cho,
Kamigyo-ku, Kyoto 602-8570, Japan
e-mail: s-takaoku34@pref.kyoto.lg.jp

Introduction

Recent years have seen calls for the effective use of timber by forestry civil engineering businesses from the viewpoints both of measures to deal with global warming and the fact that the trees planted during the post-war period in Japan are now mature and ready for use. In particular, check dams, which are constructed to prevent the flash flooding and erosion of mountain streams, have a volume that may reach several hundred cubic meters. As such, if timber could be used for their construction, the use of large amounts of wood would be anticipated. Timber consumes less energy and produces less CO_2 emissions during the production process compared with alternative materials such as steel and aluminum [1], and its use as a substitute for other materials may thus contribute to alleviating global warming. Effectively utilizing a moderate number of trees that are mature and ready for use would also result in appropriate forest management, and maintaining forests in a good state of growth might help prevent damage due to intense rainfall, which has become more frequent in recent years. Against this backdrop, Akita Prefecture has been engaged in the research and development of all-wood timber check dams made from timber and connectors alone

(Fig. 1a), as well as hybrid timber check dams made from a steel frame containing thinnings obtained during forest management as a filler (Fig. 1b) [2, 3, 4].

Investigation of the effectiveness of replacing other materials with timber in alleviating global warming requires the concept of life cycle assessment (LCA), which takes into account the environmental burden of a product throughout its entire life cycle, from resource extraction through product manufacture and use to disposal. Various studies using the LCA method have already been carried out with respect to the reduction in life cycle CO_2 emissions achieved through the use of timber. Previous studies of structures other than check dams include Jönsson et al.'s [5] evaluation of the life cycle CO_2 emissions and other environmental effects of linoleum, vinyl, and wood as flooring materials. Börjesson and Gustavsson [6] compared the life cycle energy consumption and greenhouse gas (GHG) emissions of wooden and concrete building construction. Petersen and Solberg [7] compared the life cycle energy consumption, GHG emissions, and cost of the use of laminated wood and steel in the construction of Oslo airport. Kayo et al. [8] compared the life cycle of GHG emissions from a sand compaction pile, cement deep mixing, and a log pile, which are used as measures against soil liquefaction.

As yet, however, no peer-reviewed academic study has performed an LCA of check dams, and there has not been any adequate investigation of the extent to which the use of timber in check dams might be expected to reduce CO_2 emissions. Although conference presentations have been made by Takaoku et al. [9], Noda et al. [10], and Hosokawa et al. [11], these have only compared timber and concrete as materials, without taking account of the fact that timber construction may involve several different methods of construction, nor has any comparison been made with check dams made of steel or other materials apart from concrete. The functional units that must be made consistent to enable the comparison of different construction methods in LCAs are also unclear; it is possible that appropriate evaluation is not being performed.

In light of these problems with previous studies, in the present study we designed check dams to prevent the same volume of sediment runoff in the same location to ensure consistency of functional units, and investigated concrete check dams, which have a long track record of construction, steel check dams, and the two types of timber check

Fig. 1 Types of check dam **a** All-wood timber check dam, **b** hybrid timber check dam, **c** Concrete check dam, **d** Steel check dam

dams developed in Akita Prefecture (all-wood timber and hybrid timber). We then carried out a comparative evaluation of life cycle CO_2 emissions, and investigated the effectiveness of timber check dams in reducing CO_2 emissions compared with non-timber check dams. We also analyzed the economic efficiency of each type of check dam, with the aim of conducting a comprehensive evaluation that takes into account economic as well as environmental perspectives, and considered the advantages of and issues with timber check dams.

Overview of the check dams studied

What is a check dam?

A check dam is a forestry civil engineering structure that prevents flash flooding and slope failure along the banks of mountain streams by smoothing out the gradient of the stream bed and moderating water flow, thus preventing erosion and stopping unstable sediment that has deposited on the stream bed from being swept downstream from streams that have undergone or are at risk of flash flooding. The check dams that were the subjects of this study are described below.

All-wood timber check dams

All-wood timber check dams (Figs. 1a, 2) are structures made by squared-off timbers of width 300 mm, height 250 mm, and length 600–3600 mm alternately along and crosswise to the orientation of the dam, and fastening these timbers together vertically with 460 mm long connectors in a zigzag fashion to form the dam body. They utilize large-diameter timbers with a top end diameter of over 300 mm, for which there is little demand as construction material, meaning that they are forestry civil engineering structures that can contribute to the effective utilization of mature trees producing large-diameter timber. Metal fittings called “lag screws” (16-mm diameter) are used as connectors at sites where the dam body is subject to a tensile load, and wing parts that are expected to exchange timber for repairs. On the other hand, steel bars (the reinforcing bars in reinforced concrete, known as “D 16 mm”) are used at other sites. In Akita Prefecture, a front apron (Fig. 1a) must be installed when an all-wood timber check dam is built, to prevent scouring on the downstream side of the structure by the flow of water from the upstream side.

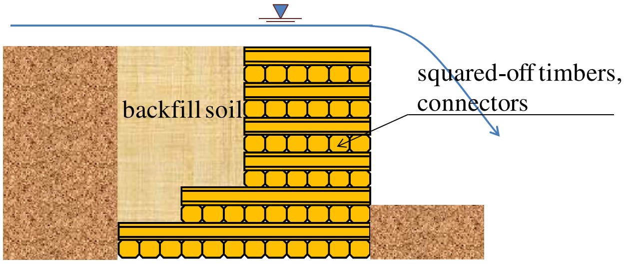

Fig. 2 All-wood timber check dam cross-sectional diagram

Hybrid timber check dams

Hybrid timber check dams (Figs. 1b, 3) are constructed by putting together an external frame made of steel and bolts, which is then stuffed with thinnings with bark, large amounts of which are generated during forest management, as a filler. Crushed stone (particle size specification c-40) is then used to stop up the gaps between the timbers. As for all-wood timber check dams, the objective of hybrid timber check dams is to make the most effective use of resources, and the size of the thinnings used as filler is therefore left unspecified. Only low-level processing is required to cut the timber to the prescribed length, and almost no waste ends are generated in preparing it for use.

As shown in Fig. 3, squared-off timbers (dressed on three sides) are placed upstream and downstream of the dam body with no gaps between them as walling materials to prevent the filling material being washed away. These dams are also constructed so that extra walling material can be added on the downstream side, to take account of the fact that the filling material may be washed away as a result of future rotting of the walling material due to biodegradation.

Concrete check dams

Concrete check dams (Fig. 1c) are the most common structural type of check dam, as they are both highly durable and appropriate for gravity-type structures that function by weight. Conventionally, the construction of concrete check dams formerly involved the use of a steel form into which concrete was cast and cured, then the form was removed. Since the Act for Promotion of the Use of Wood in Public Buildings (2010, Law no. 36) [12] was put

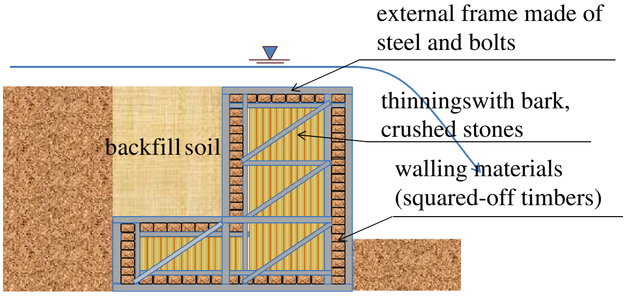

Fig. 3 Hybrid timber check dam cross-sectional diagram

Fig. 4 Concrete check dam with timber forms left in place

into force in October 2010, however, wooden forms that are left in place have been used as the forms for all concrete check dams in Akita Prefecture (Fig. 4). In this study, we looked at two types of concrete check dam design: those for which the forms are removed (Fig. 1c, "concrete check dams (without forms)") and those for which the forms are left in place (Fig. 4, "concrete check dams (with forms)").

Steel check dams

Steel check dams (Fig. 1d) are generally made by constructing an external frame from steel and bolts, and packing it with a filler consisting of rubble of roughly 150–200 mm in diameter. The structural body itself is lighter in weight than that of concrete check dams, and the fact that its components are fastened together with bolts make the dam body a flexible structure with a high degree of resilience to exposure and submersion. As putting the structural components together mainly involves assembling the steel components and pouring in rubble, without the curing period required for concrete, this type is suited for use when short-term installation is required, such as in times of disaster, and when filling materials such as pebbles and boulders are easily obtainable. It should not be used, however, if there is a risk of a landslide or other impact load.

Materials and methods

Method of evaluating CO_2 emissions

Design of check dams covered by the study

We chose a site at which timber check dams could be installed, and designed timber, concrete, and steel check dams to prevent the same volume of sediment runoff at the same site in order to ensure consistency of functional units. We calculated the use of materials and fuels from the operation of machinery at the construction site for each type of check dam. Table 1 lists the dimensions of each type of check dam, and the materials used and fuel used at the construction site. Variation in the legal requirements (see "All-wood timber check dams" through "Steel check dams") for the installation of different kinds of dams resulted in somewhat different dimensions. Nonetheless, they all prevented the same amount of sediment runoff, ensuring that the functional unit was consistent.

Scope of evaluation and inventory analysis

The life cycle processes evaluated in this study are shown in Fig. 5. The scope of our study included processes from the production of materials and fuels to construction, maintenance, and management. We also calculated the amount of CO_2 emissions derived from fossil fuel consumption in each process. Background data were used for the material and fuel production processes, whereas foreground data were used for the construction process, maintenance, and management process. The disposal process was omitted from this study as none of these types of check dam is generally dismantled and removed. The evaluation period was set at 50 years on the basis of the period of durability for the maintenance and management process described below (see "Maintenance and management process"). The carbon sequestered in timber was not evaluated in this study.

Material and fuel production process

The material and fuel production processes took into account the processes for extracting the resources for materials and fuel (used to operate machinery at the construction site) through to the transport of these resources and their manufacturing processes. CO_2 emissions during each stage of resource extraction, resource transport, and manufacturing processes were calculated by multiplying the amount of each material and fuel used (Table 1) by its corresponding CO_2 emissions conversion factor [13, 14], (Table 2). The figures used for the conversion factors were obtained from the MiLCA Database [13] to assure maximum consistency of the system boundary and the accuracy of the conversion factors among the types of check dam. Because local wood is generally used in the construction of timber check dams, it is desirable to use the conversion factors of squared-off timber based on local conditions. However, such conversion factors are not available in the MiLCA Database; therefore, the values of "Lumber products" category of the database were used. An artificial

Table 1 Sizes of each type of check dam and materials and fuels used

	Unit	Timber		Concrete		Steel
		All-wood	Hybrid	Without forms	With forms	
Structure specifications						
Length	m	21.00	20.00	20.50	20.50	20.00
Height	m	3.00	4.00	4.00	4.00	4.00
Volume	m^3	186.90	156.00	129.40	129.40	132.90
Amount of sediment runoff prevention	m^3	850.00	850.00	850.00	850.00	850.00
Materials used						
Squared-off timber (dressed on four sides)	m^3	186.90	–	–	–	–
Wooden forms	m^3	–	–	–	6.06	–
Thinnings with bark	m^3	–	68.80	–	–	–
Squared-off timber (dressed on three sides)	m^3	–	32.61	–	–	–
Concrete	m^3	–	–	145.78	145.78	–
Artificial lawn	m^2	75.66	71.09	46.58	46.58	70.11
Rubble	t	–	–	–	–	255.60
Crushed stone	t	–	98.28	–	–	–
Steel	t	–	10.05	–	–	12.27
Lag screw	t	1.02	–	–	–	–
Steel bar	t	1.26	–	–	–	–
Vinyl chloride pipe	t	0.23	0.11	0.16	0.16	0.11
Fuels used (light oil)						
Backhoe	L	355.46	450.83	282.66	282.66	1209.77
Truck-mounted crane	L	939.79	27.72	–	–	–
Vibrating roller	L	1.16	1.25	0.81	0.81	0.80
Concrete pump vehicle	L	–	–	22.66	22.66	–
Generator	L	172.94	43.47	71.21	71.21	40.69
Total	L	1469.35	523.27	377.34	377.34	1251.26
Fuels used (gasoline)						
Tamper	L	1.81	1.88	1.23	1.23	1.23
Total	L	1.81	1.88	1.23	1.23	1.23

lawn was not listed in the MiLCA, and therefore the values were obtained from Social Capital LCA Database [14]. The forms used in the construction of concrete check dams (without forms) are removed after construction and reused at other sites several times (although the number of uses is limited), and hence they were not taken into account in CO_2 emissions.

Construction process

The construction process is the process of installing the check dam, divided into three work stages: earthworks (ground excavation, backfilling, etc.), installation (check dam assembly, etc.), and temporary works (stream water drainage, etc.). The construction of roads was not included in the evaluation range. The study covered the CO_2 emissions produced by the combustion of fuel (light oil and gasoline) for the backhoes, truck-mounted cranes, concrete-pump vehicles, generators, and other vehicles used during these various work stages. Fuel use was calculated from the duration of use of each type of machinery with reference to the *Chisan and Forest Road Manual, Quantity Surveying and Construction Volume* [15] (Table 1), and multiplied by the conversion factor for the CO_2 emissions produced by the combustion of each type of fuel [16] to obtain CO_2 emissions. The conversion factors used were 2.59 kg-CO_2/l for light oil and 2.32 kg-CO_2/l for gasoline.

Maintenance and management process

In terms of the period of durability and the period of maintenance and management for each type of check dam, a timber dam constructed in Aomori Prefecture in 1916 has functioned for more than 80 years [17]. In Akita Prefecture

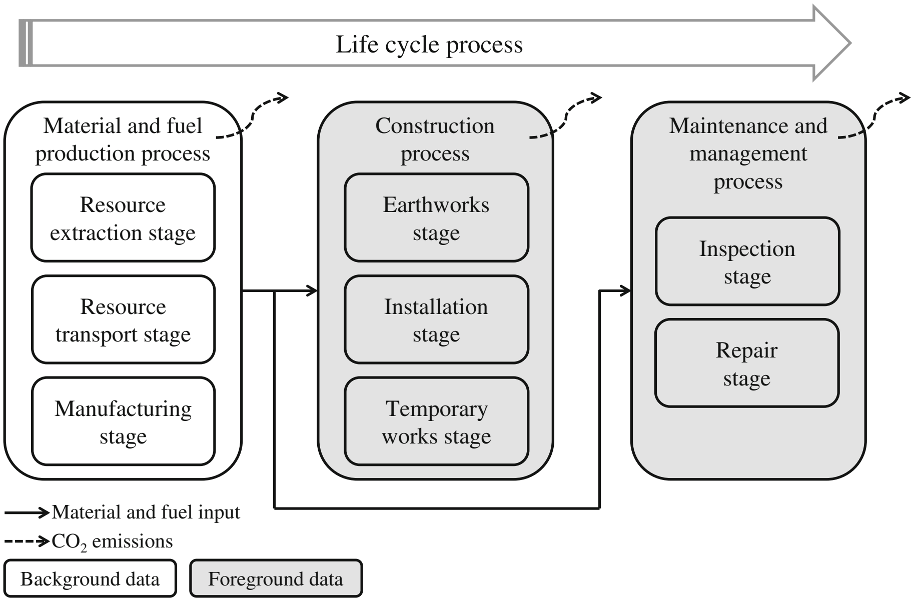

Fig. 5 The life cycle processes evaluated in this study

Table 2 CO_2 emissions conversion factors during the production processes for materials and fuels used in each type of check dam

	Unit	Timber		Concrete		Steel
		All-wood	Hybrid	Without forms	With forms	
Squared-off timber (dressed on four sides)	kg-CO_2/m^3	54.09	–	–	–	–
Wooden forms	kg-CO_2/m^3	–	–	–	238.60	–
Thinnings with bark	kg-CO_2/m^3	–	9.89	–	–	–
Squared-off timber (dressed on three sides)	kg-CO_2/m^3	–	54.09	–	–	–
Concrete	kg-CO_2/m^3	–	–	289.50	289.50	–
Artificial lawn	kg-CO_2/m^2	18.08	18.08	18.08	18.08	18.08
Rubble	kg-CO_2/t	–	–	–	–	11.78
Crushed stone	kg-CO_2/t	–	7.08	–	–	–
Steel	kg-CO_2/t	–	1824.00	–	–	1824.00
Lag screw	kg-CO_2/t	2321.00	–	–	–	–
Steel bar	kg-CO_2/t	860.40	–	–	–	–
Vinyl chloride pipe	kg-CO_2/t	3352.00	3352.00	3352.00	3352.00	3352.00
Light oil	kg-CO_2/L	0.21	0.21	0.21	0.21	0.21
Gasoline	kg-CO_2/L	0.40	0.40	0.40	0.40	0.40

For the materials used, the values for squared-off timber (dressed on four sides) and squared-off timber (dressed on three sides) were taken from the "Lumber products" category of the MiLCA, those for timber (forms left in place) from the "Plywood for general use" category, those for rubble and crushed stone from the "crushed stone" category, steel from the "Hot rolled sheet steel for general use" category, lag screws from the "Bolts/nuts" category, and steel bars from the "Steel bars for general use" category. Other materials are listed in the MiLCA under the same names, and those values have therefore been used

as well, some timber check dams constructed of Akita-grown *Cryptomeria cedar* timber have also maintained their functionality for over 40 years [3]. The *Ministerial Ordinance concerning the Useful Life*, etc. *of Depreciable Assets* [18] states that among structures constructed of steel-framed reinforced concrete or steel-reinforced concrete, water-use dams have a period of durability of 50 years. In this study, we therefore assumed a period of durability of 50 years for all the different types of dam, and set the maintenance and management period as 50 years.

The maintenance and management process is divided into inspection and repair stages. We assumed that inspections would be performed once every 5 years for a total of 10 times for timber check dams, and once every

10 years for a total of 5 times for concrete or steel check dams. CO_2 emissions during inspections were calculated in terms of the gasoline consumption of a light van (1500 cm^3) used by the staff carrying out the inspections. Based on interviews with staff of the Akita Prefecture Management Office, the distance from the Management Office to the dam location was set as 15 km each way, and the time required as 30 min. This was used to calculate gasoline consumption according to the *Chisan and Forest Road Manual*, *Quantity Surveying and Construction Volume* [15] and CO_2 emissions were then calculated according to the same method used for the fuel production and combustion processes, as described above.

For repairs, it was assumed that all-wood timber check dams would require timber replacement every 20 years, and that this would therefore be performed twice. The repair period was set at once every 20 years because at present, 13 years after their installation, the all-wood timber check dams constructed thus far do not yet exhibit sufficient loss of functionality to require repairs, and have been judged not to require repairs for around 20 years. Previous on-site surveys [19, 20, 21] of all-wood timber check dams and other timber check dams have revealed progressive decay in the wings due to repeated drying and submersion. It was therefore assumed that the components requiring replacement would consist of the top layer of timbers in the wings, together with their lag screws (Fig. 6). Because there has been no previous work on hybrid timber check dams, it was assumed that these check dams would require timber replacement every 20 years, as is the case for all-wood timber check dams. This would require that new walling materials equivalent to 40 % of the volume of materials used for the downstream wall would need to be added to the portion of the downstream wall that is exposed above ground (Fig. 7). Concrete and steel check dams are generally constructed so as to be maintenance free, although some steel dams have required repairs owing to corrosion; we assumed that no repairs would be performed. CO_2 emissions during repair were therefore calculated for timber check dams as the emissions during the material manufacturing process for the timber and lag screws to be replaced, by the same method as described above. The timbers replaced during repairs were assumed to be left in the forest rather than disposed of, in line with previous experience.

Method of evaluating economic efficiency

We calculated the cost required to install each type of check dam. This cost was evaluated in terms of direct installation costs, incorporating the costs of both materials and construction. Materials costs comprised the procurement costs of the materials used to construct each type of check dam, including the cost of timber, stone, concrete, and steel. The cost of materials used for repairs during the maintenance and management process was also added. Construction costs comprised the costs of machinery use and labor during the construction of each type of check dam, including the cost of the use of vehicles such as backhoes, truck-mounted cranes, and concrete-pump vehicles as well as the wages of the workers engaged in construction tasks. The types of machinery and days used, as well as the categories of workers and number of working days, were calculated from the construction yardsticks set out by Akita Prefecture [15, 22]. Table 3 shows the unit prices for the materials, machinery, and fuel used.

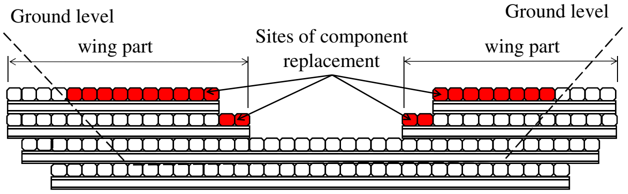

Fig. 6 Sites of component replacement in all-wood timber check dam (*front elevation*)

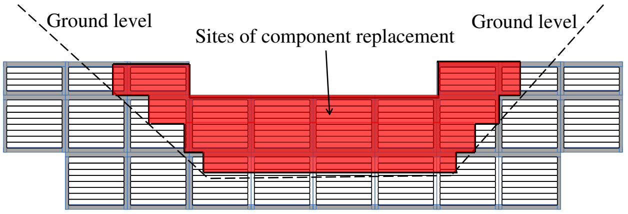

Fig. 7 Sites of component replacement in hybrid timber check dam (*front elevation*)

Results and discussion

Results of evaluation of CO_2 emissions

Table 4 shows the results of the evaluation of CO_2 emissions for check dams during each process. In terms of the different types of construction, CO_2 emissions were lowest for all-wood timber check dams, followed by hybrid timber, steel, concrete (without forms),and concrete (with forms). CO_2 emissions for all-wood timber check dams were 48 % of those for concrete check dams (without forms) and 46 % of those for concrete check dams (with forms), whereas the corresponding figures for hybrid timber check dams were 59 and 57 %, respectively, indicating that switching from concrete check dams to timber check dams would reduce CO_2 emissions. Previous case studies that have evaluated timber and concrete check dams [9,

Table 3 Unit prices of materials, machinery use and fuels

	Unit	Unit prices
Materials used		
Squared-off timber (dressed on four sides)	yen/m^3	36800
Wooden forms	yen/m^3	122375
Thinnings with bark	yen/m^3	3343
Squared-off timber (dressed on three sides)	yen/m^3	30482
Concrete	yen/m^3	10300
Rubble	yen/m^3	3300
Crushed stone	yen/m^3	2500
Artificial lawn	yen/m^2	160
Steel	yen/t	346000
Lag screw	yen/t	1155000
Steel bar	yen/t	63500
Vinyl chloride pipe	yen/t	245000
Construction machinery		
Backhoe	yen/h	4570
Truck-mounted crane	yen/d	24000
Concrete pump vehicle	yen/h	8330
Vibrating roller	yen/d	1560
Tamper	yen/d	520
Generator	yen/d	1105
Fuels		
Light oil	yen/l	121
Gasoline	yen/l	142

Unit prices are the values set by Akita Prefecture as of November 2011. The unit price of timber (forms left in place) has been calculated by converting from the amount per square meter. The unit price of lag screws has been calculated by converting from the amount per screw and the weight (662.6 g/screw)

11], have reported that CO_2 emissions for timber check dams are 47–60 % of those for concrete check dams; the check dams investigated differed from those addressed in this study in terms of factors including method of construction, size, period of durability, and functional units. Although this suggests that a simple comparison is impossible, both sets of results show the same general trend. CO_2 emissions for all-wood check dams and hybrid timber check dams were 72 and 89 %, respectively, of those for steel check dams; this indicates that switching from steel check dams to either type of timber check dam would reduce CO_2 emissions, although the difference between steel and hybrid timber check dams was only slight. A comparison of the two types of timber check dam shows that all-wood timber check dams used 184 % more timber than hybrid timber check dams and produced 81 % of their CO_2 emissions. This reveals that although their structural forms differ, a construction method using large amounts of timber may be expected to result in greater reductions in CO_2 emissions. It is also possible that hybrid timber check dams show greater CO_2 emissions than all-wood timber check dams because they use steel, which entails high CO_2 emissions during the steel production process.

In terms of each separate life cycle process, CO_2 emissions were greatest from the production processes for material and fuel for all types of check dam, accounting for 75 % of the total in all-wood timber check dams and over 90 % of the total in the other types. Focusing on a breakdown of the emissions during the material and fuel production processes, timber, which is used in large quantities in all-wood timber check dams, accounts for over 60 %, and connectors for over 20 %. Steel accounts for over 80 % of hybrid timber check dams and steel check dams. Concrete accounts for over 90 % of concrete check dams, irrespective of the use or otherwise of timber forms. This shows that for steel check dams and concrete check dams, almost all the CO_2 emissions produced during the construction of check dams are generated during the production process for their main materials. The CO_2 emissions per dam volume from the concrete-dam construction process used in this study and that from a previous study [9] were 8.2 and 18.4 kg-CO_2/m^3, respectively; i.e., the emissions were smaller for this study. This is mainly because this study used manpower to build the forms, while the previous study assumed the use of a machine (rough-terrain crane) for the same task. Had the present study also used a machine, the emissions would have increased up to 16.0 (=8.2 + 7.8) kg-CO_2/m^3, which is not significantly different from those obtained in the previous study.

There was little difference between with and without forms, with respect to CO_2 emissions from concrete check dams. Moreover, since wooden forms have been used for all concrete check dams by legal requirements (see "Concrete check dams"), we discuss only the case with forms for concrete check dams from next section.

Results of evaluation of economic efficiency

Figure 8 shows the direct installation costs of each type of check dam. The costs were cheapest for concrete check dams, followed by hybrid timber check dams, steel check dams, and all-wood timber check dams (values of actual condition in Fig. 8). The cost of all-wood timber check dams was 241 % that of concrete check dams, whereas for hybrid timber check dams the corresponding figures were 132 %, confirming that they could be competitive in terms of price. The costs of all-wood timber check dams and hybrid timber check dams were 179 and 98 %, respectively, of that of steel check dams, with hybrid timber check dams costing slightly less.

Focusing on the relative proportions of material and construction costs, for concrete check dams material costs accounted for 57 % and construction costs for 44 %. In

Table 4 CO_2 emissions for each type of check dam (kg-CO_2/dam)

	Timber		Concrete		Steel
	All-wood	Hybrid	Without forms	With forms	
Material and fuel production process					
Squared-off timber (dressed on four sides)	10108.8	–	–	–	–
Wooden forms	–	–	–	1446.8	–
Thinnings with bark	–	690.1	–	–	–
Squared-off timber (dressed on three sides)	–	1763.5	–	–	–
Concrete	–	–	42202.4	42202.4	–
Artificial lawn	1368.0	1285.3	842.1	842.1	1267.6
Rubble	–	–	–	–	3011.0
Crushed stone	–	696.0	–	–	–
Steel	–	19152.0	–	–	22378.1
Lag screw	2373.6	–	–	–	–
Steel bar	1084.1	–	–	–	–
Vinyl chloride pipe	780.7	367.4	551.1	551.1	367.4
Light oil	285.3	168.7	79.6	79.6	263.9
Gasoline	0.6	0.7	0.4	0.4	0.4
Total	16001.1	24123.7	43675.6	45122.4	27288.4
Construction process					
Earthworks					
Light oil combustion	920.5	1126.8	731.4	731.4	746.9
Gasoline combustion	3.7	3.8	2.5	2.5	2.5
Installation					
Light oil combustion	2657.1	88.9	58.6	58.6	1519.8
Temporary works					
Light oil combustion	448.6	113.8	185.6	185.6	106.7
Total	4029.9	1333.3	978.1	978.1	2375.9
Maintenance and management process					
Inspection					
Gasoline combustion	30.6	30.6	15.3	15.3	15.3
Repair					
Timber, lag screw	1230.8	705.4	–	–	–
Total	1261.4	736.0	15.3	15.3	15.3
Total	21292.4	26193.0	44669.0	46115.8	29679.6

contrast, the corresponding figures were 80 and 20 % for all-wood timber check dams, 89 and 11 % for hybrid timber check dams, and 83 and 17 % for steel check dams. Material costs accounted for a high proportion of direct construction costs for the three types of check dam other than those made of concrete, and the cost of material procurement was a factor driving up direct construction costs. Attempting to reduce material costs will therefore be a more effective cost-cutting measure than improving construction efficiency to keep down direct construction costs.

We investigated the possibility of reducing the costs of all-wood timber check dams, which had the highest costs among the five types of check dam addressed in this study. When considering measures for keeping down the costs of all-wood timber check dams, reducing the amount of timber used is undesirable from the perspective of timber use, and it would be preferable to investigate cost-cutting in areas other than timber. We therefore calculated the direct construction costs for three different cases: (a) using steel bars for all connectors, (b) not taking into account front apron construction, and (c) not taking into account front apron construction and also using only steel bars for all connectors. The assumption that steel bars could be used for all connectors was based on initiatives currently underway to replace lag screws with steel bars, as their material procurement costs are less than 10 % of those of lag screws [2, 3, 4]. We also considered not taking into account front apron construction, because although this is mandatory for the design of all-wood timber check dams in Akita Prefecture, it is not required for other types of check dams.

Direct construction costs in these three cases (values of (a), (b) and (c) in Fig. 8) were 88 % of current costs (values of actual condition) in case (a), 72 % in case (b), and 60 % in case (c). Compared with concrete check dams, however, the respective figures were 213 % in case (a), 173 % in case (b), and 144 % in case (c), showing that although they might be competitive with concrete check dams in terms of costs if these could be reduced to the level of case (c), further cost reductions or subsidies would be required to make them competitive in cases (a) and (b). To reduce the cost differential between their current structural forms and concrete check dams may require cost-cutting by means such as either a major reduction in the amount of timber used, which accounts for the greater part of material cost, or by promoting the commercialization of an on-site production system that integrates all the stages from timber procurement through to material preparation, processing, and construction at the construction site [23]. Focusing on the price of timber, to keep the direct construction costs of all-wood timber check dams in their present form down to around 1.5 times those for concrete check dams would require the price of timber (dressed on four sides) to fall to 42 % of its current level, and to 60 % of this level in case (a) and 78 % in case (b) above. The direct construction costs in the three cases described above were 158, 128, and 107 % of those for steel check dams in cases (a), (b), and (c), respectively. In case (c), the cost was very nearly equivalent to that for steel check dams, and even cases (a) and (b) might possibly be cost-competitive. The CO_2 emissions for all-wood timber check dams in these three cases were (a) 19.9 t-CO_2, (b) 16.0 t-CO_2, and (c) 14.7 t-CO_2, respectively. These results indicate cutting costs would also contribute to reducing CO_2 emissions at the same time.

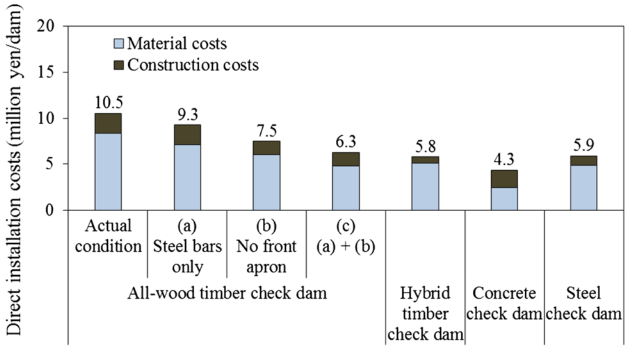

Fig. 8 Direct construction costs for each type of check dam

Marginal abatement cost of reducing CO_2 emissions

As described above, although timber check dams entail lower CO_2 emissions compared with concrete or steel check dams, their cost is higher. The extra costs generated by switching from concrete or steel check dams to timber can be regarded as additional costs required to reduce CO_2 emissions (marginal abatement costs) [24]. We performed calculations of these marginal abatement costs using Eqs. (1) and (2) below.

$$C = (\alpha \times C_a - \alpha \times C_b)/R \qquad (1)$$

$$\alpha = r/(1 - (1 + r)^{-n}) \qquad (2)$$

Here, C (yen/t-CO_2) is the cost required to reduce carbon emissions by 1 t/year, C_a (yen/year) is the direct installation cost of a timber check dam (all-wood or hybrid construction), C_b (yen/year) is the direct installation cost of a non-timber check dam (concrete or steel construction), R (t-CO_2/year) is the yearly reduction in CO_2 emissions resulting from the switch from a non-timber check dam to a timber check dam, r (%) is the social discount rate (assumed to be 4 %), and n (years) is the period of durability of a check dam (assumed to be 50 years for both timber and non-timber check dams, from "Maintenance and management process" above). These equations did not take account of the yearly maintenance and management costs for each facility, nor of cost conversions of secondary effects such as amenity value, safety, and preventing air pollution.

Table 5 shows the results of these calculations for the marginal abatement costs. Switching from concrete or steel check dams to all-wood timber check dams would be a high-cost measure of reducing CO_2 emissions, whereas if (c) all-wood timber check dams using without a front apron and only steel bars were used to replace concrete or steel check dams, the marginal abatement costs would be only 25 or 5 %, respectively, of those of switching to all-wood timber check dams. The corresponding figure if steel check dams were to be replaced by hybrid timber check dams is around −83 thousand yen/t-CO_2, suggesting that this might be an effective method of reducing CO_2 emissions while gradually reducing costs.

For comparison with other measures of reducing CO_2 emissions [24], the marginal abatement costs of switching from concrete check dams to all-wood timber check dams would come to a similar amount to improvements to the urban automotive driving environment (the use of intelligent transport systems), for example. If (c) all-wood timber check dams without a front apron and only steel bars were

Table 5 Marginal abatement costs and CO_2 emission reductions by switching from non-timber to timber check dams

	(Thousand yen/t-CO_2)	(t-CO_2/dam)
Switching from concrete check dams to all-wood timber check dams	577	25
Switching from concrete check dams to all-wood timber check dams (no front apron, steel bars only)	143	31
Switching from concrete check dams to hybrid timber check dams	164	20
Switching from steel check dams to all-wood timber check dams	1283	8
Switching from steel check dams to all-wood timber check dams (no front apron, steel bars only)	62	15
Switching from steel check dams to hybrid timber check dams	−83	3

used instead of steel check dams, this would cost around the same amount as using gas turbine combined-cycle power generation. These costs are around 4–38 times greater than the marginal abatement cost of 15 thousand yen/t-CO_2 (54 thousand yen/t-C) for using thinnings or logging residues as an energy source to reduce CO_2 emissions (average emission factors for all power sources) [24], suggesting that switching from concrete or steel check dams to timber check dams would not constitute a cheap means of reducing CO_2 emissions compared to other methods for reducing CO_2 emissions. Further cost reduction measures, as well as political support such as subsidy systems, are required for the use of timber in check dams.

Conclusions

We carried out a comparative evaluation life cycle CO_2 emissions and direct installation costs for concrete check dams, which have a long track record of construction, steel check dams, and two types of timber check dams developed in Akita Prefecture (all-wood and hybrid timber), and investigated the effectiveness of timber check dams in reducing CO_2 emissions and their economic efficiency compared with non-timber check dams. We found the following results.

(a) Switching from concrete to all-wood and hybrid timber check dams would reduce CO_2 emissions by 54 and 43 %, respectively. Switching from steel to all-wood and hybrid timber check dams reduced CO_2 emissions by 28 and 11 %, respectively.

(b) In the various life cycle processes, CO_2 emissions were greatest during the production processes for materials and fuel for all types of check dam, with 75 % of the emissions for all-wood timber check dams and over 90 % of those for hybrid timber, concrete, and steel check dams emitted during this process.

(c) In terms of economic efficiency, all-wood timber check dams are the most expensive, whereas concrete check dams are the cheapest, with all-wood timber check dams being expensive at 241 % of the cost of concrete check dams. However, it is possible to reduce the cost of all-wood timber check dams to around 60 % of its current level by changing the construction method and materials. Hybrid timber check dams are 132 % of the costs of concrete check dams, and slightly less expensive than steel check dams, and can therefore be competitive with them in terms of cost.

(d) The marginal abatement costs required to reduce CO_2 emissions when switching from concrete to timber check dams are around 143–577 thousand yen/t-CO_2 for all-wood timber check dams and around 164 thousand yen/t-CO_2 for hybrid timber check dams. Therefore, switching from non-timber check dams to timber check dams does not constitute cheap means of reducing CO_2 emissions compared with other policies.

This study placed an emphasis on integrating the evaluation conditions for timber and non-timber check dams, and on obtaining widely applicable results that do not depend on local characteristics. Based on the concept, data were collected about the production processes of construction materials. However, an important challenge in the near future is to evaluate using data that are based on local conditions, and make a comparative review with the results from this study. Areas for future study includes the investigation of how to deal with the carbon sequestered in timber, which was excluded from the evaluation in this study, as well as with GHGs as a whole rather than CO_2 alone. With respect to economic efficiency, future topics could include studies covering on-site production systems, as well as investigations of procurement prices for resources such as timber, steel, and fuel, which are subject to comparatively large fluctuations. Consideration of costs associated with secondary effects, such as amenity value, safety, and preventing air pollution, is also a topic for future research on marginal abatement costs.

Acknowledgments We are deeply grateful to Mr. Shota Ogasawara and Mr. Mamoru Takeishi of the Akita Prefectural Government and to Mr. Yasuhiro Miura, Akita Prefecture Forestry Consultant, for providing valuable data and extending us various facilities. This research was supported by the Agriculture, Forestry and Fisheries Research

Council Project, Development of Climate Change Mitigation Technologies in the field of Forests and Forestry (2010–2014), and MEXT KAKENHI Grant Number 25282115.

References

1. IPCC (2007) IPCC Fourth assessment report: climate change 2007 (AR4)
2. Chida T, Sasaki T, Noda R, Miura Y (2012) Pull-out performance of lag screw and deformed steel bar for connector of wooden civil engineering structures (in Japanese). J Struct Eng 58A:785–792
3. Noda R, Sasaki T, Chida T, Inoue T, Harata T, Miura Y (2012) Development of original wooden check dam in Akita Prefecture (in Japanese). J Jpn Soc Eros Control Eng 65:39–46
4. Chida T, Sasaki T, Noda R, Inoue T, Miura Y (2012) The optimum design used FEM analyses and the development of wooden check dam I: the optimum design of all wood type wooden check dam (in Japanese). J Jpn Soc Eros Control Eng 64:14–23
5. Jönsson A, Tillman AM, Svensson T (1997) Life cycle assessment of flooring materials: case study. Build Environ 32:245–255
6. Börjesson P, Gustavsson L (2000) Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspective. Energy Policy 28:575–588
7. Petersen AK, Solberg B (2002) Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction. Case: beams at Gardermoen airport. Environ Sci Policy 5:169–182
8. 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
9. Takaoku S (2010) The wooden check dam of Kyoto (in Japanese). J Jpn Soc Eros Control Eng 62:59–62
10. Noda R, Kayo C, Sasaki T, Ogasawara S (2012) Reductions in greenhouse gas emissions of wooden check dam (in Japanese). In: Proceedings of the 11th symposium on use of wood for civil engineering, 30 Aug–31 Aug 2012, Tokyo, Japan, pp 103–108
11. Hosokawa T, Takaoku S, Hashimoto S (2013) Life cycle assessment of wooden erosion-control dam (in Japanese). In: Proceedings of the 8th Meeting of the Institute of Life Cycle Assessment, 6 March–8 March 2013, Shiga, Japan, pp 376–377
12. Forestry Agency of Japan (2010) Act for promotion of use of wood in public buildings (in Japanese) http://www.rinya.maff.go.jp/j/riyou/koukyou/. Accessed 15 Oct 2013
13. Japan Environmental Management Association for Industry (2010) MiLCA
14. 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
15. Nihon Chisan Chisui Kyokai/Nihon Rindo Kyokai (2011) 2011 Chisan and forest road manual, quantity surveying and construction volume (in Japanese)
16. Ministry of the Environment of Japan (2012) Calculation and report manual of greenhouse gas emissions, Ver. 3.2 (in Japanese)
17. Karouzi K (1999) The current status of existing wooden dams (in Japanese). J Jpn Soc Eros Control Eng 51:46–50
18. Ministry of Finance Japan (2013) Ministerial ordinance concerning the useful life, etc. of depreciable assets (in Japanese). http://law.e-gov.go.jp/htmldata/S40/S40F03401000015.html. Accessed 20 Nov 2013
19. Noda R, Sasaki T, Horie T, Ito R, Yoneya Y, Sato Y (2013) Durability investigation of all-wood timber check dams (in Japanese). In: The 68th annual meeting of the JSCE. 4 Sept–6 Sept 2013, Chiba, Japan
20. Sasaki T, Kanetaka S, Hanada K (2006) Durability investigation of timber check dams using a Japan Cedar material (in Japanese). In: The 56th Annual Meeting of the JWRS. 8 Aug–10 Aug 2006, Akita, Japan
21. Ishikawa Y, Naitou Y, Ochiai H, Kamihara I (2003) Durability, degree of deterioration, and methods for evaluating the bending strength of members of wooden structures based on various tests (in Japanese). J Jpn Soc Eros Control Eng 56:21–31
22. Nihon Chisan Chisui Kyokai/Nihon Rindo Kyokai (2011) 2011 Forestry civil engineering wooden structure construction manual (in Japanese)
23. Sasaki T, Noda R, Chida T, Morikawa M, Toda M (2012) Construction of wooden check dam using on-site production system (in Japanese). In: Proceedings of the 11th symposium on use of wood for civil engineering, 30 Aug–31 Aug 2012, Tokyo, Japan, pp 39–42
24. Ministry of the Environment of Japan (2001) Interim Summary, Sub-Committee on Scenarios to Achieve the Target (in Japanese), http://www.env.go.jp/council/06earth/r062-01/. Accessed 10 Dec 2013