Biomass carbon sinks in Japanese forests: 1966–2012

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Summary

The role of forests in absorbing atmospheric carbon has been recognized under the Kyoto Protocol, which allows signatory countries to use forests as a mitigation option. Although several studies have estimated carbon stock changes in Japanese forests, most only estimate changes up to 1995 or ignore carbon stock changes in natural forests. This study is the first attempt to estimate carbon stock changes in Japanese forests from 1966 to 2012, to coincide with the final year of the Kyoto Protocol's first commitment period. Forest area and growing stock data were analysed. Then, two models for predicting the change in forest area and growing stock were developed. Results showed that most natural forest loss resulted from conversion to plantation forest. The total above-ground and below-ground carbon stock in Japanese forests has been estimated to have increased from 1114.8 TgC in 1966 to 2076.0 TgC in 2012, representing an increase of 20.9 TgC year^{-1} over the same period. During the first commitment period of the Kyoto Protocol (2008–2012), annual carbon sinks were estimated at 20.1 TgC, of which ~76.9 per cent were sequestered in plantation forests. Of the 20.1 TgC year^{-1}, eligible carbon sinks are estimated at 10.2 TgC or ~78.7 per cent of the maximum or capped amount as allowed under the Marrakesh Accord. Although further effort is needed so that the capped amount of 13 TgC year^{-1} could be achieved, this study suggests that carbon sinks through forest management could be used to offset industrial carbon emissions.

Introduction

Depending on management regimes, forests can play a role in either sequestering atmospheric carbon or releasing carbon into the atmosphere. While forests in most temperate regions are net carbon sinks, tropical forests account for about one-third of global carbon emissions (IPCC, 2001). Officially known as land use, land use change and forestry, the issue of terrestrial carbon sinks has been among the most contentious and difficult issues in the international climate change negotiations (Jung, 2004). Based on a decision made at the seventh session of the Conference of the Parties to the United Nations Framework Convention on Climate Change in Marrakesh in 2001 (UNFCCC, 2002), carbon sinks through afforestation and reforestation (Article 3.3 of the Kyoto Protocol) and through forest management (FM) (Article 3.4) are eligible for credits. Under the Kyoto Protocol, which was adopted in 1997 and enforced as of 16 February 2005, signatory countries are allowed to credit forest carbon sinks against greenhouse gas (GHG) emissions in order to fulfil their emissions reduction commitments. Japan is committed to reducing carbon emissions by 6 per cent below 1990 emission levels by the end of the first commitment period.

Forestry, Vol. 82, No. 1, 2009. doi:10.1093/forestry/cpn049
Advance Access publication date 4 November 2008

However, according to the latest report on GHG emissions published by the Ministry of Environment (2005), the necessary reductions amount to 52.5 TgC annually (1 TgC = 10^6 ton C = 3.6 × 10^6 CO_2) or 14.1 pr cent of 2005 carbon emissions. For a heavily forested country like Japan, forest carbon sinks must be considered a necessary complement to reduced emissions for meeting the reduction target in the first commitment period between 2008 and 2012. In order to meet its commitment, Japanese government has considered three options for reducing emissions, namely reductions through the Kyoto mechanisms, forest carbon sinks and domestic measures. Since carbon sinks in managed forests are allowed up to 13 TgC year^{-1} (UNFCCC, 2002) or ~3.9 per cent out of the 6 per cent reduction commitment as agreed in 1997, FM is playing a vital role in meeting reduction commitment in Japan. In recent years, several studies on carbon stock changes have been conducted (Fukuda *et al.*, 2003; Fang *et al.*, 2005; Hiroshima and Nakajima, 2006; Yoshimoto and Marusak, 2007). Carbon stock changes in Japanese forests have been well studied (Fukuda *et al.*, 2003; Fang *et al.*, 2005; Hiroshima and Nakajima, 2006). According to Fang *et al.* (2005), above-ground carbon stocks in plantation and natural forests increased from 26.1 and 32.5 MgC ha^{-1} to 46.5 and 40.7 MgC ha^{-1}, respectively, between the periods 1957–1961 and 1991–1995. Summed over the whole country, above-ground carbon stocks in plantation and natural forests were estimated at 692.0 and 1027.7 TgC for the last year of the periods 1957–1961 and 1991–1995, respectively. By analysing the forestry statistics for two major species in plantation forests, Fukuda *et al.* (2003) estimated carbon stocks at 406.4 and 166.4 TgC in 1995 increased from 346.4 and 139.2 TgC in 1990 (~9.2 and 4.4 TgC year^{-1} between 1990 and 1995) in Sugi (*Cryptomeria japonica* D. Don) and Hinoki (*Chamaecyparis obtusa* Endl.) plantation forests, respectively. Only one study has focused on potential carbon sinks in Japanese plantation forests during the first commitment period (Hiroshima and Nakajima, 2006). According to their estimate, carbon sinks in plantation forests could range from 8.2 to 8.9 TgC year^{-1} depending on FM subsidies because as timber price has continued to fall below the operational cost (weeding, tending, thinning, harvest etc.), forest owners have already suspended and are likely to suspend their management activities until they are subsidized or the price of timber goes up above the thinning cost. These figures account for ~63 to 68 per cent of the capped amount under the Marrakesh Accord. However, no studies incorporating changes in land area and carbon stocks in all forest types have been performed. By analysing the changes in forest area and carbon stocks, the aim of this paper is to estimate the biomass carbon sinks in Japanese forests under the current management trends between 1966 and 2012 with special emphasis on the first commitment period of the Kyoto Protocol between 2008 and 2012. It is the first attempt to analyse potential carbon stock changes and sinks in both natural and plantation forests during this period.

The report is organized as follows: firstly, past change in areas of natural and plantation forests is analysed and based on this, predictions are made up to 2012. Secondly, carbon stock changes in both forest types are analysed as above. Thirdly, eligible carbon sinks in managed forests are estimated and the sensitivity of the results to the assumptions is considered.

Materials and methodology

This study only covers the above-ground carbon in stems, branches and foliage and below-ground carbon in roots. Carbon fluxes in harvested wood products (HWPs) are not eligible carbon sinks for the first commitment period of the Kyoto Protocol between 2008 and 2012 and are therefore not included in this study. Since soil organic carbon (SOC) is sensitive to temperature (Knorr *et al.*, 2005) and the geography of soil resources (Galbraith *et al.*, 2003), and because both variables are not implemented for simplicity, SOC is not considered in this study.

Sources of data and analysis

Data on the changes in areas of and growing stock in plantation and natural forests for 1966, 1971, and 1976 were obtained from the Japan FAO Association (1997). Data for 1981, 1986, 1990, 1995, 1999 and 2002 were obtained from forestry statistical survey books published by the

Japan Forestry Foundation (Japan Forestry Foundation, 1992) and the Forestry Agency (Forestry Agency, 2005). The year 2002 is the latest for which forest survey data are available for Japan collected every 5-year period. In these surveys, forest land use is classified as natural and plantation forests, treeless land (land recently cleared) or bamboo forests. The total area of bamboo forest is small and is therefore not considered. Treeless land (*muritsu boku chi to*) is integrated into the natural forest classification because it represents recently felled areas that will be converted to plantation forests in few years (Japan Forestry Foundation, 1992). In terms of area, coniferous species account for 98 per cent of all species in plantation forests, while broadleaved species account for 84.6 per cent of the species found in natural forests.

Weighted average stand volume per hectare was calculated for each forest class and year. Growing stock data, usually expressed in terms of cubic metre (m^3), were converted to carbon units ($MgC = 10^6$ gC) using equation of Brown (1997), as follows:

$$CS_i = CD \times VD_i \times WD_i \times BEF_i, \tag{1}$$

where the variables are defined as follows: CS_i, above-ground carbon stock of forest '*i*' (MgC ha^{-1}); CD, carbon density (0.5 MgC Mg wood); VD_i, growing stock of forest *i* (m^3 ha^{-1}); WD_i, weighted wood density of forest *i* (Mg m^{-3}), WD is 0.509 and 0.342 for natural and plantation forests, respectively (see to Table 1); BEF_i, weighted average of biomass expansion factor of forest *i* (BEF = 1.872 for natural forest, BEF = 1.724 for plantation forest, see Table 1) and *i*, natural forest or plantation forest.

According to the Wood Industry Handbook (Forestry Experimental Report, 1982), wood density in Japanese tree species is estimated at 0.32 Mg m^{-3} for Sugi (*C. japonica*), 0.34 Mg m^{-3} for Hinoki (*C. obtusa*), 0.44 Mg m^{-3} for Karamatsu (*Larix leptolepis*), 0.43 Mg m^{-3} for Matsu (*Pinus spp.*), 0.35 Mg m^{-3} for Todomatsu (*Abies sachalinensis*), 0.37 Mg m^{-3} for trees classified as 'other' and 0.54 Mg m^{-3} for broadleaved trees (0.45 Mg m^{-3} for broadleaved deciduous trees and 0.61 Mg m^{-3} for broadleaved evergreen trees). Therefore, WD's weighted average for coniferous and broadleaved trees are 0.338 and 0.540 Mg m^{-3}, respectively (see Table 1).

Land use model

The study used a land use model modified from the study of Kim Phat *et al.* (2004). The model estimates change in the area of natural and plantation forests in Japan:

$$\frac{\mathrm{dNF}(t)}{\mathrm{d}t} = -(k_a + k_b) \times \mathrm{NF}(t), \tag{2}$$

$$\frac{\mathrm{dPF}(t)}{\mathrm{d}t} = k_a \times \mathrm{NF}(t), \tag{3}$$

where the variables are defined as follows: NF(*t*), area of natural forest (million ha); PF(*t*), area of plantation forest (million ha); k_a, conversion rate of natural forest to plantation forest, per unit time; k_b, conversion rate of natural forest to other uses, per unit time and *t*, time step (year).

Trends in forest land use change in Japan can be broadly classified into two periods,

Table 1: Weighted averages of wood density (WD, Mg m^{-3}) and *i* for use in carbon stock conversion

Variables	Natural forest			Plantation forest		
	Coniferous	Broadleaved	Weighted	Coniferous	Broadleaved	Weighted
Proportion of total forest area in 1990	15.4%	84.6%	100% (total)	98.0%	2.0%	100% (total)
WD	0.338	0.540	0.509	0.338	0.540	0.342
BEF	1.720*	1.900†	1.872	1.720*	1.900†	1.724

* Average number taken from Fukuda *et al.* (2003).

† GHG Inventory Report in Japan, published by Center for Global Environmental Research (CGER, 2005) in 2005.

1966–1984 with high rates of conversion of natural forest to plantation and 1984–2002 with lower conversion rates (Figure 1). To simplify the analysis, the time series were divided into these two periods and separate submodels were then fitted to the data of forest areas for each period by simple linear regression. Equating and solving the equations for the two submodels obtained the coordinate of the intersection between the submodels. The slope parameter of the regression models gave the parameters ($k_a + k_b$) and k_a in equations (2) and (3), respectively. Land use changes after 2002, the last year for which data are available, were predicted by using the submodel for 1984–2002 as a based model.

Carbon stock change per hectare

Per hectare (ha^{-1}) carbon stock change in natural and plantation forests can be estimated by the Richards' growth model (Richards, 1959) as follows:

$$CS_i(t) = \frac{a_i}{(1 + e^{b_i - c_i \cdot t})^{1/d_i}} \times (1 + r), \qquad (4)$$

where the variables are defined as follows: a_i, b_i, c_i, d_i, parameters for each forest type obtained by fitting equation (4) to a data set of per-hectare carbon stocks for Japanese forests over the period 1966–2002; $CS_i(t)$, average carbon stock in forest i at time t (MgC ha^{-1}); i, natural forest or plantation forest and r, the proportion of above-ground carbon to root carbon. Proportion of root carbon to above-ground carbon range was estimated at 13.4–30.2 per cent in subtropical broadleaf forest in Taiwan (Lin *et al.*, 2006). Fearnside (1997) estimated below-ground carbon at 33.6 per cent of above-ground carbon. For this study, 30 per cent is assumed.

Average carbon stock per hectare for each forest type was calculated by taking the total growing

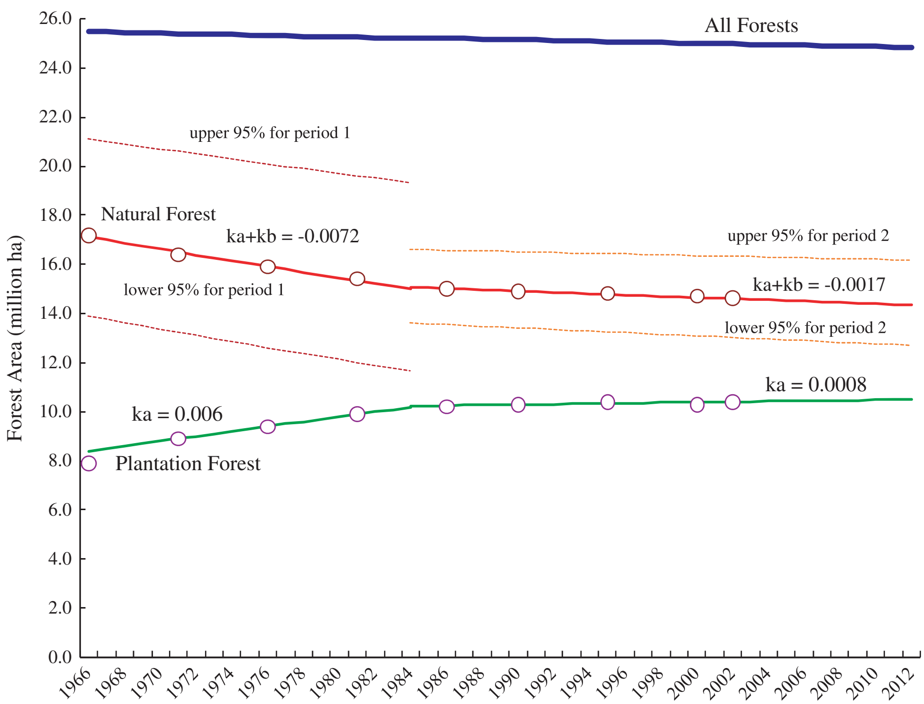

Figure 1. Change in area of plantation and natural forests in Japan (1966–2012). The dotted lines show the 95% confidence intervals for changes in area of natural forest.

stock of each forest (natural or plantation forest) and dividing by the respective area of each forest in the relevant year. The resulting time series of carbon stock per hectare was used to derive the parameters of equation (4) with the aid of the CurveFit Expert 1.3 software package, a comprehensive curve fitting system for Windows developed by Hyams (for more information, see Hyams, 2007).

Carbon stock changes in all forests

Total carbon stock changes in Japanese forests can be estimated by

$$
\begin{aligned}
C_i(t_0) &= L_i(t_0)\cdot \mathrm{CS}_i(t_0)\\
C_i(t_1) &= L_i(t_0)\cdot \mathrm{CS}_i(t_1) + L_i(t_1)\cdot \mathrm{CS}_i(t_0)\\
C_i(t_2) &= L_i(t_0)\cdot \mathrm{CS}_i(t_2) + L_i(t_1)\cdot \mathrm{CS}_i(t_1) +\\
&\qquad L_i(t_2)\cdot \mathrm{CS}_i(t_0) \qquad (5)\\
&\vdots\\
C_i(t_n) &= L_i(t_0)\cdot \mathrm{CS}_i(t_n) + L_i(t_1)\cdot \mathrm{CS}_i(t_n - 1) + \cdots +\\
&\qquad L_i(t_n)\cdot \mathrm{CS}_i(t_0),
\end{aligned}
$$

where the variables are defined as follows: $C_i(t_n)$, carbon stock in forest i in year 'n' (MgC year^{-1}); and $L_i(t_n)$, change in area of forest i in year n compared with previous year, derived by equations (1) and (2) (million ha).

Equation (5) was applied for each year from 1966 to 2012, with extrapolated forest land use data (see above) for the period after 2002 for which no land use data are available.

Results and discussion

Area of forest land

Based on the land use submodels, the area of natural forest in Japan decreased from 17.1 million ha in 1966 to 15.0 million ha in 1984, representing a change of –0.72 per cent or a loss of ~0.12 million ha year^{-1} (Figure 1). Over the same period, the plantation forest area increased by 0.6 per cent or ~0.10 million ha year^{-1}. For the second period from 1984 to 2012, the loss of natural forest decreased to ~0.17 per cent or 25 294.7 ha annually. Plantation forest area increased by ~0.08 per cent, or ~11 250.0 ha year^{-1}, during the second period between 1984 and 2012 (Figure 1). Overall, Japan lost ~60 431.5 ha of natural forest, but gained ~46 586.5 ha of plantation forest between 1966 and 2012, giving a net loss in forest area of 13 845.0 ha year^{-1} (Figure 1).

Carbon stock change per hectare

The carbon stock model, equation (4), suggested that the carbon stock (above-ground and root carbon) in natural forests increased from 48.7 MgC ha^{-1} in 1966 to 76.0 MgC ha^{-1} in 2012, representing an annual increase of ~0.6 MgC ha^{-1}. During the first commitment period between 2008 and 2012, annual carbon sequestration is estimated at 0.5 MgC ha^{-1}. In contrast to the moderate increase of carbon sequestered in natural forests, carbon stock in plantation forests increased about ~5-fold between 1966 and 2012, from 24.3 MgC ha^{-1} in 1966 to 101.6 MgC ha^{-1} in 2012. This represents an average increase of 1.7 MgC ha^{-1} year^{-1} over the whole period and ~1.2 MgC between 2008 and 2012 (Figure 2). On average, carbon stocks of all Japanese forests increased from 36.5 MgC ha^{-1} in 1966 to 88.8 MgC ha^{-1}, a rate of ~1.1 MgC ha^{-1} year^{-1}.

Our results of periodic annual increment (PAI) between 1990 and 1995 is 2.2 MgC ha^{-1} year^{-1}, which is slightly greater than that estimated by Fukuda *et al.* (2003) whose estimates were 2.1 and 1.8 MgC in Sugi and Hinoki plantation forests, respectively (Table 2). This minor difference may have resulted from the different study methods that were used in our study and their study. These rates of change in carbon stocks may be compared with the results of studies in experimental forests under controlled management regimes. In the experimental forest at Rokuman Mountain in Ishikawa Prefecture, the mean annual increment (MAI) of Sugi (*C. japonica*) plantations was estimated to range from 4.7 m^3 ha^{-1} year^{-1} (corresponding to ~1.6 MgC according to equation (1) at 15 years of age to 20.7 m^3 ha^{-1} year^{-1} (7.0 MgC year^{-1}) at 50 years, Hosoda, 1998). In another experimental forest at Shinotani Mountain in Tottori Prefecture, Hosoda (1999) estimated an MAI for Sugi of 15.9 m^3 ha^{-1} year^{-1} (5.4 MgC year^{-1}) at 31 years of age and 17.5 m^3 ha^{-1} year^{-1} (5.9 MgC year^{-1}) at 71 years. Takeuchi (2005) estimated the growth (PAI) for Sugi to be

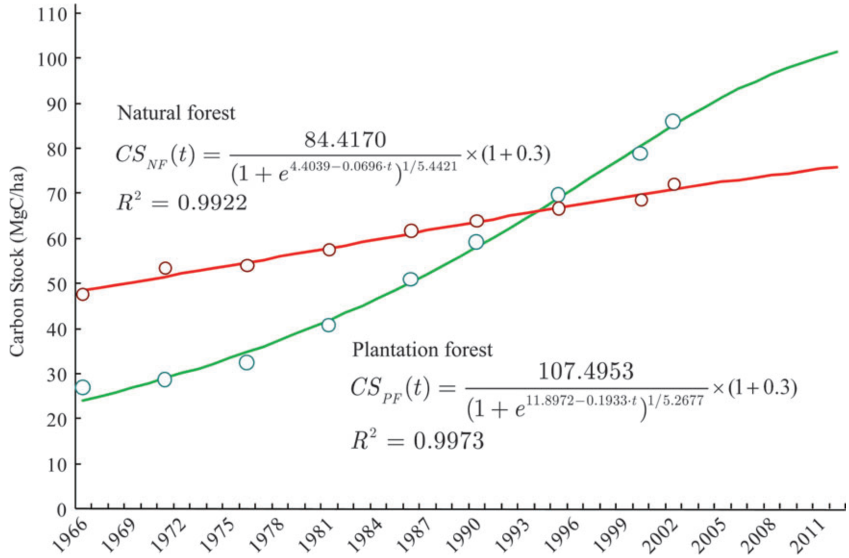

Figure 2. Per hectare carbon stock changes in Japanese forests (1966–2012).

more than 10 m^3 ha^{-1} $year^{-1}$ (3.4 MgC $year^{-1}$) at 200 years of age in Kawakami Village in Nara Prefecture, while Matsumura *et al.* (1999) found annual growth to average 14.5 m^3 ha^{-1} $year^{-1}$ (ranging from 6.5 to 21.0) or ~4.9 MgC ha^{-1} $year^{-1}$ at 25–93 years of age in Kochi Prefecture. MAI of Hinoki (*C. obtusa*) at 60 years of age was estimated at ~5.4 m^3 ha^{-1} $year^{-1}$ (1.8 MgC ha^{-1} $year^{-1}$), ranging from 1.1 m^3 ha^{-1} $year^{-1}$ (0.4 MgC ha^{-1} $year^{-1}$) to 5.4 m^3 ha^{-1} $year^{-1}$ (1.8 MgC ha^{-1} $year^{-1}$) at Okushima Mountain in Siga Prefecture (Hosoda, 1997). In three separate pilot plots of Hinoki plantation, mean growth was estimated at 15.8 m^3 ha^{-1} $year^{-1}$ (standard error: 2.3) or 5.4 MgC (Matsumura *et al.*, 1999) (Table 2).

Table 2 suggested that the result of our study is smaller than that found at experimental sites across Japan. This is due to the fact that intensive thinning was conducted in those sites in order to accelerate the growth, while our study focused on the average growth of thinned and unthinned forests in the whole Japan. Table 2 also suggested that thinning could improve the growth of forest plantations and therefore, if Japanese government undertakes thinning in all 80 per cent of the immature forests that require thinning, more carbon sinks are likely to occur in forests.

Total carbon stock change in Japanese forests

According to the model (Equation (5)), total carbon stocks in plantation and natural forests, respectively, increased from 144.0 and 970.8 TgC in 1966 to 883.1 and 1192.9 TgC in 2012 (Figure 3). Averaged over the period 1966–2012, carbon sequestration in Japanese forests is estimated at ~16.1 and 4.8 TgC $year^{-1}$ for plantation and natural forests, respectively. For the first commitment period (2008–2012), the sequestration is estimated at 15.3 and 4.8 TgC $year^{-1}$ for plantation and natural forests, respectively (Figure 3). This gives a total of 20.1 TgC $year^{-1}$, higher than the allowable carbon sinks as capped under the Marrakesh Agreement. Discussion on eligible carbon sinks under the Kyoto agreement is given in the next section.

Discussion on eligible carbon sinks

According to article 3.3 and article 3.4 of the Kyoto Protocol, only carbon sinks in managed forests resulted from additional human activities are eligible for crediting. Ikusei-rin or managed forests (forests where practices for establishment and maintenance of even-aged have been undertaken after clear cut or selective cut) and

Table 2: Mean increments of biomass carbon sinks in Japan

Forest	Period	Increments (MgC ha^{-1} year^{-1})	Description	Source
Sugi*	1990–1995	2.1	Average the whole Japan	Fukuda *et al.* (2003)
Hinoki*	1990–1995	1.8	Average the whole Japan	Fukuda *et al.* (2003)
Plantation	1990–1995	2.2	Average of all plantations	This study
Sugi	Age 15 years	1.6	Experimental site at Rokuman mountain in Ishikawa prefecture where intensive thinning was practiced	Hosoda (1998)
Sugi	Age 50 years	7.0	Experimental site at Rokuman mountain where intensive thinning was practiced	Hosoda (1998)
Sugi	Age 31 years	5.4	Experimental site at Shinotani mountain in Tottori prefecture where intensive thinning was practiced	Hosoda (1999)
Sugi	Age 71 years	5.9	Experimental site at Shinotani mountain in Tottori prefecture where intensive thinning was practiced	Hosoda (1999)
Sugi	Age 200 years	3.4	Experimental site at Kawakami village in Nara prefecture	Takeuchi (2005)
Sugi	Age 25–93 years	4.9	Experimental site at Nichino Kawa mountain in Kochi prefecture where intensive thinning was practiced	Matsumura *et al.* (1999)
Hinoki	Age 60 years	1.8	Experimental site in Okushima mountain in Siga prefecture where intensive thinning was practiced	Hosoda (1997)
Hinoki	Age 77 years	5.4	Experimental site at Nichino Kawa mountain in Kochi prefecture where intensive thinning was practiced	Matsumura *et al.* (1999)

* Sugi and Hinoki are accounted for 44 and 24% of all planted species in Japan. The rest are Larix (10%), other Pines (*Pinus spp.*, also 10%) and other species.

Tennensei-rin or naturally regenerated forests (forests where practices such as establishment and maintenance depending mainly on natural regeneration are carried out) are the two forest types that Japan has chosen for management. Carbon sinks under FM option could be eligible for fulfilment of its GHG emission reductions target. According to report released by the government of Japan (Japanese Government, 2007), proportion of FM as considered to be eligible under the Kyoto Protocol agreement ranges from 0.31 (31 per cent of the respective forest area) in Shikoku, Kyushu, Chukoku and Kinki regions to 0.48 in Tohoku, Hokuriku, Kita Kanto and Toyama regions, with a weighted average of 0.39 (39 per cent) for Sugi plantations managed by private landowners and to as high as 0.66 for Sugi plantations managed by the state (Table 3). The proportion of FM for Hinoki plantation managed by private land owners ranges from 0.48 to 0.53 with a weighted average of 0.50, but the proportion of FM in national forests is 0.66 for all regions and species (Table 3). The differences in the proportion are due mainly to the decrease in domestic timber price which encouraged private land owners to temporarily abandon their management activities in contrast to the state (government) whose budget availability permits the continuous management of forests.

Table 3 can be rearranged (Table 4) in such a way that the information can be used for estimating potential eligible carbon sinks in Japanese forests during the first commitment period. According to Table 4, weighted averages of the proportion of FM in Japan are estimated at 0.48 (48 per cent) and 0.60 (60 per cent) for plantation and natural forests, respectively (Table 4).

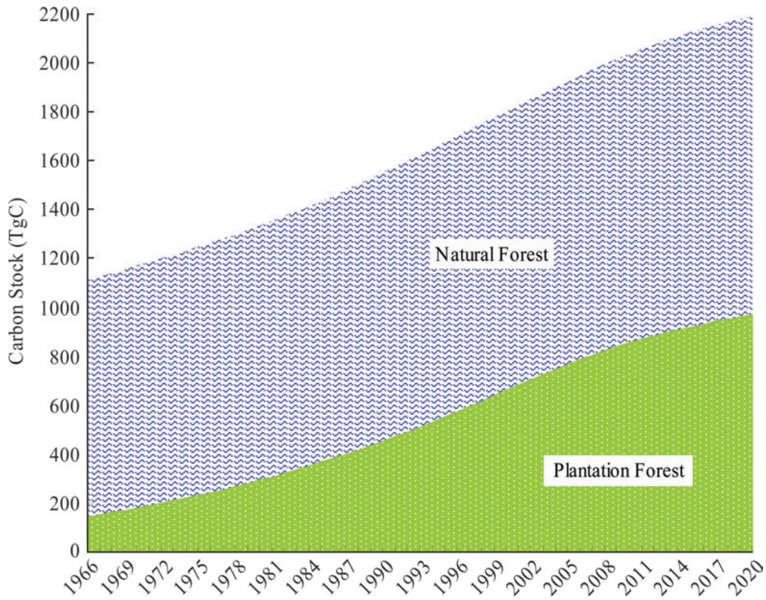

Figure 3. Overall carbon stock changes in Japanese forests (1966–2012).

By taking these 0.48 and 0.60 proportions as the proportions of eligible forests for the whole modelling period, eligible carbon sinks due to FM are estimated at 7.3 and 2.9 TgC year^{-1} in plantation and natural forests, respectively. Totally, Japanese forests are able to sequestrate ~10.2 TgC annually during the first commitment period of the Kyoto Protocol between 2008 and 2012, reaching 78.7 per cent of the capped amount of 13 TgC, the maximum amount of carbon sinks that Japan can use to meet its GHG reduction commitment as agreed under the Marrakesh Accord (UNFCCC, 2002). Using satellite data, GIS (Geographic Information System) and national data, the Japanese Government (2007) gave an estimate of ~9.7 TgC year^{-1}, only 0.5 TgC less than our findings.

Sensitivity analysis

BEF play a major role in estimating carbon stock in forests as needed for the GHG reporting under the climate convention (Lehtonen *et al*., 2007). The BEF used in equation (1) varies depending not only on the four forest type classes considered in this study (Table 1) but also on tree species, the age of the forests and a number of other factors including altitude, climate, provenance, soil type and management (Lehtonen *et al*., 2004). Uncertainty surrounding BEF is the greatest potential source of error in estimating carbon stock change in natural and plantation forests (Lehtonen *et al*., 2007). Dividing the estimates among species and age classes, and using separate BEFs for each, could go a long way towards reducing this uncertainty.

FM rates affect the eligible carbon sinks in Japanese forests. Because of Japan's commitment to improve carbon stocks in the forests through thinning and subsidies providing to forest owners coupled with the adoption in December 2002 of a 10-year FM action plan aiming to achieve maximum carbon sinks in the forests (Matsushita and Taguchi, 2006), the rates of FM are likely to increase, leading to the increase of eligible carbon sinks. Therefore, a 13 TgC year^{-1} cap of carbon sinks in forest sector could be achieved.

Conclusion

This study provides an estimate of forest land use change, carbon stock changes and carbon sequestration in Japanese forests, under current

Table 3: The proportion of different types of forest eligible under the Kyoto Protocol

Regions	FM rates*	Area† (ha)	FM area (ha)
Private forests (forests owned by private land owners)			
Sugi (*Cryptomeria japonica*)			
Kinki, Chukoku, Shikoku, Kyushu	0.31	2 066 114.0	640 495.3
Minami Kanto, Tokai	0.36	516 019.0	185 766.8
Tohoku, Hokuriku, Kita Kanto, Toyama	0.48	1 894 873.0	909 539.0
Subtotal	0.39	4 477 006.0	17 35 801.2
Hinoki *(Chamaecyparis obtusa)*			
Tohoku, Kita Kanto, Minami Kanto Chubu	0.53	697 089.0	369 457.2
Kinki, Chukoku, Shikoku, Kyushu	0.48	1 336 545.0	641 541.6
Subtotal	0.50	2 033 634.0	10 10 998.8
Larch *(Larix leptolepis)*			
All regions	0.37	698 204.0	2 58 335.5
Other plantations			
All regions	0.52	1 385 518.0	7 20 469.4
Natural forest			
All regions	0.38	1 385 267.0	5 26 401.5
National forests			
Plantation			
All regions and species	0.66	2 281 254.0	15 05 627.6
Natural forest			
All regions	0.66	4 754 554.0	31 38 005.6

* Data were taken from Japanese Government (2007).
† Data were in 1990, the base-year data taken from MAFF (2000).

Table 4: Weighted averages and areas of plantation and natural forests

Forest types	Rate of FM	Total area (ha)	Area of FM (ha)
Plantation			
Plantation (private forest)			
Sugi	0.39	4 477 006.0	1 735 801.2
Hinoki	0.50	2 033 634.0	1 010 998.8
Karamatsu	0.37	698 204.0	258 335.5
Others	0.52	1 385 518.0	720 469.4
Plantation (national forest)			
All	0.66	2 281 254.0	1 505 627.6
Subtotal	0.48 (weighted average)	10 875 616.0	5 231 232.5
Natural forests			
Private	0.38	1 385 267.0	526 401.5
National	0.66	4 754 554.0	3 138 005.6
Subtotal	0.60 (weighted average)	6 139 821.0	3 664 407.1

management practices, between 1966 and 2012. Due to government policies aimed at meeting increasing demand for domestic timber after World War II, a large portion of natural forests has been replaced by plantation forests whose commercial timber growth and yield is much greater. Between 1966 and 1984, the area of natural forest area decreased at an annual rate of 0.72 per cent. Carbon stocks in natural forests increased slowly, while they increased rapidly in plantation forests over the same period. During the first commitment period of the Kyoto protocol, Japanese forests are likely to sequester 20.1 TgC year^{-1}, of which 10.2 TgC is considered as eligible carbon sinks, or ~78.7 per cent of the capped amount of 13 TgC year^{-1}. Further effort, i.e. intensive thinning by the governmental and private forest owners, is needed to accelerate the growth and therefore increase more carbon sinks in Japanese forests. Nevertheless, our study results suggest that Japanese forests play a vital role in climate change mitigation.

Funding

The Sumitomo Foundation (Number 043195); the Hyogo Science and Technology Association and the Charles Bullard Fellowship in Forest Research for Advanced Research and Study.

Conflict of Interest Statement

The authors declare no conflict of interest.

Acknowledgements

Authors gratefully thank editor and reviewers for their invaluable comments.

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Received 2 April 2008