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Potential carbon stock in Japanese forest soils - simulated impact of forest management and climate change using the CENTURY model

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Shortened title: Potential carbon stock in Japanese forest soils

Abstract

Forest management and climate change may have a substantial impact on future soil organic carbon (SOC) stocks at the country scale. Potential SOC in Japanese forest soils was regionally estimated under 9 forest managements and a climate change scenario using the CENTURY ecosystem model. Three rotations (30, 50, 100 yr) and three thinning regimes were tested: no-thinning; 30 % of the trees cut in the middle of the rotation interval (e.g. year 15 in 30-yr rotation) and thinned trees all left as litter or slash (ThinLef) and the trees from thinning removed from the forest (ThinRem). A climate change scenario was tested (ca. 3 °C increase in air temperature and 9 % increase in precipitation). The model was run at 1 km resolution using climate, vegetation and soil databases. The estimated SOC stock ranged from 1600 to 1830 TgC (from 6800 to 7800 gC/m^2), and the SOC stock was largest with the longest rotation, and was largest under ThinLef with all three rotations. Despite an increase in net primary production, the SOC stock decreased by 5 % under the climate change scenario.

Keywords: soil organic carbon, forest soil, carbon sequestration, Kyoto Protocol, forest management

Introduction

Country scale carbon stocks and carbon budgets of forests are of great interest in climate change research (Kurz *et al.*, 2009). The Kyoto Protocol requires each signatory to reduce carbon emissions by limiting fossil-fuel combustion, as well as allowing countries to increase terrestrial carbon sinks to meet emission reduction targets. In Japan the national target for the forest C sink is set as 13 MtC, so that the forest carbon sink is of critical importance.

Globally, the soil carbon stock (ca.1500 PgC) is significantly greater than that in living plant biomass (500 PgC) or in the atmosphere (730 PgC in 1980s) (IPCC, 2001), hence the dynamics of soil organic matter are important for understanding the carbon cycle (Smith *et al.*, 1997, 2005, 2006; Falloon *et al.*, 1998; Liski *et al.*, 2001; Lal, 2004). In contrast to forest plant biomass inventories, soil inventory datasets are generally limited due to the high costs of soil sampling and analysis. As a result modelling approaches are often needed (Liski *et al.*, 2001; Seely *et al.*, 2002; Peltoniemi *et al.*, 2007).

Forests (plant biomass and soil) are an important carbon stock and harvested timber is also a key natural resource. The importance of forest wood products is increasing since they are renewable resources with multiple uses. It is essential to assess the impact of forest management on forest carbon stock in order to balance the competing needs of increasing forest carbon stocks and meeting the increased demand for timber. Forest management (e.g. through rotation length and thinning regime) affects the amount of carbon not only in plant biomass, but also in soil (Liski *et al.*, 2001; Taylor *et al.*, 2008). When forests are harvested or thinned, some of the plant carbon is removed from the forest ecosystem, and a fraction is left on the forest floor or in soil. The change of tree biomass results in a changes in litterfall and in the forest micrometeorological environment (temperature and moisture). The biomass left on the forest floor can decompose and contribute to soil carbon inputs. It is therefore important to assess the impact of forest management on forest soil organic carbon (SOC) stocks (Ågren & Hyvönen, 2003).

Predicted climate change will also alter the stock and budget of forest carbon. In particular, climate change will strongly influence the carbon stock and budget. Plant photosynthesis probably increases with climate change to some extent which can result in an increase in litter input to soil, although this is potentially counteracted by increased litter and soil organic matter decomposition (Smith *et al.*, 2006). Because the stock of SOC results from the balance between litter input and decomposition, the change of the SOC stock due to climate change is quite uncertain, and probably differs between regions and vegetation types.

Here we present the first regional assessment of carbon stocks in Japanese forest soils using the CENTURY ecosystem model. We combined climate, vegetation and soil databases and ran the model at 1-km resolution for all Japanese forests. The annual NPP data product of the Moderate Resolution Imaging Spectroradiometer (MODIS) was used for the parameterization of net primary production (NPP) submodel. We applied different scenarios of forest management and climate change and determined the impact on SOC stocks.

Materials and methods

Forest vegetation and soils in Japan

Japan lies between 45 °33' N, 153 °59' E and 20°25 N', 122 ° 56'E, and consists of four main islands with thousands small islands. The total land area is ca. 378000 km^2 of which >240000 km^2 are forested (ca. 66 % of the land area) (Sasse, 1998). The annual mean temperature ranges from around 0 °C in areas of high elevations in the north to >20 °C in southern islands, and annual precipitation ranges from ca. 700 mm to >3500 mm. In Japan rainfall is high in summer and low in winter. The southern regions experience high rainfall, mainly due to a monsoon season and typhoons, and the coastal areas of Japan receive greater snowfall during the winter.

Figure 1 shows the distribution of forest vegetation types and soil groups. The distribution of forest vegetation was derived from the database of the Japanese Integrated Biodiversity Information System (J-IBIS), and distribution of soil groups was derived from Digital National Land Information; these databases are described briefly below. The two most prevalent forest types are coniferous (mainly evergreen) and broad-leaved (mainly deciduous) forests. The coniferous forests are widely distributed from north to south; the broad-leaved forests are mainly in the north. Brown forest soils, mainly equivalent to Cambisols (FAO, ISRIC, & ISSS, 1998), are the most widely distributed group (70 %) and other major soil groups are Black soil (Andosols; 12 %), Immature soils (Regosol, Arenosol, Fluvisol, Leptosols 4 %) and Podzolic soils (Podozol 4 %) (Table 1).

Datasets

We used the databases at a resolution of 1km. Monthly rainfall and monthly mean air temperature were taken from the Mesh Climatic Data 2000 (Japan Meteorological Agency, 2002). The database includes 30-yr monthly means for the period 1971-2000.The land-cover dataset from the Japanese Integrated Biodiversity Information System (J-IBIS) was used in this study. The database has >300 small vegetation units from which we aggregated forest vegetation to 4 types (coniferous, broad-leaved, mixed, and shrub forest).

The raster soil map in the Digital National Land Information system was used. The soil units used in the database correlate with the Japanese forest soil classification system (Forest Soil Division, 1976) and we aggregated the detailed soil units into 8 soil groups (Podzolic soils, Brown forest soils, Red and Yellow soils, Black soils, Dark red soils, Gley soils, Peaty soils, and Immature soils) and 2 other classifications (Rocky, and no-classification) (Table 1). In order to apply the CENTURY model, we excluded Peaty soils, Gley soils and Podzolic soils; the area of those soils is ca. 5.5 % of the Japanese forest area. In a previous study of SOC stock in Japanese forests (Morisada *et al.* 2004), soils were categorized into 15 soil units; we categorized soils into 10 groups (8 + Rock + NoData). Morisada *et al.* (2004) divided some soils into subgroups, but the sub-grouping was not standard. For simplicity, we adopted the "group" level of categorization, and did not divide into subgroups. We used soil physical and chemical properties derived from the soil database compiled by Morisada *et al.* (2004). We calculated the average values of those soil properties for each soil group and used them in the model calculations (Table 1).

The CENTURY model and its parameterization

We estimated the potential carbon stock by running the CENTURY ecosystem model with scenarios of different forest management and climate change. The CENTURY model can simulate C and N cycling in various ecosystems, from grass land to forest, and it is one of the most widely used plant-soil ecosystem models (Parton *et al.*, 1988; Falloon & Smith, 2002). The model is described in detail elsewhere, for example Parton *et al.* (1988).

The parameters used in this study were mostly from the default parameters in “AND” (evergreen coniferous) and “CWT” (broad-leaved deciduous) vegetation types which were included in the CENTURY ver. 4 package. We applied the CWT parameter set for broad-leaved forest and applied the AND parameter set for other vegetation types in our calculations. Several parameters were changed in order to reconstruct a database of NPP and stem biomass data (see below). The parameters tuned from the default parameter sets are shown in Appendix A. In addition, we modified the source code of the CENTURY model in order to apply the model to volcanic ash soils and change the allocation pattern of NPP in tree submodels. The modifications are given in Appendix B.

Forest management scenarios

We combined the three rotation lengths and three thinning types to examine the impact of forest management on SOC stocks. The assumed rotation lengths are 30 yr (short), 50 yr (middle), and 100 yr (long). The three assumed different thinning regimes are as follows:

1. NoThin: no-thinning was assumed, and no biomass removal was done except for the harvest at the end of the rotation.

2. ThinLef: 30 % of the trees were cut in the middle of the rotation (e.g. 15 yr in 30-yr rotation), and thinned trees were all left as litter.

3. ThinRem: 30 % of the tree volume was cut in the middle of the rotation as with ThinLef, but the boles of the thinned trees were removed from the forest.

In every clear-cutting and thinning, it is assumed that the branches and leaves were left at the site. The decline in the domestic timber market has led to a reduction of forest maintenance with some forests left without thinning whilst for others thinned trees are left on the forest floor.

Parameterization of NPP

We parameterized the model for NPP and biomass. The annual NPP data product (MOD17A2/A3) of the MODIS which is available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) was used for NPP parameterization. Unfortunately there are only limited NPP data on Japanese forests, while the MODIS NPP dataset is the most widely used global NPP dataset and covers Japan at 1 km resolution. We considered that parameterizing the NPP submodel with a limited number of ground-based NPP observations was not necessarily sound given the difficulty of comparing regional output of modelling and ground-based measurements;

instead we concluded that parameterization with the regional-scale NPP database (or MODIS NPP) was suitable for our regional assessment. The dataset was derived by combining a simple ecological model (algorithm) and satellite data. Although this has not been specifically evaluated for Japanese forests, the dataset has been evaluated against ground observation data, and the MODIS NPP estimates showed no overall bias in that evaluation (Turner *et al.* 2005, 2006). However the dataset could produce high NPP estimates for some grids (Pan *et al.* 2006; Hashimoto *et al.* 2011), which could be caused by mixed pixels of land and sea. The detail of the NPP estimation of MOD17 is described by Running *et al.*(2000). The mean value from 2000 to 2006 at 1 km resolution was calculated and was used in this study. After parameterization the correlation coefficient for the results from MODIS NPP and CENTURY was 0.41, and the mean deviation measured by the Root Mean Square Error (RMSE) was 223 gC/m ^{2}/yr (Janssen & Heuberger, 1995). The total NPP estimates were between 170 to 190 TgC/yr (average, 180 TgC/yr and a range from 700 to 800 gC/m^2/yr).

Parameterization of plant biomass

Allocation patterns which are carbon distribution patterns were parameterized using two databases, the long-term yield plot database of the Forestry and Forest Products Research Institute for coniferous forest (Forestry and Forest Products Research Institute, 2001), and data in the World Forest Biomass database for broad-leaved forest (Cannell, 1982). The model output of stem carbon for coniferous forests was compared against the long-term yield plot database of the Forestry and Forest Products Research Institute, Japan. We used the dataset in Kanto district (central area of Japan; Forestry and Forest Products Research Institute, 2001). The data for Sugi (Japanese cedar; *Cryptomeria japonica D. Don*) and Hinoki (Japanese cypress; *Chamaecyparis obtusa Endl.*) which are the major two species in Japanese forests were used. The stem volume data (m^3/ha) were converted to the carbon mass using a bulk density of 319 kg/m^3 for Sugi and 360 kg/m^3 for Hinoki and the assumption was that the carbon content is ca. 50 % of the dry weight (Fukuda *et al.*, 2003).

The model output of stem biomass for broad-leaved forests was compared against observed data reported by Cannell (1982) which contains the amount of dry weight of world forests. We selected data representative of Japanese broad-leaved forests, and calculated the amount of stem biomass, assuming that the carbon content was ca. 50 % of dry weight. The data were obtained mainly by the International Biological

Programme (IBP) during 1960s and1970s. After parameterization, although the model failed to reproduce the very high stem volume, the model outputs correlated well with observations. The correlation coefficients calculated using data <15000 gC/m^2 were 0.91 and 0.86, respectively, and the RMSEs were 1702 and 1701 gC/m^2, respectively.

Impact of climate change

We evaluate the predicted impact of climate change on SOC stocks by conducting the simulation under a climate change scenario (Table 2). The scenario was based on projections of regional averages of temperature and precipitation from a set of 21 global models for the A1B scenario and for East Asia which is reported in chapter 11 of IPCC (2007). We used the median values of the predictions. The CENTURY model requires maximum and minimum monthly mean temperatures; then, all temperature measures in every month were increased in the climate change calculation. In this study we simulated the steady state conditions (average of the last 100 yr of a 4100 yr simulation; see below), not the transient impacts. We investigated the relative change of the NPP and SOC stock corresponding to the climate change.

Calculation

The number of forest grid cells simulated was ca. 235000. For each grid cell the model was first run for the first 400 yr (spin-up) to distribute the carbon between the different pools in the soil. The model was then run with each forest management scenario for 4100 yr. We used the average values of the last 100 yr in our calculations. Because the output of SOC from the CENTURY model is for 20 cm soil depth, the estimated SOC values in our calculation were SOC to 20 cm depth.

Results

Comparison of SOC estimates with other studies

It is difficult to directly compare our SOC estimates with other studies because no previous study has regionally estimated SOC stocks to 20 cm depth in all Japanese forest soils, and the values we estimate are the equilibrium value or the potential carbon stock, not the estimates of present stocks. However we have compared our estimates with previous estimates of SOC stocks to 30 cm depth (Morisada *et al.*, 2004) to check whether our estimates were of the same magnitude. Morisada *et al.* (2004) compiled previously reported SOC data and estimated SOC stock to 30 cm and 100 cm depth for Japanese soil units. Figure 2 shows the comparison between SOC to 30 cm depth reported by Morisada *et al.* (2004) and the estimates from our study. In general, SOC stock decreases with increasing depth; then, SOC stock to 20 cm depth is larger than 2/3 of SOC stock to 30 cm depth (above the 3:2 line in Figure 2), and smaller than the SOC stock to 30 cm depth (below 1:1 line in Figure 2). The estimates of most soil groups were between the 1:1 and 3:2 lines, except for Im (Immature soils). The approximate ratio of SOC stock to 20 cm depth to that to 30 cm is 80 % (A. Imaya, personal communication based on data of Imaya *et al.* (2008) and Imaya (2008) for mainly Brown forest soils but including other soil types). The points for the two major soil types, B and Bl, were near the 5:4 line, indicating the ratio of SOC stock estimated in this study is 80 % of the Morisada's estimates. Immature soils are, as the name suggests, still far from equilibrium. Immature soils occur mostly in areas strongly affected by previous over-use. Forests were established on Immature soils in the recent past while soils have probably not yet recovered because SOC accumulation is slow. Our estimate is the value at equilibrium which is probably the reason for the over estimation by the model.

Potential carbon stock

The estimated SOC stock for all of Japan's forests ranged from 1600 to 1830 TgC (average, 1720 TgC; from 6800 to 7800 gC/m^2; Figure 3a). The SOC stock increased with increasing rotation length under NoThin, while those under 100 yr were largest, and those under 50 yr were smallest under ThinLef and ThinRem. The differences between rotation lengths were smaller under ThinLef and ThinRem than under NoThin. With regard to thinning type, the SOC stock was largest under ThinLef with all three rotation lengths.

The biomass stock of all Japan's forests was estimated to be between 480 to 1940 TgC (average 1110 TgC; from 2000 to 8300 gC/m^2; Figure 3b). Under every thinning type the stock increased with increasing rotation length. The biomass carbon stock was largest under NoThin with all rotation lengths. The carbon stock in non woody litter (leaf and fine root litter) ranged from 180 to 210 TgC (average 190 TgC; from 800 to 900 gC/m^2; Figure 3c). As for the SOC stock, the carbon stock in non woody litter under NoThin increased with increasing rotation length, while the carbon stock was largest with the shortest rotation length of 30 yr under both ThinLef and ThinRem. The largest stock was under ThinLef with every rotation length. The differences in stock among scenarios were very small. The carbon stock in woody litter (branch, stem and coarse root litter) ranged from 170 to 450 TgC (average 310 TgC; from 700 to 1900 gC/m^2; Figure 3d). The carbon stock increased with increasing rotation length. The stock was largest under ThinLef with all rotation lengths, while the values for NoThin were of the same magnitude with each rotation length. The stock was smallest under ThinRem.

Distribution of SOC

Figure 4 shows the estimated distribution of SOC stocks. The values were the average values of the nine forest management types (3 rotation lengths × 3 thinning types). The estimated SOC was high in the north-east regions, especially the northern island and east coast (>8000 gC/m^2). In the south-west regions, the SOC was higher inland (>8000 gC/m^2) than in coastal areas (ca. 6000 gC/m^2). The area of volcanic ash soil (Figure 1) has higher SOC than other areas.

Impact of climate change

Figure 5 shows the changes in NPP and SOC under the climate change scenario. On average, the NPP increased by ca.14 % whilst the SOC stock decreased by ca. 5 %. Although there were no major differences in impact of climate change among the nine management scenarios, the longest rotation length resulted in the smallest loss of SOC and with regard to thinning regime, ThinLef showed the smallest loss of SOC.

Discussion

Impact of forest management

Our simulations suggest that the longest rotation length results in the largest SOC stock. There are several modelling studies which investigated the impact of forest management on SOC stock: for example, Liski *et al.* (2001) analyzed using models the impact of rotation length (60, 90, 120 yr rotation length) on the forest carbon budget in plantations of Scots pine and Norway spruce in southern Finland. Although the rotation lengths they tested (60, 90 120 yr) were different from our study, they showed that SOC stock slightly decreased with increasing rotation length. Seely *et al.* (2002) investigated the effect of harvesting practices on carbon stocks and budget with an ecosystem simulation model called FORECAST (30-200 yr rotation length). In their results, SOC stock increased with increasing rotation length, which agrees with our results using CENTURY.

Other modelling studies such as by Liski *et al.* (2001) and Seely *et al.* (2002) show that biomass carbon stock increased considerably with greater rotation length though changes in SOC stock were relatively small compared to biomass carbon stock. The difference in non-woody litter stock was relatively small, but the difference in coarse woody litter was larger than that of non-woody litter and the same magnitude as that of the soil; this is to be expected since coarse woody litter (e.g. bole and dead roots) is one of the most substantial carbon pools in forest ecosystems.

The effect of leaving cut trees as residue (sometimes referred to as brash or slash) on the surface (ThinLef) resulted in the largest SOC stock. Our simulations show that not only the rotation length but also the thinning type affects SOC stock. For example, even with the short rotation length (30 yr), SOC stock was relatively higher when thinned trees were left at the site (ThinLef). This result may help with balancing the competing needs of increasing forest carbon stocks and increasing timber/bioenergy production.

Impact of climate change

In our simulations, climate change increased NPP but decreased total SOC, indicating that the potential increase of plant production due to climate change would not compensate for possible increases in decomposition of SOC due to climate change. Similar predictions are also reported, for example by Ågren & Hyvönen (2003) who investigated the impact of climate change on SOC stock in Swedish forests, and found that the SOC stock decreased by 10-30 % with +4 °C warming after 100 yr (simulation results of both production and decomposition increased). Smith *et al.* (2006) found that increased litter inputs balanced increased decomposition under climate change projections in Europe, but the increased inputs were largely derived from projected changes in the age class structure of European forests over the coming decades, rather than by climate mediated increases in NPP.

Potential importance of Immature soils

The estimated SOC stock in Immature soils was larger than that of observations and the difference was probably because Immature soils are still far from equilibrium. This indicates that Immature soils could act as a large sink for SOC despite occupying only a small portion of the total soil area (about 4 %). Similar areas with Immature soils can be seen in Asia such as in Korea and China. These areas could be significant for carbon sequestration in the future if forests are allowed to recover and are well managed.

Conclusion

This study is the first regional assessment of potential carbon stock in Japanese forest soils and of the impact of forest management and climate change on SOC stocks. The CENTURY model which is one of the most widely applied ecosystem models was used with detailed data on climate, vegetation and soil. This study shows the equilibrium value of SOC stocks but did not consider the required time for this change. The equilibrium values are useful for understanding the impact of forest management and climate change, and the limitation (maximum amount) of the carbon sequestration potential of forest soils. It is important to also predict the changes in SOC stocks and budgets which will be investigated in future studies. The area of forest in Japan has been almost constant for a hundred years and it is not considered likely that this will change much in the future. Rather, it is possible that forest management will change for higher timber/bioenergy production or carbon sequestration. Our simulations show that the longest rotation length results in the largest SOC stock, but the type of thinning also affects SOC stock as well as the rotation length. This result may offer a key to balancing the competing needs to increase forest carbon stocks and to increase timber/bioenergy production. Our predictions for Japanese forests are that climate change will increase NPP but decrease SOC. The possible impacts of forest management and potential climate impacts on SOC stock need to be considered to guide the planning of soil carbon management in Japanese forests.

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Tables

Table 1: Soil categories used in this study and physical and chemical properties. Soil properties for rock and debris were assumed by the author using that of Immature soil. Soil properties of Brown forest soil, which is the most widespread soil was used for the sites which could not classified (No-data in the table). Gley soils, Podozolic soils, and Peaty soils were not simulated in this study.

Soil Categories	Japanese classification	FAO	Area (%)	Bulk density (Mg/m^3)	Sand fraction	Silt fraction	Clay fraction	pH
B	Brown forest soils	Cambisols, Andosols	69.5	0.62	0.47	0.28	0.25	5.05
Bl	Black soils	Andosols	12.4	0.48	0.49	0.27	0.24	5.23
Dr	Dark red soils	Cambisols, Luvisols	0.2	1.03	0.40	0.26	0.34	6.13
G	Gley soils	Gleysols	1.4	0.57	0.46	0.28	0.26	5.17
P	Podzolic soils	Podzols	3.8	0.48	0.45	0.31	0.24	4.44
Pt	Peaty soils		0.3	0.43	0.44	0.32	0.24	4.80
Im	Immature soils	Regosols, Arenosols, Fluvisols, Leptosols	4.2	0.94	0.69	0.18	0.13	5.22
RY	Red and Yellow soils	Acrisols, Alisols, Cambisols	1.7	1.02	0.50	0.27	0.23	4.95
RK	Rock and debris	Regosols, Arenosols, Fluvisols, Leptosols	3.2	1.00	0.80	0.15	0.05	5.22
ND	No-data	-	3.3	0.62	0.47	0.28	0.25	5.05

Table 2: Climate change scenario used in this study. Those predictions are based on the regional averages of temperature and precipitation projections from a set of 21 global models for the A1B scenario and for East Asia, which is reported in chapter 11 of IPCC (2007). The changes are the differences between the 1980 to 1999 period and the 2080 to 2099 period. The values are the median of the predictions, and the maximum and minimum values are in parenthesis.

Season	Temperature (°C)	Precipitation (%)
Dec., Jan., Feb.	3.6 (2.1~5.4)	10 (-4~42)
Mar., Apr., May	3.3 (2.1~4.6)	11 (0~20)
Jun., Jul., Aug.	3.0 (1.9~5.0)	9 (-2~17)
Sep., Oct. Nov.	3.3 (2.2~5.0)	9 (-13~29)

Appendix A

Changed parameters in the default parameters in the CENTURY model. All parameters were in “tree.100”, which includes the parameters concerning tree growth and death. PPDF(1) is the optimum temperature for photosynthesis, and PPDF(2) is the maximum temperature. PPDF(3) and PPDF(4) are the shape parameters for temperature effect on photosynthesis.

Parameter	Coniferous forest	Broad-leaved forest
PPDF(1)	25.0	23.0
PPDF(2)	45.0	45.0
PPDF(3)	1.0	1.0
PPDF(4)	3.5	3.5
FCFRAC(1,1)	0.48	0.32
FCFRAC(2,1)	0.435	0.38
FCFRAC(3,1)	0.045	0.09
FCFRAC(4,1)	0.01	0.19
FCFRAC(5,1)	0.03	0.02
FCFRAC(1,2)	0.335	0.30
FCFRAC(2,2)	0.29	0.29
FCFRAC(3,2)	0.045	0.08
FCFRAC(4,2)	0.30	0.28
FCFRAC(5,2)	0.03	0.05
SWOLD	10	10

Appendix B

B 1 Modification of the CENTURY model

B 1.1 DECOMPOSITION CONSTANT FOR VOLCANIC ASH SOIL

Volcanic ash soils (Black soil) have been known to accumulate extremely large amount of organic carbon probably due to the stabilization by active metals like Al and Fe (Hiradate *et al.*, 2004). Accordingly, the model parameterized for non-volcanic ash soils (most soil organic models in the world) often failed to simulate volcanic ash soil and need to be improved for adaption (Shirato *et al.*, 2004). Shirato *et al.* (2004) proposed a scheme for modifying RothC model for Andosols, which used the pyrophosphate-extractable Al as the indicator for decomposability. They changed the decomposition constant of the HUM pool (humified organic matter pool or recalcitrant pool in the Roth C model), and find the model can simulate the SOC change in Andosols well. In consideration of the modification in RothC model, in this study, we modified the decomposition constant for passive pool (most recalcitrant pool) in the CENTURY model. The details of modification are as follows:

Total SOC in the model is the sum of three different SOM pools,

$$P_1+P_2+P_3=TC \quad (1)$$

where P_1 is the active SOC pool, P_3 is the passive SOC pool, P_2 is the intermediate SOC pool, and TC is the total SOC. According to the compilation by Morisada *et al.* (2004), the amount of SOC in Andosols in Japan (TC') is, in general,1.5 times larger than the normal soil type (e.g. Brown forest soil).

$$TC'=1.5\ TC \quad (2)$$

Our preliminary calculation showed that the ratio of P_3 to TC is 0.39 in the CENTURY model.

$$P_3=0.39\ TC \quad (3)$$

We assumed the high SOC stock in volcanic ash soil is the large passive soil pool (P_3'), which was modelled by the low decomposition constant.

$$P_1+P_2+P_3'=TC' \quad (4)$$

Combining these equations, we obtained following relationships between P_3 and P_3':

$$P_3'-P_3=TC'-TC=0.5\ TC \quad (5)$$

$$P_3'=P_3+0.5/0.39\ P_3=(1+0.5/0.39)\ P_3 \quad (6)$$

Assuming the steady state, SOC input to the pool (L) and the amount of decomposition are balanced,

$$L=k\ P_3=k'\ P_3' \quad (7)$$

where k is the decomposition constant of default value and k' is the modified decomposition constant for volcanic ash soil.

Then, we obtained modified decomposition constant for volcanic ash soil.

$$k'=1/(1+0.5/0.39)k=k/2.3 \quad (8)$$

We divided the default decomposition constant with 2.3 for volcanic ash soil.

B 1. 2 Allocation pattern for young age

The CENTURY model can change allocation patterns for each biomass compartment (e.g. foliage, stem) between a younger age stand and an older aged stand; however, we noticed that this switching is only valid at the initial rotation in the original code, and does not work in second or later rotations. We therefore modified the source code in order to implement the switching trees are cut and newly planted.

Figure Captions

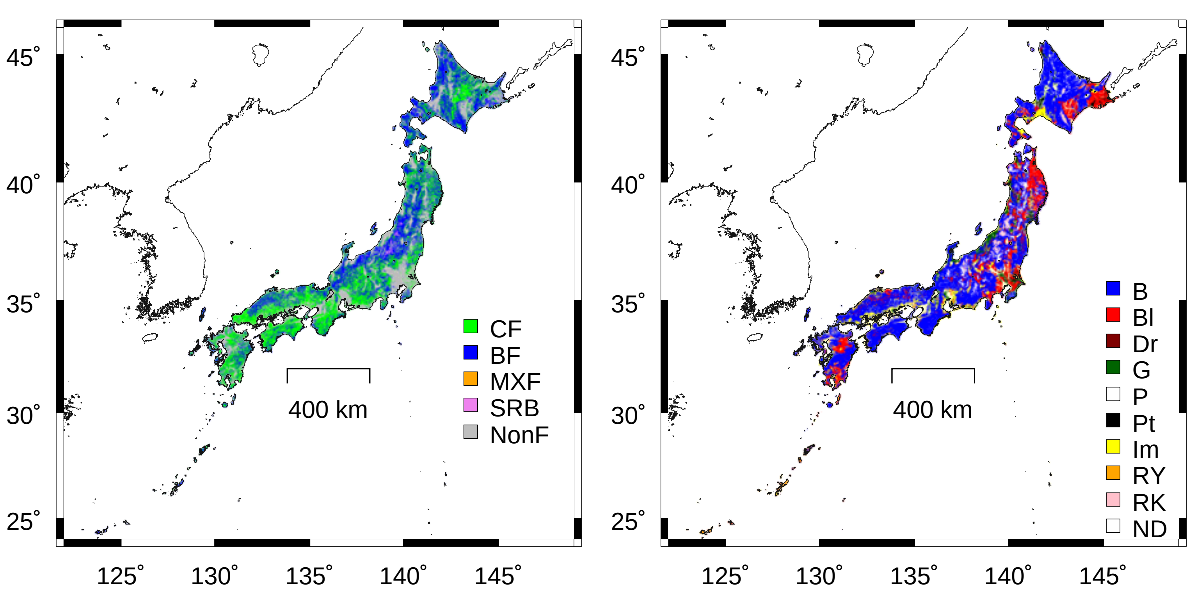
Figure 1: Distributions of biome types in Japan, based on the J-IBIS (left), and distributions of soil group (Digital National Land Information). Both databases were compiled by the authors for simpler classification. CF: coniferous forest, BF: broad-leaved forest, MXF: mixed forest, SRB: shrub forest, and NonF: non-forest area. See Table 1 for a list of soil types.

Figure 2: Comparison of SOC estimates with other study. SOC to 30 cm depth is the results from Morisada *et al.* (2004), and SOC to 20 cm depth are our estimates, and the average value of the all scenarios; bar indicates the standard deviation. See Table 1 for the soil types.

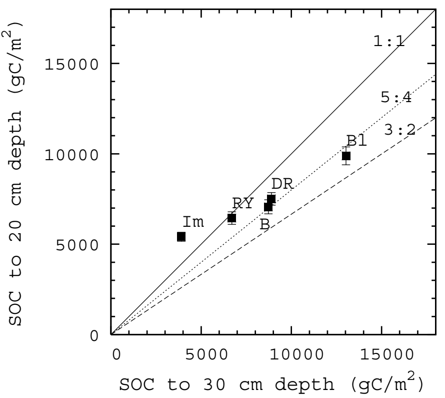
Figure 3: Total (left axis) and mean (right axis) carbon stocks under different management (30-yr rotation length, R30; 50-yr, R50; 100-yr, R100); SOC stock (a), biomass (b), non woody litter (leaf and fine root) (c) and coarse woody litter (branch, stem and coarse root) (d).

Figure 4: Distributions of the estimated forest SOC stock in Japan. The value is the average of all scenarios.

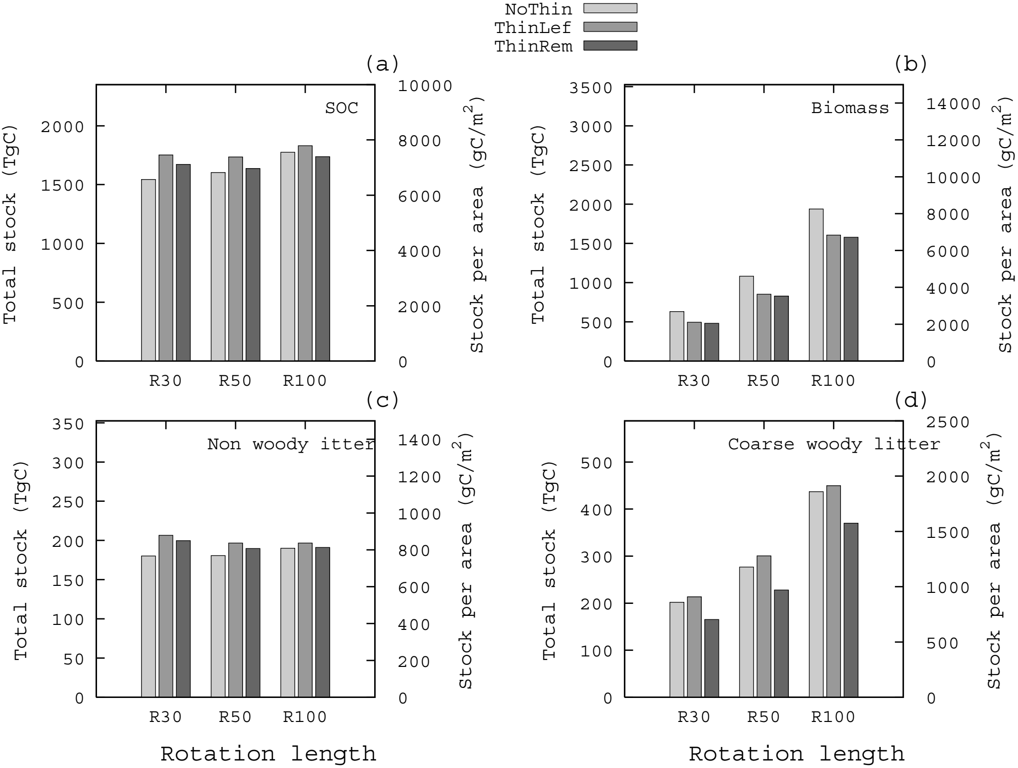
Figure 5: Change in total NPP and SOC under a climate scenario (30-yr rotation length, R30; 50-yr, R50; 100-yr, R100).



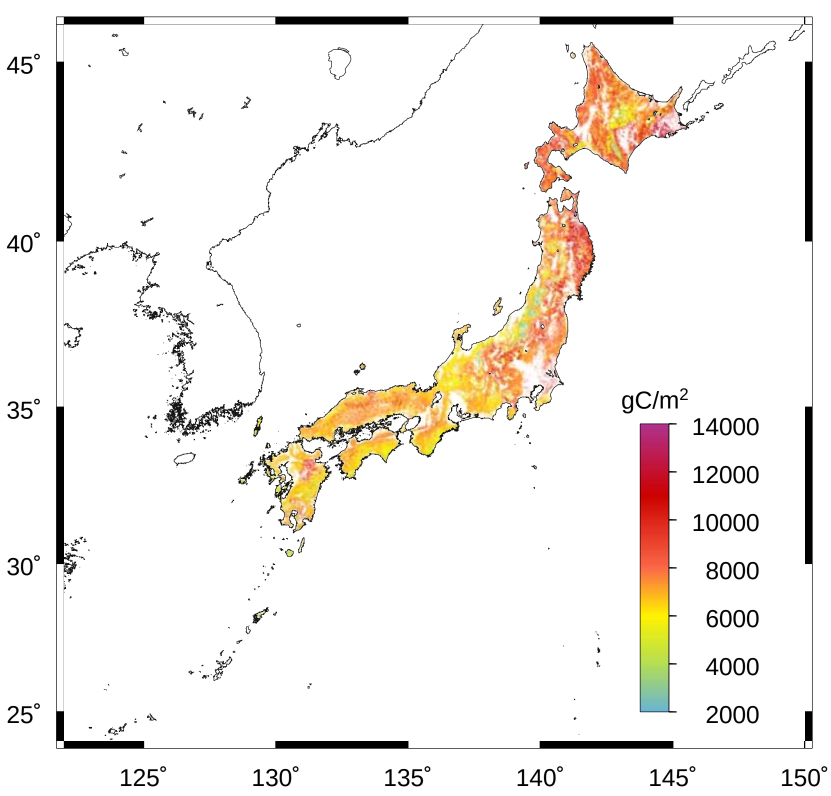
45°
40°
35°
30°
25°
125°
130°
135°
140°
145°
400 km
CF
BF
MXF
SRB
NonF
B
Bl
Dr
G
P
Pt
Im
RY
RK
ND



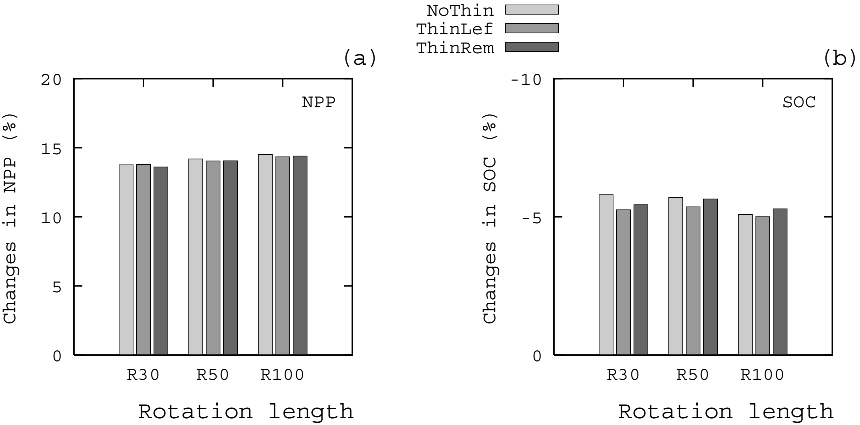
SOC to 20 cm depth (gC/m^2)
SOC to 30 cm depth (gC/m^2)
0
5000
10000
15000
1:1
5:4
3:2
Im
RY
B
DR
Bl



NoThin
ThinLef
ThinRem
(a)
SOC
Total stock (TgC)
Stock per area (gC/m2)
(b)
Biomass
(c)
Non woody itter
(d)
Coarse woody litter
R30
R50
R100
Rotation length



45°
40°
35°
30°
25°
125°
130°
135°
140°
145°
150°
gC/m²
14000
12000
10000
8000
6000
4000
2000


NoThin
ThinLef
ThinRem
(a)
NPP
Changes in NPP (%)
20
15
10
5
0
R30
R50
R100
Rotation length
(b)
SOC
Changes in SOC (%)
-10
-5
0
R30
R50
R100
Rotation length