Litter carbon inputs to the mineral soil of Japanese Brown forest soils: comparing estimates from the RothC model with estimates from MODIS

Shoji Hashimoto, Martin Wattenbach, Pete Smith

Soil Resources Laboratory, Department of Forest Site Environment, Forestry and Forest Products Research Institute (FFPRI), Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen

Full postal address of corresponding author
Soil Resources Laboratory, Department of Forest Site Environment, Forestry and Forest Products Research Institute (FFPRI), Incorporated administrative Agency, Matsunosato 1, Tsukuba, Ibaraki 305-8687, Japan
Tel: +81-29-829-8227, Fax: +81-29-874-3720
e-mail: shojih@ffpri.affrc.go.jp

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Abstract

The level of organic carbon found in soil is the result of the balance between litter input to the soil and decomposition. Litter input to the soil is closely related to net primary production (NPP); at equilibrium, the NPP is equal to the litter input to soil. Plant litter input to a depth of 30 cm in the mineral soil was estimated for the Japanese forest area using the Rothamsted Carbon model (RothC) and an average value of soil organic carbon (SOC) content, and was compared with estimated litter inputs from the NPP dataset from Moderate Resolution Imaging Spectroradiometer (MODIS). A Monte Carlo uncertainty analysis about the input SOC was also conducted in order to reveal the sensitivity and uncertainty of the model to input SOC. The litter carbon input calculated using RothC and that derived from MODIS NPP were positively correlated, but the mean estimated litter input from RothC was 17.2% smaller than that estimated from MODIS. Mapping the normalized difference showed spatial biases in the difference. The discrepancy was probably because of the different temperature controls between MODIS algorism and RothC model, and also our simple assumption of RothC calculation. This comparison shows a close linkage between litter inputs estimated from SOC data and litter inputs estimated from satellite-based NPP data. The discrepancies between the estimates merit further study.

Key words: soil organic matter, Rothamsted model, MODIS, NPP, modeling
Introduction

The global soil organic carbon pool size (~1500 PgC [1 Pg = 10^15 g]) is significantly greater than that in living plants (~500 PgC) or in the atmosphere (~730 PgC in 1980s) (IPCC 2001), hence, the dynamics of soil organic matter is critical for understanding of the global carbon cycle. Countries are required to assess changes in the carbon stocks of forest soils under the United Nations Framework Convention on Climate Change (UNFCC) and (for industrialized countries) under the Kyoto Protocol. However, in contrast to forest plant biomass inventories, soil inventory datasets are, in general, limited due to the higher cost of sampling and measuring soils. As a result, modelling approaches are often needed for the assessment (Peltoniemi et al. 2007).

The soil organic carbon level results from the balance between the rate of organic matter input (e.g. litter) to the soil and decomposition rate of the soil organic matter (Raich et al. 1997). Soil C inputs are closely related to net primary production (NPP), with higher productivity tending to lead to higher carbon inputs to the soil (Smith 2008). Higher soil carbon levels could result from either high NPP/litter input, low decomposition rates or a combination of the two (Smith 2008). An accurate assessment of NPP is hence essential for understanding the soil carbon cycle. NPP indicates the net carbon gain by the plant, and is an important index for evaluating changes in soil organic carbon, and also for estimating net ecosystem production. The International Biological Program (IBP) reported NPP values, mostly calculated from dry matter measurements (Cannell 1982), the data from which has been used in many models (Alexandrov et al. 2002). Ecosystem models are a useful tool for estimating NPP and for studying the carbon cycle (Cramer et al. 1999; Kurz et al. 2008) especially at regional scales (Ito 2003; Ito and Sasai 2006); ecosystem models are often applied at regional scale and used as a tool for estimating regional carbon stocks. The combination of ecological models with satellite data and field observation is a common approach for understanding and quantifying C turnover (Ciais et al. 2005; Chiesi et al. 2007; Maselli et al. 2008).

One of the most widely used NPP datasets, which was derived by combining a simple ecological model (algorithm) and satellite data, is the NPP data product of the Moderate Resolution Imaging Spectroradiometer (MODIS; dataset MOD17A2/A3). Gross primary production (GPP), and maintenance and growth respiration are estimated by satellite radiometric indices, and then NPP is calculated by subtracting respiration from GPP. GPP and maintenance respiration are estimated daily, and NPP is estimated annually. The method for deriving NPP was described in detail in Running et al. (2000). The dataset covers the global terrestrial surface at 1 km spatial resolution. MODIS NPP has been evaluated against ground observation data, and the MODIS NPP and GPP products showed no overall bias in the evaluation (Turner et al. 2005, 2006).

Jenkinson et al. (1999) proposed a method to estimate NPP utilizing measurements of soil organic matter and a soil organic matter model (RothC, Rothamsted Carbon turnover model). At equilibrium, NPP will equal plant litter C input to the soil (Jenkinson et al. 1999): when a forest is at equilibrium with respect to carbon, carbon inputs to the tree/soil system are balanced exactly by carbon losses from the tree/soil system, mainly through soil and tree respiration. Under these circumstances, the net carbon capture (i.e. the total amount captured through photosynthesis minus the amount respired back to the atmosphere through plant respiration; defined as the NPP) is equal to the carbon input from the tree to the soil. Under equilibrium conditions, therefore, the NPP is equal to the litter carbon input to the soil. Usually, soil carbon
turnover models receive organic matter input, and estimate changes in the soil organic matter content of the soil. In the Jenkinson et al. (1999) method, the NPP required to balance the measured SOM content is inversely calculated, if the soils can be assumed to be at equilibrium (Jenkinson et al. 1992, 1999; Jenkinson and Coleman 1994). In other words, in the inverse application, the amount of soil carbon is used by the soil carbon model to back-calculate the litter carbon input needed to maintain this carbon stock. This is a very common initialization process in applying the RothC model (e.g. Smith et al. 2005, 2006). However, there are few studies that have examined the relationships between estimated litter input from RothC model and estimated litter inputs from other NPP data (e.g. biometric based estimates, flux based estimates, satellite based estimates).

If satellite-derived NPP data can be used to update soils models, modeling systems could be developed that use soil carbon or ecosystem models and remotely sensed NPP data to estimate changes in forest soil carbon stocks under future climate/land management (potentially in real time), for scientific purposes or for accounting under post-Kyoto climate agreements. In this study, we test how well estimated of litter input to the soil from satellite derived NPP estimates match estimated carbon inputs required by soil models, by back-calculating the input of carbon to the soil with the RothC model (using mean soil carbon values) and comparing these with litter inputs estimated from MODIS (equal to MODIS NPP values). If they match well, the approach deserves further evaluation. If the match is poor, this suggests that the approach may not be fruitful.

The purpose of this study is, therefore, to estimate litter input to mineral soil from soil organic matter using Rothamsted soil carbon model in Japanese forests on Brown Forest Soils, to compare the values to those of the MODIS NPP dataset, and to examine the spatial distribution of any discrepancy. In this study, we assume equilibrium so that MODIS NPP is equivalent to plant litter input to soil. Hereafter, we refer to this as “MODIS litter input”. The C input estimated by RothC to match the observed mean carbon content is hereafter referred to as “RothC litter input”

**Materials and methods**

**Study site**

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 (Fig. 1). The total land area is about 378000 km², of which over 240000 km² are forested (about 66 % of the land area) (Sasse 1998). Annual mean temperature ranges from around 0 °C (north area) to above 20 °C (south islands), and annual precipitation ranges from around 700 mm to above 3500 mm. In Japan, rainfall is in general high in summer and low in winter, but in the coastal regions and in the northern region, the amount of precipitation is constant throughout the year because of relatively low rainfall in summer and high snowfall in winter. The southern regions experience large rainfall, mainly due to a rainy season and typhoons, and northern coastal areas receive large snowfall during the winter.

The raster soil map of the Digital National Land Information was used in this study (Ministry of Land, Infrastructure, Transport and Tourism 1979). The raster map consists of 30” (latitude) × 45” (longitude) grid (about 1-km grid) data. The database classified the Japanese soil into more than 70 soil units, which was too detailed for our purpose. The soil unit used in the database is correlated with the Japanese forest
soil classification system (Forest Soil Division 1976); so we aggregated 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. In this study, we focus on the forest on Brown forest soil (mostly Cambisols and some Andosols; FAO, ISRIC, and ISSS 1998), the most widely distributed soil group. About 70 % of the forest soils are Brown forest soil (Morisada et al. 2004). The area with Immature soils (Regosols, Arenosols, Fluvisols, Leptosols) and Black soils (Andosols), which are the other major soil groups, are not included in this study. Immature soils are, as the name suggests, strongly affected by the previous forest use and erosion; the soil organic matter content is much smaller than Brown forest soil, and the soils are very unlikely to be in equilibrium. Black soils (Andosols) have higher soil carbon content, probably due to the inhibition of decomposition and, in some cases, previous grass vegetation (Hiradate et al. 2004). Like immature soils, it is difficult to simulate soil carbon dynamics of Andosols using most commonly-used models. Shirato et al. (2004) proposed a scheme for modifying RothC model for Andosols, which used the pyrophosphate-extractable Al as the indicator for decomposability. However, the pyrophosphate-extractable Al for Japanese forest soils is not yet known regionally. The brown forest soils group also includes some Andosols; however, we could not eliminate the area of Andosols because of the limitation of the database and classification. But most of the Andosol area is extracted by excluding the Black soil group.

MODIS NPP dataset
The annual NPP data product of the Moderate Resolution Imaging Spectroradiometer (MODIS) was used (MOD17A2/A3), which is available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC; 2005). In the products, daily GPP, leaf and fine root maintenance respirations, and net photosynthesis are calculated using satellite radiometric indices. Solar radiation, temperature and moisture affect GPP. The influence of temperature, which ranges from 0 to 1, increases linearly with increasing daily minimum temperature (TMIN) between minimum TMIN (-8 °C) and maximum TMIN (8-10 °C; for forest biomes), which are defined for each biome classification. The factors for below minimum TMIN and above maximum TMIN are 0 and 1, respectively. The influence of VPD, which ranges from 0 to 1, is decreases linearly with increasing vapor pressure deficit (VPD) between minimum VPD (650-1100 Pa) and maximum VPD (2500-3900 Pa; for forest biomes). The factors for below minimum VPD and above maximum VPD are 1 and 0, respectively. Leaf and fine root maintenance respirations exponentially increases with daily average temperature. Daily net photosynthesis is calculated by subtracting maintenance respiration from GPP. NPP is calculated annually by subtracting growth respiration from GPP. The method for deriving NPP for MOD17 is described in detail elsewhere (Running et al. 2000). The averaged value from 2000 to 2006 at 1 km resolution was calculated and used in this study.

RothC model
There are a number of soil organic carbon models (Smith 2002). The Rothamsted carbon model (RothC) is one of the most widely used and tested in a wide variety of ecosystems including croplands, grasslands, and forest and in various climate regions (Jenkinson 1990; Coleman et al. 1997; Smith et al. 1997, 2005, 2006; Falloon et al. 2006). It is described in detail in Coleman and Jenkinson (1996). RothC is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of
soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon, microbial biomass carbon and $\Delta^{14}$C (from which the radiocarbon age of the soil can be calculated) on a years to centuries timescale (Jenkinson 1990; Jenkinson and Coleman 1994). The input is monthly rainfall (mm), monthly open pan evaporation (mm), average monthly mean temperature (°C), clay content of the soil, an estimate of the decomposability of the incoming plant material, soil cover, monthly input of plant residues (tCha⁻¹), monthly input of farmyard manure (FYM) (t C ha⁻¹), and depth of soil layer sampled (cm). Incoming plant input is split into decomposable plant material (DPM) and resistant plant material (RPM), and then during the decomposition process, they are split into CO², microbial biomass (BIO) and humified organic matter (HUM). The IOM compartment is resistant to decomposition. Each compartment decomposes by a first-order process with its own decomposability. For most agricultural and improved grassland, a DPM/RPM ratio of 1.44 is used; for a deciduous or a tropical woodland a DPM/RPM ratio of 0.25 is used. Both DPM and RPM decomposes into CO$_2$, BIO and HUM, and the proportion that goes CO$_2$ and BIO + HUM is controlled by clay content of the soil. The decomposition constant is controlled by the factors for temperature, moisture and plant cover. The effect of temperature is given by $a=47.9/(1+e(106/(tm+18.3)))$, where tm is the average monthly air temperature (°C); the effect of moisture is controlled by the moisture deficit of the top soil. There is no limitation until topsoil moisture deficit exceeds 20 mm. The effect of moisture decreased linearly with increasing deficit when the deficit is between 20-44.4 mm. RothC has been used to make regional and global scale predictions in a variety of studies (Falloon and Smith 2002; Smith et al. 2005). The model was adapted to run with large spatial datasets and to use potential evapotranspiration (PET) in place of open pan evaporation and has been used for pan-European studies of cropland, grassland and forestry soil carbon change under climate change (Smith et al. 2005, 2006).

Input data
Mesh Climatic Data 2000 (Japan Meteorological Agency 2002) was used for the input for the monthly rainfall and monthly mean air temperature. The database includes 30-year means for the period 1971-2000 of monthly values of climate data. We used the subroutine for potential evapotranspiration included in CENTURY version 4, which was originally from Linacre (1977).

The distribution of Brown forest soils was taken from the raster soil map of the Digital National Land Information (see Study site, Ministry of Land, Infrastructure, Transport and Tourism 1979). The raster map consists of about 1-km grids, and each grid contains one soil classification. Note that the dataset does not tell us the detailed soil type distribution in the grid. We pick up the grids with Brown forest soil and conducted the calculation.

A mean SOC stock to 30 cm depth for Brown forest soil group was calculated by the data of Morisada et al. (2004), and the mean value was used at every grid. Morisada et al. (2004) compiled from 3391 soil profiles obtained in a national soil survey, and reported as the representative value of soil organic matter for 15 soil units, which was established by grouping related soil types and groups. The organic matter content and coefficient of variance were reported for each unit in the study of Morisada et al. (2004). They classified Brown forest soil group into 6 units (moist, wet, dark, reddish and yellowish, and surface gleyed); then we calculated the weighted average using the area of each soil unit to calculate the representative carbon stock of Brown forest soil...
group. The value calculated is 8.7 kgC m\(^{-2}\) with SD=2.45 kgC m\(^{-2}\) and CV (coefficient of variation) = 28 % in the upper 30 cm, which was used in this study. Note that one mean SOC stock was used for every grid calculation. For all grids, clay content of 23 % was assumed, and a DPM/RPM ratio of 0.25 was assumed (the default for temperate forest; Coleman & Jenkinson, 1996). The seasonality of plant residues was assumed to be constant through the year. The RothC model is known to be relatively insensitive to the seasonality of C inputs (Smith et al. 2005). The inert organic matter pool (IOM) was set to zero in this study. The age of the IOM fraction is assumed to be 50000 yr and of geological age, rather than of pedological age. In many studies, IOM is assumed to be present and is often calculated using the relationship of Falloon et al. (1998). In a preliminary calculation, we included IOM. However, unlike European agricultural sites, Japanese forests are on steep hills and sometimes experience landslides; as a result, soils in Japanese forests are considered to be younger so IOM was excluded. The impact of excluding IOM in this study is discussed later in the paper.

Calculation
The procedure for estimating plant litter input is the same as the widely-used initialization procedure of RothC model, and is as follows. We ran the RothC model for 2000 yr with an arbitrary litter carbon input. After that, the amount of soil organic carbon was compared to the assumed SOC; if the SOC simulated was larger than the SOC assumed, then the organic matter input was reduced. In the opposite case, the organic matter input was increased. This iterative procedure was continued until the difference became less than 0.5 % of the 8.7 kgC m\(^{-2}\). This procedure was conducted at each grid cell, and the plant litter input was estimated for each grid. Although the amount of soil organic carbon and soil texture were the same among grids, the climate data varied among grids (see Input data). The calculation was done at 1-km resolution, and the number of the grids which were categorized as both forest and forest brown soil, was 174454. We defined the normalized difference (NDI) as follows and mapped the value.

\[
\text{NDI} = \frac{(V_r - V_m) \times 100}{(V_r + V_m)/2}
\]

where \(V_r\) is the plant litter input estimated by RothC model and \(V_m\) is the MODIS litter input estimate.

Sensitivity and uncertainty
To test the sensitivity and uncertainty of this approach, we conducted a Monte Carlo analysis. A probability density function with a normal distribution with a SD of 2.450 kgC m\(^{-2}\) was assumed (see above), and the Monte Carlo simulation was conducted at 1% of the grid cells selected at random (1712 grid cells). The 100 samples (SOM input) were generated by the Latin Hypercube sampling method (LHS) using Simlab software (available at http://simlab.jrc.ec.europa.eu/). Simlab is free software for uncertainty and sensitivity analysis, developed by the Joint Research Centre of the European Commission. LHS is a method of generating effective samples for uncertainty analysis. Simlab and LHS are widely used in sensitivity analysis (e.g. Gottschalk et al. 2007; White et al. 2008). The standard deviation of the generated 100 samples was 2.431 kgC m\(^{-2}\), and the CV was 27.9 %. At each selected grid, 100 calculations were conducted using the 100 samples (SOM input). The standard deviation and coefficient of variation were calculated at each grid cell. Further, to clarify the sensitivity of estimated litter input to soil, we calculated the relationship between normalized deviance of soil organic matter and normalized deviance of litter
input. The R software package was used for the calculation (R Development Core Team 2005).

**Results**

Figure 2 shows the spatial distribution of MODIS litter input (a) and RothC litter input (b). Both MODIS and RothC litter input were larger in the south west region and smaller in north region; however, the gradient of RothC litter input was clearer than MODIS litter input. The difference in the northeast region (Hokkaido island), was especially larger. Total litter input of the forest on Brown forest area was 0.14 PgC yr⁻¹ from MODIS litter input and 0.12 PgC yr⁻¹ from RothC litter input, respectively.

Figure 3 shows the histogram of the MODIS litter input (a) and RothC litter input (b), respectively. MODIS litter input ranged from 200 gC m⁻² yr⁻¹ to 1600 and showed a peak around 800 gC m⁻² yr⁻¹. RothC litter input ranged from 200 gC m⁻² yr⁻¹ to 1200 gC m⁻² yr⁻¹, and did not show as clear a peak than did MODIS litter input.

Figure 4 shows the relationship between RothC and MODIS litter inputs. The data showed a positive relationship, and the data clouds were scattered around the 1:1 line, but some of MODIS litter inputs were larger than RothC litter input at higher values. For values over 1200 gC m⁻² yr⁻¹, RothC litter inputs were smaller than those of MODIS litter input.

Figure 5 shows the relationship between annual mean temperature and annual rainfall, and estimated litter input. The litter input was averaged for each 1 °C mean annual temperature and 100 mm annual rainfall, and is shown where the number of data points was more than 50 for each interval. Both MODIS and RothC litter inputs are sensitive to temperature; however, the MODIS litter inputs was relatively less sensitive to the temperature when temperature was low, and RothC litter input was generally not sensitive to annual precipitation.

The normalized difference between RothC litter input and MODIS litter input is shown in Fig. 6. The white area indicated that the difference was within ± 5 %, and distributed from north (except for the northeast island) to south. Spatial biases can be seen; for the regions along the northwest coast of Honsyu island, and the west region, RothC litter input was larger than that of MODIS (red in Fig. 6). Conversely, in the north region (Hokkaido island), north east coast and middle region of Honsyu island, RothC litter input was smaller than that of MODIS (blue in Fig. 6).

Figure 7 shows the histogram of normalized difference. The peak was found around 0, but the distribution was biased to negative values. The mean and median were -17.2 and -16.1 %, respectively.

The Monte Carlo simulation showed that the standard deviation varied among grids depending on the climate, but the coefficient of variation did not vary among grids. The relationship between the normalized deviance of SOC and normalized deviance of RothC litter input was almost on 1:1 (y=1.01 x -0.0009, R² = 0.99, p < 0.01), which indicates the linearity of this approach, and the uncertainty of the input SOC (CV=28 %) linearly influenced the estimated RothC litter input, as expected from model structure (Coleman & Jenkinson, 1996). Therefore the uncertainty of the estimated litter input about the input SOC was CV=28 %.
Discussion
Because litter input to soil is equivalent to NPP at equilibrium, we can compare our estimates of litter inputs with NPP estimates of other studies. Total litter input of the forest on Brown forest soil area was 0.14 PgC yr\(^{-1}\) from MODIS litter input and 0.12 PgC yr\(^{-1}\) from RothC litter input, respectively. Although there are no previous studies which focus only on only forests with Brown forest soil in Japan, considering that about 70% of the forest soil was Brown forest soil, the litter inputs of MODIS and RothC were larger than those of previous studies. Previously estimated NPP of forest in Japan was 0.14 and 0.15 PgC yr\(^{-1}\) (Alexandrov et al. 1999; Hoshika et al. 2007). In the previous study, the estimated NPP ranged from 200 gC m\(^{-2}\) yr\(^{-1}\) to 1014 (Hoshika et al. 2007), which was quite similar to the range of estimated RothC litter carbon input. The spatial distribution was also similar to that of Hoshika et al. (2007): NPP was larger in the south west region and smaller in north region. The value of NPP in Hokkaido region was smaller than 600 gC m\(^{-2}\) yr\(^{-1}\), and that of south coast area was larger than 800 gC m\(^{-2}\) yr\(^{-1}\).

RothC litter input was more sensitive to temperature than MODIS litter input (Fig. 5), which resulted in the relatively flatter distribution of RothC litter input than MODIS litter input (Fig. 3). MODIS litter input at lower temperature was less sensitive to the annual temperature, which resulted in the larger difference in the northeast region (Fig. 2 and Fig. 6). One possible reason is the difference of the temperature functions. In MODIS NPP estimation (equivalent to litter input), daily minimum temperature linearly affects GPP, but the temperature does not affect GPP when minimum temperature is below a certain temperature, which could reduce the variation in NPP estimation in colder regions. On the other hand, in RothC model temperature exponentially affects the decomposition or inversely estimated litter input. Being different from MODIS estimation, there is no assumption of threshold in the RothC model; therefore, the estimate from RothC model is probably more predictably affected by temperature. Both MODIS and RothC litter inputs were relatively less sensitive to annual precipitation. This is probably due to high precipitation in Japan, meaning that litter input (or NPP) is, roughly speaking, not water limited and therefore controlled only by temperature. The annual precipitation in Japan ranges from 700 to 3500 mm, and the average is about 2000 mm, which are relatively quite large. As described above, MODIS daily GPP is controlled by VPD but when VPD is smaller than the minimum VPD, VPD does not affect the GPP. As for the RothC model, top soil moisture deficit controls decomposition, but when top soil moisture deficit is smaller than a certain degree, top soil moisture does not affect the decomposition.

Although this is not specifically confirmed for Japanese forest, the MODIS NPP product has been evaluated against plot-level measurements of NPP (Turner et al. 2005, 2006). These results revealed that MODIS NPP showed no overall bias. However, MODIS NPP (litter input to soil) included quite high value (e.g. more than 1500 gC m\(^{-2}\) yr\(^{-1}\)), which are questionable, although the number of such high values was small (Fig. 3). Similar high values were reported at the mid-Atlantic region of the United States (Pan et al. 2006). We plotted the values on a map and found that those values were all located on evergreen forests (MODIS vegetation classification) along coastlines or on small islands of the southern part of Japan (Nansei islands). We therefore speculate that noise from mixed pixels (sea and land) may have yielded high NPP value in the MODIS algorithm for evergreen forests or the regulation of NPP by temperature and VPD may not work well at those grids.
It is important to assess the uncertainty of model estimates. Broadly speaking, there are three sources of uncertainty in this procedure to estimate litter input from soil organic matter: the amount of inert organic matter, the assumed depth, and the input value of soil organic matter. These three factors all influence the amount of the soil organic matter input. The Monte Carlo simulation revealed the linearity of this procedure. For example, if the soil organic matter input was larger by 10%, then estimated litter input would be larger by 10%, and vice versa. These results show how the uncertainty of actual soil organic carbon level affects the estimated litter input.

IOM was set to zero in this study, which, we think, is a reasonable assumption, because the soil in Japan is generally young. But if we assume an IOM content using the relationship suggested by Falloon et al. (1998), about 9% of SOM would be assumed to be IOM. Considering the linearity of this procedure, including IOM would decrease the estimated litter input by 9%.

Saito (1981) compiled litterfall studies conducted in Japan (170 plots and n=342) and estimated the average litterfall for each forest type; the litterfall ranged from 4.51 t d.w. ha\(^{-1}\) yr\(^{-1}\) (226 gC m\(^{-2}\) yr\(^{-1}\); deciduous broad-leaved) to 6.07 t d.w. ha\(^{-1}\) yr\(^{-1}\) (304 gC m\(^{-2}\) yr\(^{-1}\); evergreen broad-leaved). Our estimates were quite larger than those estimates, which is because our estimates include both above and below ground litter input, while litterfall observations, which were done using litter trap, only include aboveground leaf and branch litterfall. Observed total litter input (both above and below, or NPP), which were measured in Japan as IBP project, ranged from 356 to 1556 gC m\(^{-2}\) yr\(^{-1}\) (average=767 gC m\(^{-2}\) yr\(^{-1}\), n=18; Esser et al. 1997), which agreed with our estimate. But we should note a difficulty of comparing satellite based data and ground-based measurement (see below).

Recently, a difficulty of comparing satellite based data and ground-based measurement has been pointed out (Turner et al. 2004, 2005), called a scaling issue. The mismatch in scale between the 1 km grid of satellite products and relatively small scale of ground-scale observation make the comparison, including model parameterization and validation, challenging. The SOC data we used is based on the ground-observation, and the MODIS NPP is the satellite-based 1-km resolution; then, our results might be affected by the scaling issue. On the other hand, the SOC value we used was calculated by the average of thousands of measurements; hence, our estimates may not seriously suffer from scaling issues. As conducted in NPP and GPP studies (Turner et al. 2004, 2005), the mismatch in scale in soil data should be investigated in future.

We excluded immature soils in this study because immature soils are thought to be far from equilibrium and cannot be assumed to be at steady state. These soils are affected by erosion, caused by overuse of forest and have lost much of the initial soil carbon. The climate of most of the area of immature soils is, however, suitable for forest establishment in general, and afforestation has been conducted in last century. It is quite probable that soil organic matter in such soil is rapidly increasing.

In order to apply this method employed in this study, steady state is assumed, which is a common assumption for initializing RothC model. Real equilibrium will rarely exist in nature due to annual and longer term fluctuations in climate, disturbance, land management etc. and we know that some of Japanese soils are likely not to be in steady state since the stock of the Japanese forest has been increasing for the last 50 yrs due to the decline of forest use and afforestation (and possibly changing climate). A recent study has pointed out that soils that have been disturbed centuries ago were not at equilibrium (Wutzler and Reichstein 2007), and relaxing the steady state
assumption resulted in better modelling performance of carbon cycle (Carvalhais et al. 2008). Despite the fact that the soils are not equilibrium, the estimates of RothC plant litter input were close to the MODIS litter input estimates in this study, and the two were positively correlated. This shows that even though we know that soils are not in equilibrium, the assumption we make is not critical in affecting the results. In other words, the inverse estimation method does not rely upon the strict equilibrium assumption and is applicable to the soils of Japan considered here. Our uncertainty analysis helps us to assess the impact of this assumption. The Monte Carlo simulation revealed the linearity between input value of soil carbon and output value of plant litter input to mineral soil. If the possible soil carbon level at steady state was 10% larger than the used input soil carbon to the model, the estimated plant litter input would be 10% smaller than the value estimated using the soil carbon level at steady state. Moreover, the comparison between litter input (NPP data) and inversely estimated plant litter input is helpful to understand the stability of soil carbon. If these two estimates were quite different, it perhaps implies that soil carbon could be rapidly changing, or that there is another mechanism/process that keeps soil carbon level low/high.

The RothC litter input and MODIS litter input were positively correlated each other (Fig. 4), but there were spatial biases of the normalized difference between RothC litter input and MODIS litter input. Because the area where RothC litter input is less than MODIS litter input (shown as a blue area in Fig. 6) roughly increased from south to north, the normalized difference seemed to relate to the temperature. But at the 35° - 40° N, the area where RothC litter input is less than MODIS litter input was dominant only in the eastern coastal area. These distributions of differences between the approaches may relate to the distribution of soil carbon distribution and/or the surface litter. In the area where MODIS litter input was larger than RothC litter input, soil carbon and surface litter could be larger than those of other areas. We are also aware that the discrepancy may indicate the areas that are far from equilibrium or where the actual soil carbon stock is far from the mean value assumed. Another possible reason for the discrepancy is the simple assumption of clay content. Because there are no data showing the distribution of clay content, we used one clay content for all calculations. The RothC model is, however, sensitive to clay content. Clay content controls the partitioning factor between CO2 evolved and (BIO+HUM) compartments, which controls the decomposition. The CO2/(BIO+HUM) ratio decreases exponentially with increasing clay content. The ratio decreases largely until 10-20% of clay content, and does not significantly change when clay content is larger than 20-30%.

Regionally distributed SOC contents might produce a closer match between RothC litter input and MODIS litter input and would improve the approach when such data become available. Nevertheless, despite the many simplifications and assumptions used in this study, RothC estimates of litter inputs and MODIS estimates are broadly in agreement. In Japan, the first forest soil carbon inventory project is now ongoing (2006-2012). The soil carbon evaluation is being conducted at 2889 plots all over Japan. Much detailed data will be available in future which will allow regionally distributed estimates of forest brown soil SOC to be used, which will decrease the uncertainty of this approach and reveal the regional characteristics in greater detail. Further improvement will also result from additional site scale validation of this approach, as done in the Jenkinson’s original research (Jenkinson et al. 1999). Comparing observed values of litter input with inversely estimated value using RothC and soil carbon stock will enhance the reliability of this method.
However, the agreement between the two methods suggests that in future, satellite based NPP measurements could be used to drive soil carbon models for compiling estimates of change in forest soil carbon stocks under future climate/land management (potentially in real time), for scientific purposes or for accounting under post-Kyoto climate agreements. Whilst improved datasets are needed to provide further proof of concept, this study shows that the approach shows promise.

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**FIGURE CAPTIONS**

**Figure 1** Maps showing the location of Japan.

**Figure 2** Maps of MODIS litter input (a) and RothC litter input (b) for forest on Brown forest soil.

**Figure 3** Histograms of MODIS litter input (a) and Roth litter input (b).

**Figure 4** Relationship between RothC litter input and MODIS litter input. The Pearson’s correlation coefficient was 0.54.

**Figure 5** Relationship between MODIS (a) / RothC litter input (b) and mean annual temperature and annual precipitation. The data was averaged for each 1 °C and 100 mm rainfall, and the averaged value was plotted when the number of the data for each interval was more than 50.

**Figure 6** Distribution of the normalized difference between MODIS litter input and RothC litter input. Red area indicates RothC litter input is larger than MODIS litter input, and blue area indicates RothC litter input is smaller than MODIS litter input. White area shows the normalized difference is within ± 5 %.

**Figure 7** Histogram of the normalized difference between RothC litter input and MODIS litter input.
MODIS litter input (gC m\(^{-2}\) yr\(^{-1}\))

RothC litter input (gC m\(^{-2}\) yr\(^{-1}\))