Potential Carbon Sequestration in Japanese Forests during the First Commitment Period of the Kyoto Protocol

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Abstract: 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 through 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, the final year of the Kyoto Protocol's first commitment period. Forest land use and growing stock data were analyzed. Then, two models of forest land use change and growing stock were developed. Analytical results showed that most natural forest loss resulted from conversion to plantation forestland, while a minor portion was converted to other forms of land use. Carbon stock in Japanese forests increased from 857.3 TgC in 1966 to 1594.2 TgC in 2012, representing an increase of 16.0 TgC $year^{-1}$ over the same period. During the first commitment period of the Kyoto Protocol, annual carbon sequestration was estimated at 15.3 TgC, of which about 77.1% was sequestered in plantation forests. Only carbon sequestration in specially managed forests is credited under the Marrakesh Accord; thus, eligible carbon is expected to be lower. When data of specially managed forests become available, further study of eligible carbon sequestration is necessary because it could provide a baseline for decision making about the use of carbon sinks for carbon emission mitigation.

1. Introduction

Depending on management regimes, forests can either play a role in sequestering atmospheric carbon or release carbon into the atmosphere, exacerbating climate forcing. While forests in most temperate regions are net carbon sinks, tropical forests account for about one third of global carbon emissions (IPCC, 2001). The Kyoto Protocol, adopted in 1997 and enforced as of 16 February 2005, allows signatory countries to credit forest carbon sinks against greenhouse gas emissions under certain conditions. Japan is committed to reducing carbon emissions by 6% below 1990 emission levels. According to the latest report on greenhouse gas emissions published by the Ministry of Environment (MoE, 2005), the necessary reductions amount to 52.5 TgC annually (1 TgC = 10^6 ton C = 3.6 x 10^6 CO_2), or 14.1% 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. Three options have been considered: (1) carbon reduction through the ‘Kyoto mechanisms’ (1.6% of the total reduction target), (2) forest carbon sinks (13 TgC, or about 2.5% of the target), and (3) reduced domestic emissions (remainder of the target).

Forest carbon sinks in Japan have received much attention in recent years (Hiroshima and Nakajima, 2006; Yoshimoto and Marušák, 2007; Fang *et al*., 2005; Fukuda *et al*., 2003). 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), aboveground 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, forest carbon stocks were estimated at 692.0 and 1,027.7 TgC for the periods 1957-1961 and 1991-1995, respectively. Fukuda *et al*. (2003) estimated carbon stock change in plantation forests of sugi (*Cryptomeria japonica* D. Don) and hinoki (*Chamaecyparis obtusa* Endl.). 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 forest management subsidies. These figures account for about 63-68% of the capped amount under the Marrakesh Accord. However, no studies incorporating land use and carbon stock changes in all forest types have been performed. This report aims to estimate the potential carbon sequestration in Japanese forests under the current management trends during the first commitment period between 2008 and 2012. It is the first attempt to analyze potential carbon stock changes and sinks in both natural and plantation forests during this period.

The report is organized as follows: First, land use change in natural and plantation forests is analyzed and predicted until 2012. Second, carbon stock changes in both forest types are analyzed and predicted until 2012.

2. Methodology

This study only covers the aboveground carbon, which includes carbon in stems, branches and foliage.

2.1. Data collection and processing

Data on growing stock and land use change in plantation and natural forests for 1966, 1971, and 1976 were obtained from the Japan FAO Association (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. In these surveys, forest land use is classified as natural and plantation forests, treeless land (land recently cleared), or bamboo forests. Bamboo forest areas are small on a national scale and are not included in this study. Treeless land (*muritsu boku chi to*) is integrated into the natural forest classification because treeless land represents recently felled areas that sooner or later will be converted to plantation forests (Japan Forestry Foundation, 1992). Coniferous species account for 98% of all planted species, while broadleaved species account for 84.6% 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 meter, was converted to carbon units (MgC = 10^6 gC) using Brown's (1997) equation, as follows:

[1] $$CS_i = CD \cdot VD_i \cdot WD_i \cdot BEF_i$$

where the variables are defined as follows:

CS_i: Aboveground 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 (refer 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)

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 (*Cryptomeria japonica*), 0.34 Mg m^{-3} for hinoki (*Chamaecyparis 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 Mg m^{-3} and 0.540 Mg m^{-3}, respectively (see Table 1).

Table 1. Weighted averages of wood density (*WD*, Mg m^{-3}) and biomass expansion factor (*BEF*) 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)

** Greenhouse Gas Inventory Report in Japan, published by Center for Global Environmental Research (CGER, 2005) in 2005

2.2. Land use model

Based on Kim Phat *et al*. (2004), change in the area of natural and plantation forests can be estimated by

[2] $$\frac{dNF(t)}{dt} = -(k_a + k_b)NF(t)$$

[3] $$\frac{dPF(t)}{dt} = k_a NF(t)$$

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

t: Time step (year)

Trends in forest land use change in Japan can be broadly classified into two periods, 1966 to 1984 with high rates of conversion of natural forest to plantation, and 1984 to 2002 with lower conversion rates (Figure 1). To reduce trends in the analysis, the time series were divided into these two periods and separate sub-models were then fitted to the land use data for each period by simple linear regression. Equating and solving the equations for the two sub-models obtained the coordinate of the intersection between the sub-models. 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 is available, were estimated by extrapolation of the sub-model for 1984-2002.

2.3. Carbon stock change per hectare

Per hectare (per-ha) carbon stock change in natural and plantation forests can be estimated by the Richard Growth Function as follows:

[4] $$CS_i(t) = \frac{a_i}{(1 + e^{b_i - c_i \cdot t})^{1/d_i}}$$

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 dataset 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

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

2.4. Carbon stock changes in all forests

Total carbon stock changes in Japanese forests can be estimated by

$$\begin{aligned}
&C_i(t_0) = L_i(t_0)\cdot CS_i(t_0)\\
&C_i(t_1) = L_i(t_0)\cdot CS_i(t_1) + L_i(t_1)\cdot CS_i(t_0)\\
&C_i(t_2) = L_i(t_0)\cdot CS_i(t_2) + L_i(t_1)\cdot CS_i(t_1) + L_i(t_2)\cdot CS_i(t_0)\\
&\cdot\\
&\cdot\\
&\cdot\\
&C_i(t_n) = L_i(t_0)\cdot CS_i(t_n) + L_i(t_1)\cdot CS_i(t_n - 1) + \cdots + L_i(t_n)\cdot CS_i(t_0)
\end{aligned} \quad [5]$$

where the variables are defined as follows:

$C_i(t_n)$: Carbon stock in forest '*i*' in year '*n*' (MgC $year^{-1}$)

$L_i(t_n)$: Change in area of forest '*i*' in year '*n*' compared to 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 is available.

3. Results and Discussion

3.1. Area of forestland

Based on the land use sub-models, the area of natural forest in Japan decreased from 17.1 million ha (95% lower = 13.9, 95% upper = 21.1) in 1966 to 15.0 million ha (95% lower = 11.7, 95% upper = 19.3) in 1984, representing a change of -0.72%

($k_a + k_b = -0.0072$), or a loss of about 0.12 million ha year^{-1} (Figure 1). Over the same period, plantation forest area increased 0.6% (k_a=0.006), or about 0.10 million ha year^{-1}. For the second period from 1984 to 2012, the loss of natural forest decreased to about 0.17% ($k_a + k_b + 0.0017$), or 25,294.7 ha annually. Plantation forest area increased about 0.08% (k_a = 0.0008), or about 11,250.0 ha year^{-1}, during the second period between 1984 and 2012 (Figure 1). Overall, Japan lost about 60,431.5 ha of natural forest, but gained about 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).

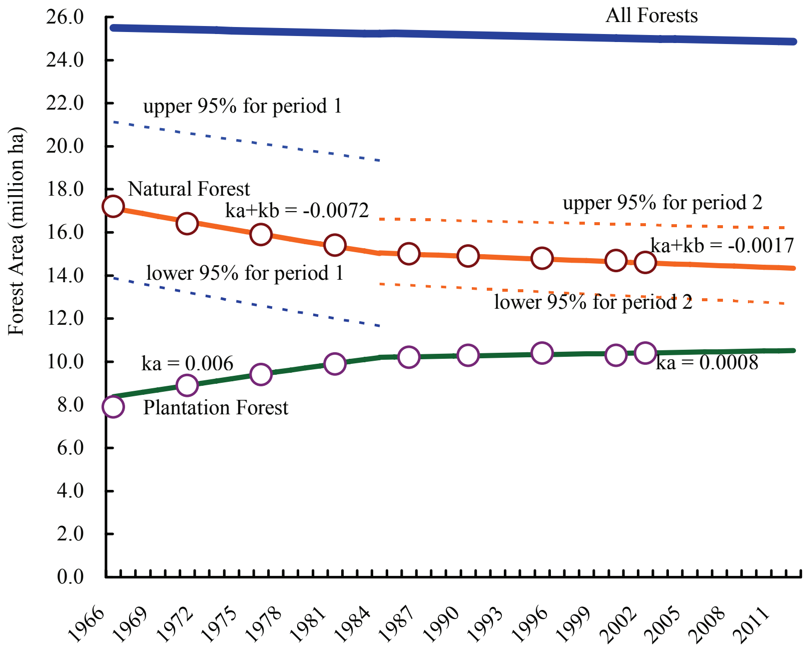

Figure 1. Change in area of all forests in Japan (1966-2012)

3.2. Carbon stock change per hectare

The carbon stock model (equation [4]) suggested that carbon stock in natural forests increased from 37.4 MgC ha^{-1} in 1966 to 58.3 MgC ha^{-1} in 2012, representing an annual increase of about 0.5 MgC ha^{-1}. During the first commitment period between 2008 and 2012, annual carbon sequestration is estimated at 0.3 MgC ha^{-1}. In contrast to the moderate increase in natural forests, carbon stock in plantation forests increased about fivefold between 1966 and 2012, from 18.7 MgC ha^{-1} in 1966 to 78.1 MgC ha^{-1} in 2012. This represents an average increase of 1.3 MgC ha^{-1} year^{-1} over the whole period and about 0.9 MgC between 2008 and 2012 (Figure 2). On average, carbon stocks of all Japanese forests increased from 28.1 MgC ha^{-1} in 1966 to 68.2 MgC ha^{-1}, a rate of about 0.9 MgC ha^{-1} year^{-1}.

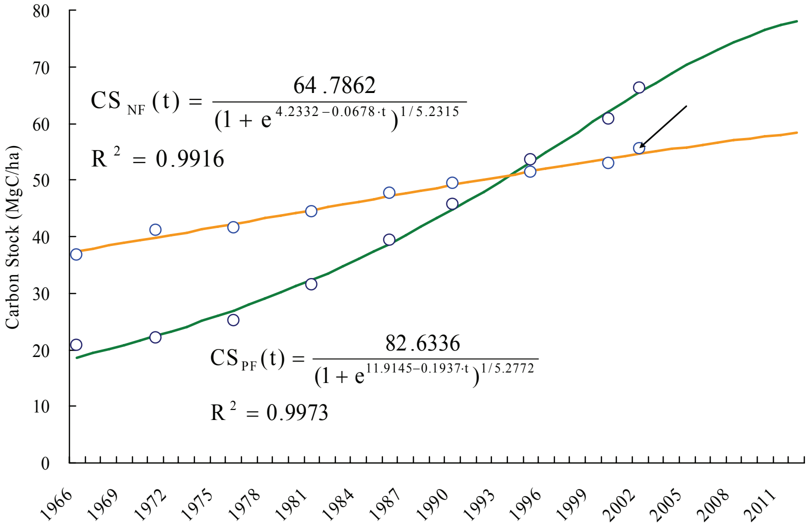

Figure 2. Per hectare carbon stock changes in Japanese forests (1966-2012)

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 (*Cryptomeria japonica*) plantations was estimated to range from 4.7 m^3 ha^{-1} year^{-1} (corresponding to about 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 (periodic annual increment) for sugi to be 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 about 4.9 MgC ha^{-1} $year^{-1}$ at 25 to 93 years of age in Kochi Prefecture.

MAI of hinoki (*Chamaecyparis obtusa*) at 60 years of age was estimated at about 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). Most of these studies were conducted in managed forests; thus, growth is likely to be higher than our model predicts because our model is based on an average of all plantation forests.

It should be noted that sugi, hinoki, and *Larix* account for 44%, 24%, and 10% of all planted tree species in Japan, respectively.

3.3. Total carbon stock change in Japan

According to the model (Equation [5]), carbon stocks in natural and plantation forests, respectively, increased from 832.3 and 128.2 TgC in 1966 to 1022.7 and 787.7 TgC in 2012 (Figure 3). Averaged over the period 1966-2012, carbon sequestration in Japanese forests is estimated at about 14.3 and 4.1 TgC for plantation and natural forests, respectively. For the first commitment period (2008-2012), the sequestration is estimated at 13.9 and 3.9 TgC $year^{-1}$ for plantation and natural forests, respectively (Figure 3). This gives a total of 17.8 TgC $year^{-1}$, higher than the allowable carbon sinks as capped under the Marrakesh Agreement. However, this study did not attempt to separate the Kyoto forests (specially managed forests whose carbon sinks are eligible under the Kyoto agreement) from other forests. Carbon sinks for eligible forests are likely to be considerably lower. Further study of carbon sinks in Kyoto forests will provide deeper insight into the increasingly important role of forest management in carbon emission mitigation. This should be the next priority study on carbon sinks in Japanese forests.

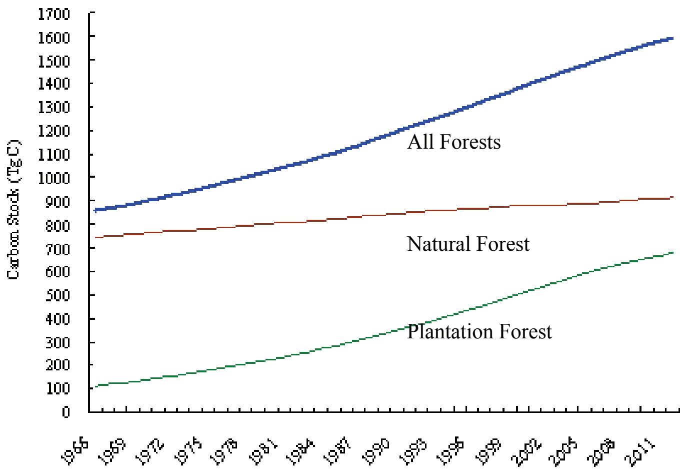

Figure 3. Overall carbon stock changes in Japanese forests (1966-2012)

3.4. Study uncertainties

The Biomass Expansion Factor (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. Dividing the estimates among species and age classes, and using separate BEFs for each, could go a long way toward reducing this uncertainty.

4. Conclusion

This study provides an estimate of forest land use change, carbon stock changes, and carbon sequestration in Japanese forests, under current 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 have been replaced by plantation forests whose commercial timber growth and yield is much faster and higher. Between 1966 and 1984, natural forest area decreased at an annual rate of 0.72%. 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 17.8 TgC $year^{-1}$, more than the amount capped under the Marrakesh Agreement. However, only carbon gained in specially managed forests is eligible under the agreement; thus, Japan must provide detailed information about the forests selected for carbon credits. Once data on specially managed forests becomes available, further study of eligible carbon sequestration will be necessary - providing a baseline for decision making using carbon sinks as an option for mitigation of greenhouse gas emissions and climate change.

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京都議定書第1約束期間における日本の森林の炭素固定可能量

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要約：大気中の炭素を吸収する森林の役割は京都議定書で認知されており，締約国は排出削減策のオプションとして森林を利用することが認められている．日本の森林における炭素貯蔵量の変化を推定した研究はいくつかあるが，大半は変化量を1995年までのみ推定しているか，あるいは天然林における炭素貯蔵量の変化を無視している．本研究は初めて，1966年から京都議定書第1約束期間の最終年度である2012年までの日本の森林における炭素貯蔵量の変化量の推定を試みた．森林地の利用状況と成長蓄積データを分析した．そして，森林地利用の変化と成長蓄積について2つのモデルを開発した．分析の結果，天然林消失のほとんどが人工林への転換によるものであり，他の利用形態への転換は少ないことが示された．日本の森林における炭素貯蔵量は1966年の857.3TgCから2012年には1594.2TgCに増加するが，これは同期間に16.0 TgC 年-1の率での増加を表している．京都議定書は第 1 約束期間における年間の炭素固定量を15.3TgC，このうち77.1 %が人工林に固定されると推定されていた．マラケシュ合意の下では特別に管理された森林における炭素固定量のみが勘定されるため，これに該当する炭素量は少なくなると考えられる．勘定に含めることのできる炭素固定量については，特別管理された森林に関するデータが炭素排出削減を目的とする炭素吸収源の利用に関する決定におけるベースラインとなり得るものであることから，これが利用可能になった時点で，さらに進んだ研究を行う必要がある．

キーワード：森林炭素吸収量，土地利用変化，森林炭素固定量