

## 論文 (Original article)

# Carbon stocks of dead wood, litter, and soil in the forest sector of Japan : general description of the National Forest Soil Carbon Inventory

Shin UGAWA<sup>1)\*</sup>, Masamichi TAKAHASHI<sup>2)</sup>, Kazuhito MORISADA<sup>3)</sup>, Manabu TAKEUCHI<sup>4)</sup>, Yojiro MATSUURA<sup>5)</sup>, Shuichiro YOSHINAGA<sup>6)</sup>, Makoto ARAKI<sup>2)</sup>, Nagaharu TANAKA<sup>1)</sup>, Shigeto IKEDA<sup>1)</sup>, Satoru MIURA<sup>1)</sup>, Shigehiro ISHIZUKA<sup>6)</sup>, Masahiro KOBAYASHI<sup>1)</sup>, Masahiro INAGAKI<sup>6)</sup>, Akihiro IMAYA<sup>1)</sup>, Kazuki NANKO<sup>1)</sup>, Shoji HASHIMOTO<sup>1)</sup>, Shuhei AIZAWA<sup>3)</sup>, Keizo HIRAI<sup>7)</sup>, Toru OKAMOTO<sup>8)</sup>, Takeo MIZOGUCHI<sup>9)</sup>, Atsushi TORII<sup>9)</sup>, Hisao SAKAI<sup>10)</sup>, Yasuhiro OHNUKI<sup>1)</sup>, Shinji KANEKO<sup>1)</sup>

### Abstract

The aims of this study were to report the C stocks of dead wood, litter, and soil at 0–30 cm in the forest sector of Japan, to clarify the spatial distribution of those C stocks according to prefecture units and to determine the ratio of soil C stock at 0–30 cm to that at 0–100 cm. To achieve these objectives, data collected by the National Forest Soil Carbon Inventory Project, which surveyed the C stocks of dead wood, litter, and soil at 0–30 cm and at 0–100 cm throughout the forest sector of Japan, were analyzed. The C stock (mean  $\pm$  sample standard deviation) of dead wood, litter, and soil at 0–30 cm was  $0.42 \pm 0.67$ ,  $0.49 \pm 0.32$ , and  $6.94 \pm 3.25$  kg m<sup>-2</sup>, respectively. This study did not detect any clear tendency in the latitudinal distribution of the C stocks of dead wood and litter, although the litter C stock was lower in prefectures with a higher annual mean temperature. On the other hand, the C stock of soil at 0–30 cm was higher in northern Japan and lower in southern Japan. Exceptions to this pattern included a high C stock in some prefectures in the volcanic regions of southern Japan. Thus, we suggest that the soil C stock at 0–30 cm is regulated by a macroscale factor, i.e., temperature, as well as by the distribution of volcanic ash soils. The soil C stock at 0–100 cm was  $14.29 \pm 8.38$  kg m<sup>-2</sup> (mean  $\pm$  sample standard deviation) and the ratio of the soil C stock at 0–30 cm to that at 0–100 cm was  $0.59 \pm 0.31$  (mean  $\pm$  sample standard deviation), suggesting that the soil C stock at 0–30 cm in the forest sector of Japan accounts for a larger portion of that at 0–100 cm compared with worldwide average.

**Key words** : carbon stock, dead wood, litter, soil, national forest inventory, systematic sampling, Kyoto Protocol

### 1. Introduction

The carbon (C) stock of a forest is the basic datum for evaluating the C sink function of the forest ecosystem. Therefore, the parties ratifying the United Nations Framework Convention on Climate Change (UNFCCC) were asked to report the C stock in the forest sector of their countries. The C stock of the total area of the forest sector is estimated using a model that describes the relationship between actual measurement data and external data prepared for the entire mesh area of the country. Thus, recent, transparent, and verifiable measurement data should be collected throughout the entire forest sector of the country for accurate estimation of the C stock in the forest sector of the country.

The main C pools in forest ecosystems are aboveground and belowground biomass, dead wood, litter, and soil (IPCC 2006). In Japan, measurement data on the C stock of aboveground and belowground biomass have been collected throughout the entire forest sector (Forestry Agency of Japan 2012). On the other hand, the C stocks of dead wood and litter have yet to be surveyed throughout the entire forest sector of Japan, although C stocks of dead wood and litter in forests dominated by major tree species were summarized by Takahashi et al. (2010). The C stock of soil was estimated by Morisada et al. (2004) throughout the entire forest land of Japan using soil profile data collected from 1950s to 1970s, but these soil profile data cannot be said to be recent. Therefore, measurement data for the C

原稿受付 : 平成 24 年 3 月 12 日 Received 12 March 2012 原稿受理 : 平成 24 年 8 月 22 日 Accepted 22 August 2012

1) Department of Forest Site Environment, Forestry and Forest Products Research Institute (FFPRI)

2) Department of Research Planning and Coordination, Forestry and Forest Products Research Institute (FFPRI)

3) Hokkaido Research Center, Forestry and Forest Products Research Institute (FFPRI)

4) Chubu Regional Forest Office, Forestry Agency of Japan

5) Bureau of International Partnership, Forestry and Forest Products Research Institute (FFPRI)

6) Kyushu Research Center, Forestry and Forest Products Research Institute (FFPRI)

7) Tohoku Research Center, Forestry and Forest Products Research Institute (FFPRI)

8) Kiso Experiment Station, Forestry and Forest Products Research Institute (FFPRI)

9) Kansai Research Center, Forestry and Forest Products Research Institute (FFPRI)

10) Shikoku Research Center, Forestry and Forest Products Research Institute (FFPRI)

\* Department of Forest Site Environment, Forestry and Forest Products Research Institute (FFPRI), Matsunosato 1, Tsukuba, Ibaraki 305-8687, Japan; e-mail: ushin@ffpri.affrc.go.jp

stocks of dead wood, litter, and soil should be collected throughout the entire forest sector of Japan, and the mean C stocks of the three pools in the forest sector of Japan should be determined.

As a subsequent step, the heterogeneity of the C stocks of the three pools should be determined because C stocks of the total area of the forest sector are estimated using a model that explains this heterogeneity. The heterogeneity of C stocks is a result of many factors of site environment and tree community. Thus, the factors that strongly influence the C stocks should be delineated. Many of these factors can be classified as macroscale factors such as temperature or microscale factors such as forest management. Therefore, it is prudent to determine whether a macroscale factor strongly influences the C stocks, that is, whether a macroscale pattern exists in the spatial distribution of the C stocks. This study focused on the heterogeneity among prefectures to detect any spatial patterns throughout the entire forest sector of Japan.

The UNFCCC requests reporting of the C stock of soil from the soil surface to a depth of 30 cm. However, soil

C is also stored in deeper soil layers, and this C storage is related to the C sink function of forest ecosystems. Soil C stock generally decreases with depth as a result of C influx from decomposing litter and dead roots in the upper soil layer and low decomposition rates in the lower soil layer. Moreover, the vertical distribution of soil C stock varies with climate, soil type, vegetation type, and volcanic ash content (Batjes 1996, Jobbágy and Jackson 2000, Yang et al. 2010, Imaya et al. 2010a, b). Thus, the vertical distribution of soil C stock indicates the character of soil C accumulation in the forest sector of Japan.

The goals of this study were to (i) report the C stocks of dead wood, litter, and soil to a depth of 30 cm in the forest sector of Japan, (ii) clarify the spatial distribution of the C stocks of the three pools at a prefecture level, and (iii) determine the ratio of the soil C stock in the 0–30-cm interval to that in the 0–100-cm interval. To achieve these objectives, measurement data collected by the National Forest Soil Carbon Inventory Project, which surveyed C stocks of dead wood, litter, and soil at 0–30 cm and 0–100 cm in FY2006–2010, were analyzed.

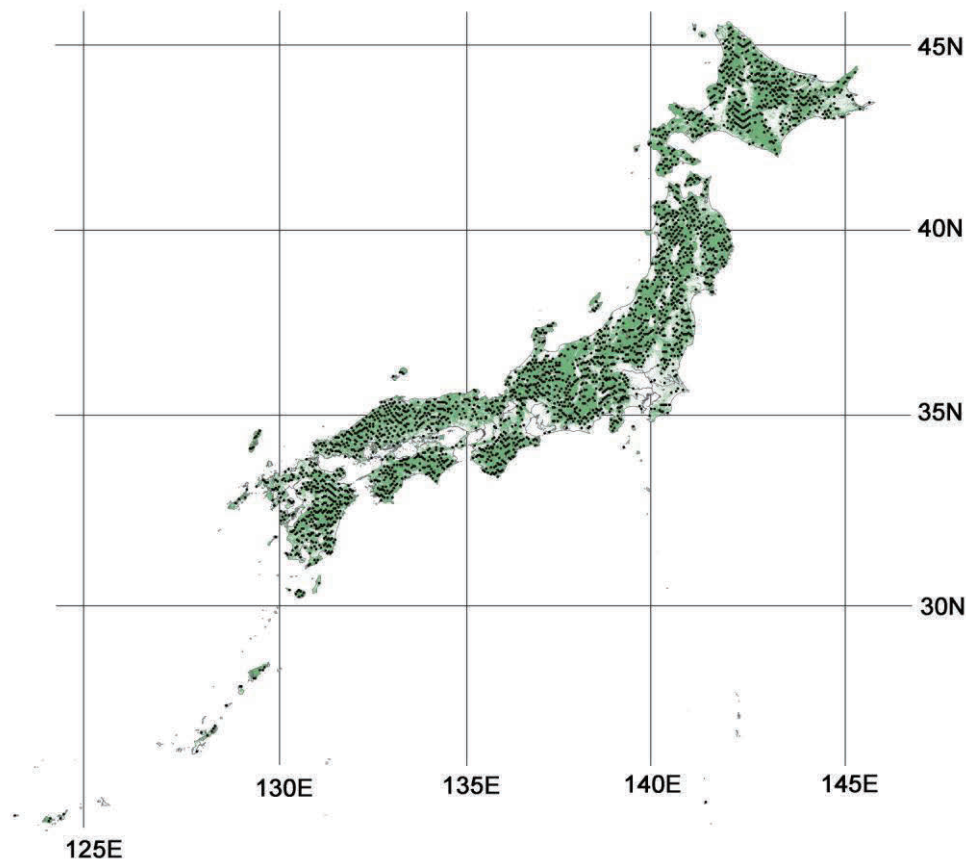


Fig. 1 Location of survey plots (solid circles) in forest sector (green area) of Japan. Forest sector is shown according to National Land Numerical Information provided by the National and Regional Planning Bureau of the Ministry of Land, Infrastructure, Transport and Tourism.

## 2. Materials and Methods

The C stock of dead wood, litter, and soil was surveyed in the National Forest Soil Carbon Inventory Project using the survey methods described below.

### Survey Plot

The 4×4-km grid points over the forest sector of Japan were systematically selected for the Forest Resources Monitoring Survey, in which tree censuses were conducted during FY1999–2003 (Forestry Agency of Japan 2012). One-fifth of these survey sites were selected in the National Forest Soil Carbon Inventory Project, giving a total of 2919 grid points (Fig. 1). A 1000-m<sup>2</sup> circular plot was established in each grid point (Fig. 2), and the C stock of dead wood, litter, and soil at 0–30 cm was surveyed in each plot. The soil C stock at 0–100 cm was surveyed in 992 of the survey plots, which were selected from every third survey plot on a north–south grid line.

### Dead Wood C Stock

According to the IPCC guidelines (IPCC 2006), dead wood includes coarse woody debris, dead coarse roots, and standing dead trees ≥10 cm in diameter. However, in this project, fallen boles and branches, stumps, and inclined dead stems ≥5 cm in diameter at the point where it

intersected a line (see below), were defined as dead wood because non-commercial thinning felled stunted trees, which usually are <10 cm in diameter in plantation forest of Japan (Sakai et al. 2008).

In each survey plot, a north–south line and an east–west line were established, and their horizontal lengths were measured (Fig. 2). Dead wood that intersected the lines at heights between 0 and 150 cm was divided into four species categories: conifer, broadleaved, unidentified woody, and bamboo. Then, the decay class of each piece of dead wood was determined according to appearance using Tables 1 and 2, and the diameter at the point where it intersected a line was measured (Fig. 3).

The C stock of dead wood was calculated for each species category and decay class by Formula 1 using the line intersect method (Warren and Olsen 1964, Van Wagner 1968, Brown 1974), where  $D$  (cm) is the diameter of dead wood,  $L_{ns}$  (m) is the horizontal length of the north–south line,  $L_{ew}$  (m) is the horizontal length of the east–west line,  $M$  (g cm<sup>-3</sup>) is the wood density of each species category and decay class (Table 3),  $CC$  (kg kg<sup>-1</sup>) is the C concentration of the dry wood (equal to 0.5), and the subscript  $i$  indicates individual dead wood, respectively. The dead wood C stocks of all species categories and decay classes were summed to give the dead wood C stock in a survey plot, although dead wood C stock was not calculated for survey plots with missing data.

Dead wood C stock for each species category and decay class (kg m<sup>-2</sup>)

$$= \frac{\pi^2 \times \sum_i D_i^2}{8 \times (L_{ns} + L_{ew})} \times M \times CC \times 10^{-1} \quad [\text{Formula 1}]$$

### Litter C Stock

The IPCC guidelines define *litter* an organic horizon (all leaves, twigs, small branches, fruits, flowers, roots, and bark) on the mineral soil surface (IPCC 2006), although the term *litter* differs in soil science, where its meaning is restricted to fallen dead leaves (e.g., Wild 1971). However, in this study, *litter* was defined as an organic horizon that is divided into four litter types: fine woody debris, which includes fallen boles, branches, twigs <5 cm maximum diameter, strobilus, and bark; fresh leaves; the fermentation layer and the humus layer. We defined the humus layer as continuously stocked humus ≥1 cm in depth.

In each survey plot, slope inclination was measured at four points, one each in the northern, eastern, southern, and western parts of the plot (Fig. 2). At each point, a sample of each litter type was taken from a 0.5-m square (Fig. 4).

These samples were oven dried at 70°C for 48 h, and weighed. Then, the samples of the same litter type were

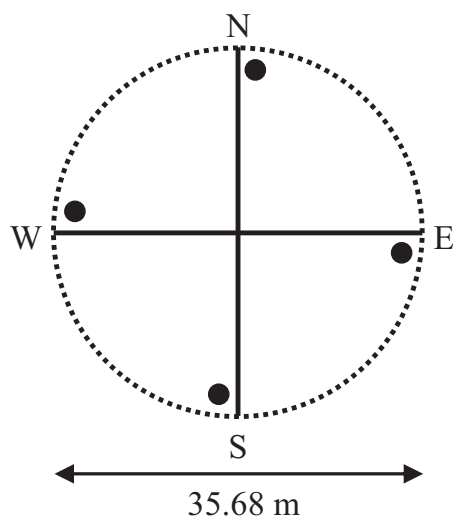


Fig. 2 Two lines (solid lines) for surveying dead wood C stock and four points (solid circles) for measuring C stock of litter and soil at 0–30 cm in a survey plot (dotted line). The diameter of the circular plot is a horizontal distance of 35.68 m. Dead wood C stock was surveyed along the north–south and the east–west lines using the line intersect method, and the C stocks of litter and soil at 0–30 cm were measured at four points, in the northern, eastern, southern, and western parts of the plot.

Table 1 Criteria determining the decay class of dead wood for conifer and broadleaved species

Decay class	Appearance of dead wood
0	No decay Branches, twigs, and leaves remain
1	Slightly decayed Only cambium decayed Branches and twigs remain
2	Most bark and branches present Some parts of wood are softened by decay
3	Moderately decayed All parts of dead wood are softened by decay Some bark is gone in conifer species Moss has sometimes adhered
4	Some parts of wood are gone Initial form is recognizable Brown rot is observed in conifer species
5	Wood collapsed ≥50% of wood is gone Some parts of wood are buried in soil Some bark remains in broadleaved species



Fig. 3 Field survey for dead wood C stock. The diameter of dead wood was measured where it intersected a line (white tape).

Table 2 Criteria determining the decay class of dead bamboo culm

Decay class	Appearance of dead culm
0	Culm separated from ground surface
1	Culm in contact with ground surface Culm is still hard
2	Culm is soft Culm is destroyed easily by a stepping

Table 3 Wood density ( $\text{g cm}^{-3}$ ) of dead wood in each species category and decay class. These values were determined by data from Forestry Agency of Japan (2007) and Sakai et al. (2008)

Decay class	Species category			
	Conifer	Broadleaved	Unidentified*	Bamboo
0	0.347	0.495	0.421	0.224
1	0.347	0.495	0.421	0.209
2	0.278	0.399	0.339	0.154
3	0.206	0.303	0.255	—
4	0.148	0.207	0.178	—
5	0.112	0.112	0.112	—

\* Dead wood that was impossible to identify as a conifer or broadleaved species was categorized to "Unidentified."





Fig. 4 Litter stock in a sampling point. Litter samples were taken from a 0.5-m square.

mixed across all sampling points of a survey plot and ground into fine particles ( $\leq 0.25$  mm) using a cutting mill and mortar. A portion of the fine particles (0.4–0.6 g) was put into a weighing bottle, and the bottle was weighed. The weighing bottle was then oven dried at  $70^{\circ}\text{C}$  for 24 h and weighed again. The water content of the fine particles was determined using Formula 2, where  $W_{bottle}$  (g) is the weight of the weighing bottle, and  $W_{before}$  (g) and  $W_{after}$  (g) are the weights of the weighing bottle containing fine particles before and after oven drying, respectively. If the resulting water content was  $>20\%$ , the sample was air dried, and the water content was measured again. These steps were repeated until the water content was  $\leq 20\%$ . The C content was measured from a different portion of the fine particles by the dry-combustion method using elemental analyzers. The C concentration was calculated using Formula 3, where  $W_{carbon}$  (kg) is C content,  $W_{sample}$  (kg) is sample weight, and  $WC$  (%) is water content. The C concentration was measured for more than two splits of fine particles, and the C concentration of a mixed sample was determined by obtaining an intermediate value of two

repeated measurement values as long as the values met the requirements of Table 4.

$$\text{Water content (\%)} = \frac{W_{before} - W_{after}}{W_{before} - W_{bottle}} \times 100 \quad [\text{Formula 2}]$$

$$\text{C concentration (kg kg}^{-1}\text{)} = \frac{W_{carbon}}{W_{sample}} \left( 1 + \frac{WC}{100} \right) \quad [\text{Formula 3}]$$

We calculated the C stock of each sampling point using Formula 4, where  $W$  (kg) is dry weight of the sample,  $CC$  ( $\text{kg kg}^{-1}$ ) is the C concentration,  $\theta$  (radians) is the slope inclination,  $S$  ( $\text{m}^2$ ) is the sampling area (equal to 0.25), and the subscript  $i$  indicates the litter type. Then, the mean C stock across sampling points was calculated to obtain the litter C stock for a survey plot. Sampling points containing a litter sample with missing data or anomalous data were excluded from the calculations (see *Quality Control of Data* section).

Litter C stock at each sampling point ( $\text{kg m}^{-2}$ )

$$= \sum_i \left( \frac{W_i}{(S \times \cos \theta)} \times CC_i \right) \quad [\text{Formula 4}]$$

#### Soil C Stock at 0–30 cm

Soil C stock at 0–30 cm was surveyed at the same points where litter was sampled, i.e., the northern, eastern, southern, and western parts of each survey plot (Fig. 2). At each point, a soil profile of  $>30$  cm depth was made and then divided into three soil layers, 0–5, 5–15, and 15–30 cm (Fig. 5). For each soil layer, the ratio of gravel area to the area of soil profile was recorded, and a volumetric sample and also a sample for analyzing C concentration were taken. For the volumetric samples, a  $400\text{-cm}^3$  cylindrical core (height, 4 cm; area,  $100\text{ cm}^2$ ) was sampled from a soil layer having low gravel content, whereas the soil sample was taken from a cuboid space (including gravels) in a soil layer having high gravel content (Fig. 5).

Table 4 Accuracy criteria for measuring carbon concentrations in litter and soil samples. The criteria were applied to two repeated measurements

Intermediate value	Accuracy criteria *
$\geq 0 \text{ g kg}^{-1}$ and $< 10 \text{ g kg}^{-1}$	Difference between two values is $\leq 1.13 \text{ g kg}^{-1}$
$\geq 10 \text{ g kg}^{-1}$ and $< 50 \text{ g kg}^{-1}$	Coefficient of variance of two values is $\leq 8\%$
$\geq 50 \text{ g kg}^{-1}$ and $\leq 600 \text{ g kg}^{-1}$	Coefficient of variance of two values is $\leq 4\%$
$> 600 \text{ g kg}^{-1}$	Re-analysis as anomalous data

\* The criteria were based on the data of Ugawa et al. (2010).



Fig. 5 Field survey for soil C stock. A soil profile of >30 cm depth was made (a). For the volumetric sample, a 400-cm<sup>3</sup> cylindrical core was sampled from a soil layer having low gravel content (b), whereas the soil sample was taken from a cuboid space in a soil layer having high gravel content (c).

The volumetric samples were oven dried at 105°C for 24 h and then weighed. The soil particles in a sample were washed out through a sieve (2-mm mesh) using water. The remaining gravels and plant roots were oven dried at 105°C for 24 h and weighed. Bulk density was calculated using Formula 5, where  $W_t$  (g) is the total weight of the volumetric sample,  $W_g$  (g) is the weight of gravels,  $W_r$  (g) is the weight of plant roots, and  $V$  (cm<sup>3</sup>) is the spatial volume of the volumetric sample, i.e., 400 cm<sup>3</sup> of cylindrical core or the volume of a cuboid space that included gravel.

$$\text{Bulk density (Mg m}^{-3}\text{)} = \frac{W_t - W_g - W_r}{V} \quad [\text{Formula 5}]$$

The samples for analyzing C concentration were air dried and sieved (2-mm mesh). The soil particles  $\leq 2$  mm in diameter were ground into fine particles ( $\leq 0.25$  mm) using an agate mortar. A split of the fine particles (2–3 g) was put into a weighing bottle, and the bottle was weighed. The weighing bottle then was oven dried at 105°C for 24 h and weighed again. Then, the water content of the fine particles was determined using the same methods as described earlier (see *Litter C Stock* section). The C concentration of a soil sample was also determined using the same methods as described in *Litter C Stock* section.

The C stock of each soil layer was calculated using Formula 6, where  $BD$  (Mg m<sup>-3</sup>) is bulk density,  $T$  (cm) is the thickness of the soil layer,  $CC$  (kg kg<sup>-1</sup>) is the C concentration,  $G$  (%) is the ratio of gravel area to the area of soil profile. The ratio of gravel area is taken as 0% for the soil layers from which we took the volumetric sample from a cuboid space containing gravels to avoid double counting of gravel content. Additionally, we considered the soil C stock as 0 kg m<sup>-2</sup> for a soil layer from which a soil profile could not be obtained due to bedrock or a large boulder. The C stock of each soil layer was summed for each sampling point, and the mean C stock across sampling points was calculated to give the soil C stock at 0–30 cm in a survey plot. Sampling points containing a soil layer with missing data, anomalous data, or outlier data were excluded from the calculations (see *Quality Control of Data* section).

Soil C stock in each soil layer (kg m<sup>-2</sup>)

$$= BD \times T \times CC \times \left(1 - \frac{G}{100}\right) \times 10 \quad [\text{Formula 6}]$$

#### Soil C Stock at 0–100 cm

Soil C stock at 0–100 cm was surveyed in the representative soil profile of >100 cm depth. A representative soil profile was made at a point with

significant microtopography and vegetation cover after an observation of the survey plot. For the representative soil survey, a soil profile was divided into generic soil horizons (e.g., A1, A2, B1, B2, and C horizons). The thickness of each soil horizon and the ratio of gravel area to the area of the soil profile were obtained. A volumetric sample and a sample for analyzing C concentration were taken from each soil horizon and bulk density, and C concentrations of these samples were determined using the same methods as described earlier (see *Soil C Stock at 0–30 cm* section).

The C stock of each soil horizon was calculated using the same methods as described in the *Soil C Stock at 0–30 cm* section and these were then summed to give the soil C stock of a representative soil profile. Representative soil profiles containing a soil horizon with missing or anomalous data were excluded from the calculation (see *Quality Control of Data* section).

#### Quality Control of Data

Criteria have been established to detect anomalous data for C concentration of a litter sample, bulk density, and C concentration of a soil sample at 0–30 cm and at 0–100 cm. Criteria have also been established to detect outlier data for bulk density and C concentration of a soil sample at 0–30 cm and at 0–100 cm.

The C concentration of a litter sample is considered anomalous if the value is  $<0.2 \text{ kg kg}^{-1}$  because organic material is defined as having a C concentration  $\geq 0.2 \text{ kg kg}^{-1}$  (Soil Survey Staff 1999). For soil samples, a bulk density  $>2.0 \text{ Mg m}^{-3}$  is considered anomalous because a

bulk density of sandy loam compacted by heavy traffic, i.e.,  $1.9 \text{ Mg m}^{-3}$ , is considered extreme in the forestry field (Lal 2002). According to Soil Survey Staff (1999), mineral soil contains  $<20\%$  organic carbon. However, in this study, a soil C concentration  $>0.25 \text{ kg kg}^{-1}$  is considered anomalous because a C concentration of  $>0.2 \text{ kg kg}^{-1}$  is often observed in Andosols, which are distributed widely in the forest land of Japan.

For soil samples at 0–30 cm, outlier data were determined statistically. Outlier values of bulk density were detected among the values in a survey plot using the Smirnov–Grubbs outlier test (upper-tail probability  $\leq 0.005$ ) and taken as outlier data of bulk density. Outlier values of C concentration among the values in a survey plot were also detected with the Smirnov–Grubbs test (upper-tail probability  $\leq 0.005$ ), and outlier values in soil layers of 5–15 cm and 15–30 cm are considered outlier data of C concentration because the soil layer at 0–5 cm is frequently disturbed, and the C concentration varies largely.

#### Results

Carbon stock of dead wood, litter, and soil at 0–30 cm were determined in 2438, 2432, and 2404 survey plots, respectively. The C stock could not be surveyed in 457 survey plots (Table 5), and the C stock of dead wood, litter, and soil at 0–30 cm could not be calculated in 24, 30 and 58 survey plots, respectively, due to missing, anomalous, and outlier data. The C stock (mean  $\pm$  sample standard deviation) for dead wood, litter, and soil at 0–30 cm was  $0.42 \pm 0.67$ ,  $0.49 \pm 0.32$ , and  $6.94 \pm 3.25 \text{ kg m}^{-2}$ , respectively (Table 6).

Table 5 Reasons for failure to complete survey and the breakdown in the number of plots. The number of plots included in soil survey at 0–100 cm is shown in parentheses

Reason for failure to complete survey	Number of plots
No way to contact land owner	70 (23)
Refusal by land owner or law regulation	113 (39)
No way to reach survey plot (e.g., collapse of road or snow coverage)	111 (40)
Land use other than forest (e.g., building site or orchard)	27 (10)
Failure to complete tree census (Forest Resource Monitoring Project)	131 (44)
Others	5 (0)
<b>Total</b>	<b>457 (156)</b>



Table 6 Carbon stocks of dead wood, litter, and soil at 0-30 cm and 0-100 cm

Carbon pool	Number of plots	Carbon stock (kg m <sup>-2</sup> )			Sample SD	Coefficient of variance (%)
		Minimum	Mean	Maximum		
Dead wood	2438	0	0.42	8.67	0.67	158.6
Litter	2432	0	0.49	2.84	0.32	64.6
Soil at 0–30 cm	2404	0	6.94	35.66	3.25	46.8
Soil at 0–100 cm	676	0.99	14.29	48.94	8.38	58.6

The C stocks of dead wood, litter, and soil at 0–30 cm in each prefecture (and each district) are shown in Table 7. These C stocks are classified into four groups: <25th percentile; ≥25th percentile and < median; ≥ median and <75th percentile; and ≥75th percentile, as shown in Fig. 6. The C stock for dead wood in each prefecture ranged from 0.08 kg m<sup>-2</sup> of Kagawa Prefecture to 0.66 kg m<sup>-2</sup> of Akita Prefecture. Dead wood C stock was high in the Hokkaido District, the central highland of the Chubu District, and the northern part of the Kinki District, but dead wood C stock was low in the eastern part of the Tohoku District, the Hokuriku area of the Chubu District, and the Shikoku and Kyushu Districts. The C stocks for litter in each prefecture ranged from 0.25 kg m<sup>-2</sup> of Kanagawa and Okinawa Prefectures to 0.63 kg m<sup>-2</sup> of Wakayama Prefecture. Litter C stock was high in the Hokkaido District, the central highland of the Chubu District, the southern part of the Kinki District and the Chugoku District, but low in the southern part of the Kanto District, the Hokuriku area of the Chubu District, and the Kyushu District. The C stock for soil at 0–30 cm in each prefecture ranged from 2.95 kg m<sup>-2</sup> of Kagawa Prefecture to 9.16 kg m<sup>-2</sup> of Ibaraki Prefecture. High C stock was observed in the Hokkaido, Tohoku, and Kanto Districts, whereas low values were observed in the Kinki, and Shikoku Districts. Soil C stock was also high in some prefectures located in the volcanic regions of the Chugoku and Kyushu Districts, such as Tottori, Shimane, Nagasaki, Oita, and Kagoshima Prefectures.

Soil C stock at 0–100 cm was determined in 676 survey plots. The soil C stock at 0–100 cm could not be surveyed in 156 survey plots (Table 5) and could not be calculated in 160 survey plots due to missing and anomalous data. The representative soil profile did not reach 100 cm in 136 survey plots due to bedrock or a large boulder. The digging depth in these plots was 62 ± 22 cm (mean ± sample standard deviation). The soil C stock at 0–100 cm was 14.29

± 8.38 kg m<sup>-2</sup> (mean ± sample standard deviation) across the 676 survey plots (Table 6). The ratio of soil C stock at 0–30 cm to that at 0–100 cm could be calculated in 667 survey plots and was 0.59 ± 0.31 (mean ± sample standard deviation).

## Discussion

### Dead Wood C Stock

The mean dead wood C stock, 0.42 kg m<sup>-2</sup> (Table 6), was within the mean values of forests dominated by the major tree species of Japan, 0.42–2.47 kg m<sup>-2</sup> (Takahashi et al. 2010). The mean C stock of dead wood ≥10 cm in diameter was estimated to be 0.69 kg m<sup>-2</sup> in Asia (FAO 2006). This value would be higher if dead wood ≥5 cm in diameter were included. We therefore suggest that dead wood C stock in the forest sector of Japan ranks low in Asia.

Dead wood C stock is higher in regions with higher altitude or higher latitude because of lower temperature (Woodall et al. 2008). In this study, high C stock was observed in some regions with low temperature, including the Hokkaido District and the central highland of Chubu District; low C stock was observed in regions with high temperature, including the Shikoku and Kyushu Districts (Fig. 6 and Table 7). However, some exceptional circumstances were observed. These include low C stock in the eastern part of the Tohoku District and the Hokuriku area of the Chubu District and high C stock in the northern part of the Kinki District. Additionally, the dead wood C stock was not related to annual mean temperature and annual precipitation in the prefectures (Fig. 7;  $p = 0.069$  and  $p = 0.893$ , respectively) when the data in Table 7 were analyzed using the Spearman rank correlation coefficient. Dead wood occurs not only by natural disturbance but also by forest management (e.g., Fridman and Walheim 2000, Siitonen 2000, Gibb et al. 2005, Lombardi et al. 2008).



Table 7 Climate condition and carbon stocks (kg m<sup>-2</sup>) of dead wood, litter, and soil at 0-30 cm in each prefecture

District	Prefecture number	Prefecture name	Mean temperature* (°C)	Annual precipitation* (mm)	Dead wood			Litter			Soil		
					Number of plots	Mean	Sample SD	Number of plots	Mean	Sample SD	Number of plots	Mean	Sample SD
Hokkaido	1	Hokkaido	4.9	1254	487	0.53	0.88	483	0.54	0.34	470	7.57	2.98
		Subtotal	4.9	1254	487	0.53	0.88	483	0.54	0.34	470	7.57	2.98
Tohoku	2	Aomori	8.2	1520	62	0.37	0.88	62	0.43	0.25	60	7.91	2.82
	3	Iwate	7.8	1434	102	0.30	0.37	104	0.57	0.36	100	8.58	2.98
	4	Miyagi	9.6	1450	42	0.21	0.37	43	0.38	0.26	42	7.00	2.52
	5	Akita	8.4	2001	94	0.66	0.73	95	0.54	0.26	94	7.97	2.90
	6	Yamagata	8.5	2189	58	0.44	0.77	59	0.47	0.30	57	8.53	3.17
	7	Fukushima	8.7	1508	89	0.25	0.39	91	0.46	0.25	87	8.14	3.20
	Subtotal	8.4	1673	447	0.39	0.62	454	0.49	0.29	440	8.11	2.99	
Kanto	8	Ibaraki	11.9	1397	24	0.35	0.50	24	0.43	0.22	24	9.16	2.95
	9	Tochigi	9.3	1597	34	0.48	0.67	34	0.48	0.28	32	7.96	3.29
	10	Gunma	8.1	1489	40	0.39	0.80	40	0.53	0.37	39	8.66	4.45
	11	Saitama	10.5	1401	14	0.57	0.53	13	0.35	0.19	13	5.07	2.18
	12	Chiba	14.2	1676	17	0.47	0.43	17	0.37	0.23	17	7.37	2.21
	13	Tokyo	12.0	1877	9	0.48	0.49	9	0.40	0.21	9	4.09	1.91
	14	Kanagawa	11.9	2138	10	0.18	0.11	11	0.25	0.16	10	4.80	2.92
	Subtotal	10.3	1577	148	0.42	0.61	148	0.44	0.28	144	7.56	3.65	
Chubu (Hokuriku area)	15	Niigata	9.8	2504	63	0.31	0.68	63	0.37	0.19	63	7.11	2.82
	16	Toyama	8.9	2732	20	0.30	0.37	19	0.57	0.38	21	8.00	6.93
	17	Ishikawa	11.2	2454	35	0.26	0.27	35	0.42	0.20	32	7.52	2.31
	18	Fukui	11.3	2518	33	0.44	0.42	33	0.34	0.11	33	5.91	1.92
	Subtotal	10.2	2532	151	0.33	0.52	150	0.40	0.22	149	7.06	3.49	
Chubu (central highland)	19	Yamanashi	8.8	1693	32	0.28	0.42	31	0.46	0.49	32	7.89	3.84
	20	Nagano	7.5	1765	93	0.53	0.81	93	0.53	0.28	89	6.56	3.58
	21	Gifu	9.2	2474	81	0.63	1.03	80	0.53	0.42	80	6.05	3.59
	Subtotal	8.3	2001	206	0.53	0.87	204	0.52	0.37	201	6.57	3.66	
Chubu (Tokai area)	22	Shizuoka	11.7	2594	49	0.44	0.59	48	0.54	0.44	49	7.23	5.11
	23	Aichi	12.7	1958	20	0.33	0.54	19	0.51	0.35	20	5.31	2.58
	24	Mie	13.0	2402	35	0.26	0.30	35	0.45	0.20	35	7.19	3.40
	Subtotal	12.3	2440	104	0.36	0.50	102	0.51	0.35	104	6.85	4.22	
Kinki	25	Shiga	11.6	2044	22	0.50	0.82	22	0.48	0.34	22	5.55	2.39
	26	Kyoto	12.3	1757	22	0.58	0.69	22	0.51	0.26	22	5.51	2.34
	27	Osaka	13.2	1447	3	0.10	0.04	3	0.45	0.10	4	3.27	1.07
	28	Hyogo	12.3	1672	38	0.46	0.57	38	0.46	0.27	38	4.58	2.26
	29	Nara	10.9	2206	32	0.44	0.46	32	0.57	0.44	32	4.94	2.19
	30	Wakayama	13.3	2416	41	0.47	0.67	34	0.63	0.38	41	5.06	1.74
	Subtotal	12.2	1961	158	0.47	0.63	151	0.53	0.35	159	5.01	2.15	
Chugoku	31	Tottori	11.1	2089	25	0.59	0.69	28	0.51	0.32	28	7.17	2.82
	32	Shimane	12.2	1910	65	0.29	0.32	65	0.61	0.37	63	6.92	2.61
	33	Okayama	11.7	1478	50	0.46	0.65	50	0.60	0.35	49	5.59	2.89
	34	Hiroshima	11.6	1656	66	0.41	0.51	66	0.62	0.36	66	6.53	3.91
	35	Yamaguchi	13.1	1955	49	0.35	0.40	51	0.49	0.26	51	4.70	1.68
	Subtotal	12.0	1783	255	0.39	0.51	260	0.57	0.34	257	6.15	3.04	
Shikoku	36	Tokushima	12.1	2414	33	0.40	0.44	32	0.52	0.42	33	6.17	2.29
	37	Kagawa	14.0	1207	9	0.08	0.11	9	0.37	0.29	9	2.95	1.27
	38	Ehime	12.9	1900	45	0.32	0.53	46	0.48	0.34	46	5.42	2.58
	39	Kochi	13.0	2820	57	0.33	0.51	57	0.53	0.28	57	6.34	2.06
	Subtotal	12.9	2301	144	0.33	0.49	144	0.50	0.33	145	5.80	2.39	
Kyushu	40	Fukuoka	13.6	2062	33	0.46	0.35	34	0.51	0.25	34	6.16	1.51
	41	Saga	13.7	2233	14	0.30	0.23	13	0.36	0.14	13	7.84	3.04
	42	Nagasaki	14.9	2103	29	0.20	0.29	29	0.45	0.18	28	6.06	2.45
	43	Kumamoto	13.0	2489	57	0.34	0.54	58	0.29	0.17	58	5.81	3.18
	44	Oita	13.0	2054	61	0.35	0.36	61	0.29	0.14	59	7.49	3.76
	45	Miyazaki	13.4	2749	71	0.25	0.37	70	0.35	0.18	70	6.04	2.98
	46	Kagoshima	16.3	2687	62	0.55	0.94	62	0.36	0.17	62	7.05	3.11
	47	Okinawa	21.9	2405	11	0.26	0.28	9	0.25	0.09	11	5.02	3.02
	Subtotal	14.4	2438	338	0.36	0.54	336	0.35	0.19	335	6.49	3.10	

\* Mean values of forest sector in 1971–2000 (Japan Meteorological Agency 2002).

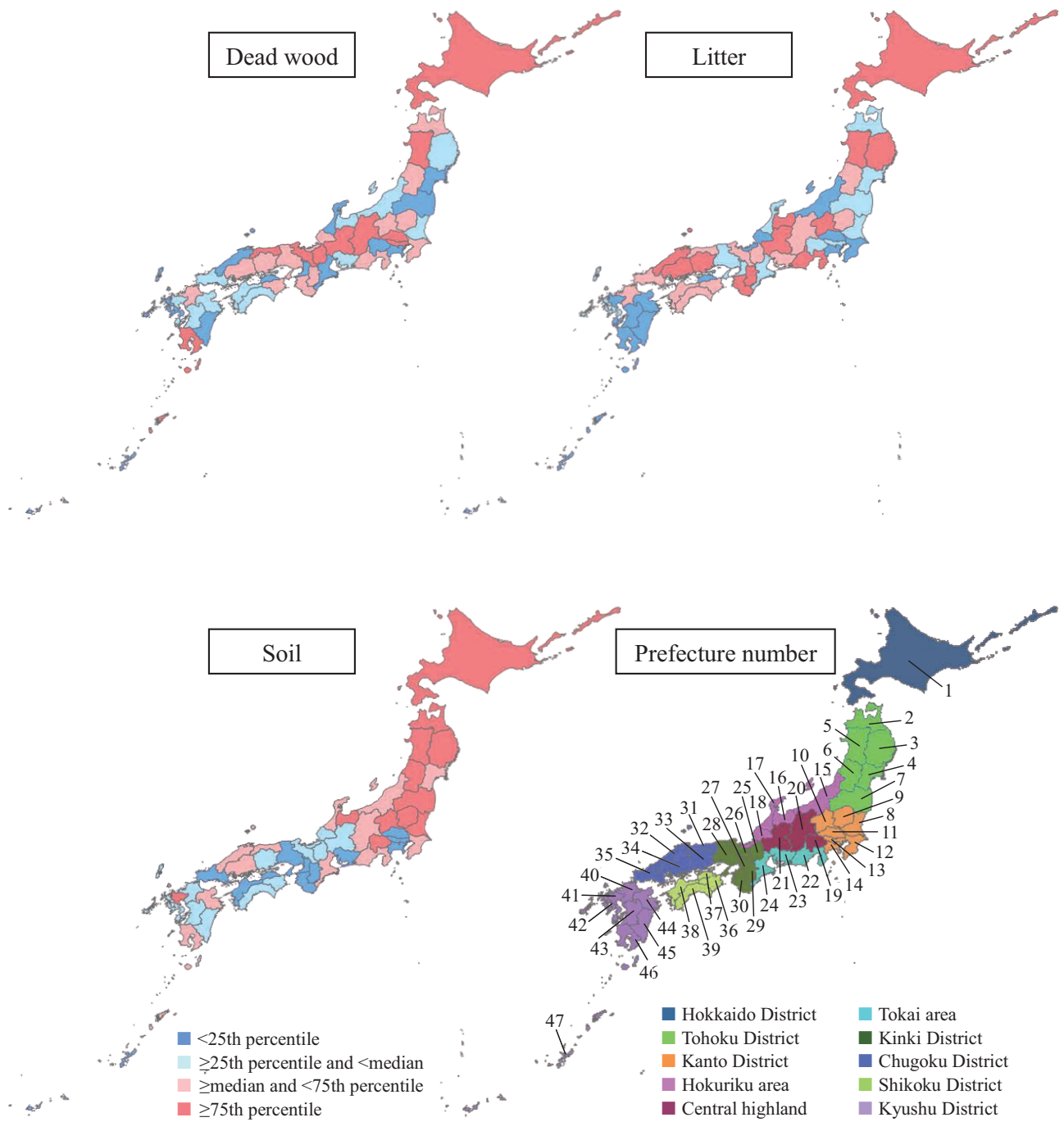


Fig. 6 Distribution of carbon stocks of dead wood, litter, and soil at 0–30 cm. Carbon stocks of the three pools in each prefecture were classified into four groups: <25th percentile; ≥25th percentile and <median; ≥median and <75th percentile; and ≥75th percentile.

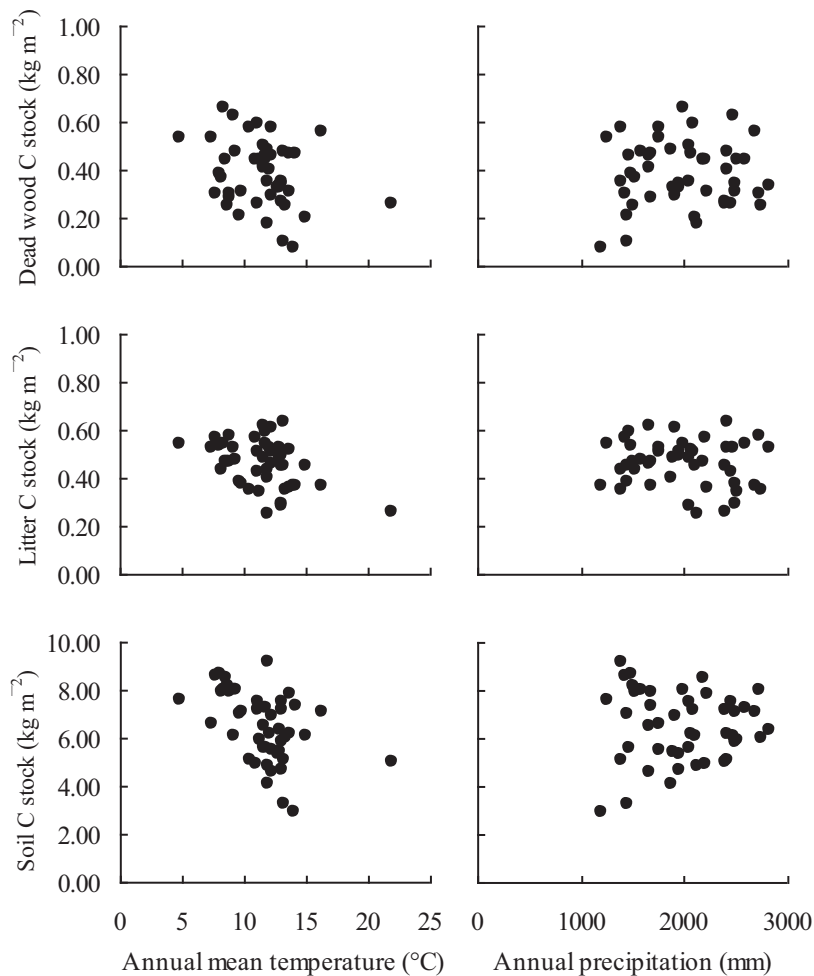


Fig. 7 Carbon stocks of dead wood, litter, and soil at 0–30 cm in each prefecture with annual mean temperature and annual precipitation of the forest sector. The annual mean temperature and annual precipitation are the mean values for 1971–2000, which were calculated using data from Japan Meteorological Agency (2002). The C stocks of litter and soil at 0–30 cm decreased with increasing annual mean temperature (Spearman rank-correlation coefficient:  $p = 0.004$  and  $p < 0.001$ , respectively).

The amount of dead wood also varies among stands with different dominant tree species (Takahashi et al. 2010). Thus, we speculate that the dead wood C stock is influenced by microscale factors such as tree community structure and forest management rather than by macroscale factors such as temperature.

#### Litter C Stock

The mean litter C stock,  $0.49 \text{ kg m}^{-2}$  (Table 6), was within the mean values of forests dominated by the major tree species of Japan,  $0.42\text{--}1.15 \text{ kg m}^{-2}$  (Takahashi et al. 2010). The mean litter C stock was estimated to be  $0.29 \text{ kg m}^{-2}$  in Asia (FAO 2006). We therefore suggest that the litter C stock in the forest sector of Japan ranks high in Asia.

Litter is decomposed easily in regions with high temperature but is decomposed with difficulty in regions with low temperature (Coûteaux et al. 1995, Aerts 1997, Trofymow et al. 2002). This pattern is consistent with the high C stock in the Hokkaido District and the central highland of the Chubu District and also with low C stock in the Kyushu District (Fig. 6 and Table 7). Moreover, the litter C stock was lower in prefectures with a higher annual mean temperature (Fig. 7;  $p = 0.004$ ). These results imply that the litter C stock is influenced to some extent by a macroscale factor, i.e., temperature. On the other hand, some exceptional instances were noted. These include low C stock in the southern part of the Kanto District and the Hokuriku area of the Chubu District and high C

stock in the southern part of the Kinki District and the Chugoku District. Litter C stock varies among dominant tree species (Takahashi et al. 2010). The exceptional results in the spatial distribution of litter C stock may be caused by microscale factors such as tree community structure (Takahashi et al. 2010). Further study is needed to determine these microscale factors precisely.

#### Soil C Stock at 0–30 cm

The mean soil C stock at 0–30 cm,  $6.94 \text{ kg m}^{-2}$  (Table 6), was lower than the value of  $9.0 \text{ kg m}^{-2}$  estimated by Morisada et al. (2004), who compiled soil profile data collected from 1950s to 1970s in national forest soil survey projects. In previous studies, the soil survey point was chosen by surveyors as a representative soil profile in which genetic soil horizons were typical in the survey plot (Government Forest Experiment Station 1955). Thus, well-developed soils with high C stock may have been selected in the soil survey, resulting in a higher mean value for soil C stock in previous studies than in our study. Additionally, the methods used to measure gravel content, soil mass, and C concentration are different between the previous work and our study. Therefore, it is not necessarily appropriate to suggest that the difference in soil C stock reflects the passage of time. Careful discussion is needed to interpret the difference in soil C stock.

We suggest that the soil C stock at 0–30 cm in the forest sector of Japan ranks slightly high in Asia because the mean soil C stock at 0–30 cm was estimated to be  $6.61 \text{ kg m}^{-2}$  in Asia (FAO 2006). Soil C stock at 0–30 cm tends to be higher in regions with higher altitude or higher latitude because of the lower temperature (e.g., Batjes 2002, Liski et al. 2002). The results of this study are generally consistent with this pattern. Soil C stock at 0–30 cm was high in northern Japan, i.e., in the Hokkaido, Tohoku, and Kanto Districts, and low in southern Japan, i.e., in the Kinki and Shikoku Districts (Fig. 6 and Table 7). This tendency was also supported by the lower soil C stock in the prefectures with higher annual mean temperature (Fig. 7;  $p < 0.001$ ). Thus, we suggest that the soil C stock is regulated by a macroscale factor, i.e., temperature. Exceptions to this pattern included high C stock observed in Tottori and Shimane Prefectures of the Chugoku District, and Nagasaki, Oita, and Kagoshima Prefectures of the Kyushu District. Active volcanoes (i.e., Mt. Daisen, Mt. Sanbesan, Mt. Unzendake, Mt. Sakurajima, and Mt. Aso) are located in Tottori, Shimane, Nagasaki, and Kagoshima Prefectures, and at the southwest border of Oita Prefecture, respectively, and have supplied volcanic ash in the last 20

years (Machida and Arai 2003). Soil derived from volcanic ash (i.e., Andosols) is known to accumulate large amounts of organic C (Shoji et al. 1993, Morisada et al. 2004). This indicates that the exceptional instance of high C stock can be explained by the existence of volcanic ash soils.

#### Ratio of Soil C Stock at 0–30 cm to Soil C Stock at 0–100 cm

The mean soil C stock at 0–100 cm,  $14.29 \text{ kg m}^{-2}$  (Table 6), was lower than the value of  $18.8 \text{ kg m}^{-2}$  reported by Morisada et al. (2004), and the mean ratio of soil C stock at 0–30 cm to that at 0–100 cm, 0.59, was higher than 0.48, the value estimated by Morisada et al. (2004). However, as discussed in an earlier section (*Soil C Stock at 0–30 cm*), the survey methods may explain the difference in the soil C stock at 0–100 cm and in the ratio of soil C stock at 0–30 cm to that at 0–100 cm between the result in this study and that reported by Morisada et al. (2004). On the other hand, the mean ratio of soil C stock at 0–30 cm to that at 0–100 cm was estimated to be 0.52 in *Cambisols* and 0.44 in *Andosols* worldwide (Batjes 1996), and these two soil types are distributed dominantly in the forest land of Japan (Morisada et al. 2004). Therefore, the ratio of soil C stock at 0–30 cm to that at 0–100 cm in the forest sector of Japan is higher than the world average, that is, the C stock of soil at 0–30 cm accounts for a larger portion of that at 0–100 cm compared with ratios worldwide. Jobbágy and Jackson (2000) reported that the ratio of soil C stock at 0–20 cm to that at 0–100 cm increased with increasing annual precipitation. The high ratio of soil C stock at 0–30 cm may reflect the monsoon climate and high humidity of Japan (Kottek et al. 2006).

#### Organic Soil

In this study, we excluded a soil layer with C concentration  $>0.25 \text{ kg kg}^{-1}$  from the calculations of soil C stock due to anomalous data resulting from a mistake in the field survey. However, according to the criteria, some organic soils were probably excluded from our count, which may have decreased the mean soil C stock at 0–30 cm. Organic soils are not common in the forest sector of Japan: the soil C stock of the Peaty Soil Group (Forest Soil Division 1976), corresponding to Histosols, was estimated to be 13 Tg at 0–30 cm depth and occupied just 0.6% of total C stock in the forest sector. On the other hand, Histosols are a major global soil type; the total extent of Histosols is estimated to be 325–375 million ha, and they are mainly observed in the boreal, subarctic, and low arctic regions of the northern hemisphere (IUSS Working Group WRB 2006). We therefore need to identify organic soils



using a description of the soil profile and evaluate the C stock of organic soils in the forest sector of Japan in future studies.

### Conclusion

In this study, we found that the C stock of dead wood, litter, and soil in the forest sector of Japan was  $0.42 \pm 0.67$ ,  $0.49 \pm 0.32$ , and  $6.94 \pm 3.25 \text{ kg m}^{-2}$ , respectively. For dead wood and litter, this study detected no latitudinal tendency in the distribution of C stocks throughout Japan. However, soil C stock at 0–30 cm was generally higher in northern Japan and lower in southern Japan. This is supported by the lower soil C stock in prefectures with a higher annual mean temperature. On the other hand, high C stock was observed in some prefectures of the volcanic region of southern Japan. We thus suggest that the soil C stock is regulated by macroscale factors, i.e., temperature, as well as by the distribution of volcanic ash soils. Additionally, our results indicate that the soil C stock at 0–30 cm in the forest sector of Japan accounts for a larger portion of that at 0–100 cm compared with forest soils around the world.

### Acknowledgements

We are grateful to researchers of the prefectural forest research institutes for collecting field data and samples. We also thank the members of the Department of Forest Site Environment and the Bureau of Climate Change of the Forestry and Forest Product Research Institute for supporting this study. This study was a result of the National Forest Soil Carbon Inventory managed by the Forestry Agency of Japan.

### References

- Aerts, R. (1997) Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. *Oikos*, 79, 439–449.
- Batjes, N. H. (1996) Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.*, 47, 151–163.
- Batjes, N. H. (2002) Carbon and nitrogen stocks in the soils of Central and Eastern Europe. *Soil Use Manag.*, 18, 324–329.
- Brown, J. K. (1974) Handbook for inventorying downed woody material, Gen. Tech. Rep. INT-16. USDA For. Serv., Ogden, UT, 24 pp.
- Coûteaux, M. C., Bottner, P. and Berg, B. (1995) Litter decomposition, climate and litter quality. *Trends Ecol. Evol.*, 10, 63–66.
- FAO (2006) Global forest resources assessment 2005. FAO Forestry Paper 147. FAO, Rome, 320 pp.
- Forestry Agency of Japan (2007) Implementation report of the National Forest Carbon Inventory in FY2007. Forestry Agency of Japan, Tokyo, 39–59. (In Japanese)
- Forestry Agency of Japan (2012) "Forest Resources Monitoring Survey in 1999–2008", <http://www.rinya.maff.go.jp/j/keikaku/monitar/index.html>, (accessed 2012-03-07).
- Forest Soil Division (1976) Classification of forest soil in Japan. *Bull. Gov. For. Exp. Sta.*, 280, 1–28. (In Japanese with English summary)
- Fridman, J. and Walheim, M. (2000) Amount, structure, and dynamics of dead wood on managed forestland in Sweden. *For. Ecol. Manag.*, 131, 23–36.
- Governmental Forest Experiment Station (1955) The manual for forest soil survey in the national forest. Governmental Forest Experiment Station of Japan Forest Agency, Tokyo, 47 pp. (In Japanese)
- Gibb, H., Ball, J. P., Johansson, T., Atlegrim, O., Hjältén, J. and Danell, K. (2005) Effects of management on coarse woody debris volume and composition in boreal forests in northern Sweden. *Scand. J. For. Res.*, 20, 213–222.
- Imaya, A., Yoshinaga, S., Inagaki, Y., Tanaka, N. and Ohta, S. (2010a) Proposal for advanced classification of brown forest soils in Japan with reference to the degree of volcanic ash additions. *Soil Sci. Plant Nutr.*, 56, 454–465.
- Imaya, A., Yoshinaga, S., Inagaki, Y., Tanaka, N. and Ohta, S. (2010b) Volcanic ash additions control soil carbon accumulation in brown forest soils in Japan. *Soil Sci. Plant Nutr.*, 56, 734–744.
- IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The Institute for Global Environmental Strategies (IGES), Hayama, 83 pp.
- IUSS Working Group WRB (2006) World reference base for soil resources 2006. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome, 128 pp.
- Japan Meteorological Agency (2002) Mesh climatic data 2000. Japan Meteorological Agency, Tokyo. (In Japanese)
- Jobbágy, E. G. and Jackson, R. B. (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.*, 10, 423–436.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. (2006) World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, 15, 259–263.
- Lal R. (2002) Encyclopedia of soil science. second edition. Marcel Dekker, Inc., New York, 1476 pp.
- Liski, J., Perruchoud, D. and Karjalainen, T. (2002) Increasing carbon stocks in the forest soils of western Europe. *For. Ecol. Manag.*, 169, 159–175.

- Lombardi, F., Lasserre, B., Tognetti, R. and Marchetti, M. (2008) Deadwood in relation to stand management and forest type in central Apennines (Molise, Italy). *Ecosystems*, 11, 882–894.
- Machida, H., Arai, F. (2003) Atlas of tephra in and around Japan. University of Tokyo Press, Tokyo, 336 pp. (In Japanese)
- Morisada, K., Ono, K. and Kanomata, H. (2004) Organic carbon stock in forest soils in Japan. *Geoderma*, 119, 21–32.
- Sakai, Y., Takahashi, M., Ishizuka, S., Inagaki, Y., Matsuura, Y., Unno, A., Nakata, K., Nagasaka, A., Niwa, H., Sawata, S., Houjyou, Y., Tamaki, Y., Kasetani, T., Takeda, H., Aiura, H., Yamanouchi, M., Shimada, H., Iwatsuki, T., Yamada, A., Yamada, T., Maeda, H. and Muro, M. (2008) Estimating decay rates of dead wood by changes in wood density in coniferous plantation in Japan. *Jpn. J. For. Environ.*, 50, 153–165. (In Japanese with English summary)
- Shoji, S., Nanzyo, M. and Dahlgren, R. A. (1993) Volcanic ash soils: genesis, properties and utilization. *Developments in Soil Science* 21. Elsevier Science Publishers B. V., Amsterdam, 312 pp.
- Siitonen, J., Martikainen, P., Punttila, P. and Rauh, J. (2000) Coarse woody debris and stand characteristics in mature managed and old-growth boreal mesic forests in southern Finland. *For. Ecol. Manag.*, 128, 211–225.
- Soil Survey Staff (1999) *Soil Taxonomy*, second edition. USDA-Natural Resources Conservation Service, Washington, 869 pp.
- Takahashi, M., Ishizuka, S., Ugawa, S., Sakai, Y., Sakai, H., Ono, K., Hashimoto, S., Matsuura, Y. and Morisada, K. (2010) Carbon stock in litter, deadwood and soil in Japan's forest sector and its comparison with carbon stock in agricultural soils. *Soil Sci. Plant Nutr.*, 56, 19–30.
- Trofymow, J. A., Moore, T. R., Titus, B., Prescott, C., Morrison, I., Siltanen, M., Smith, S., Fyles, J., Wein, R., Camiré, C., Duschene, L., Kozak, L., Kranabetter, M. and Visser, S. (2002) Rates of litter decomposition over 6 years in Canadian forests: influence of litter quality and climate. *Can. J. For. Res.*, 32, 789–804.
- Ugawa, S., Hashimoto, T., Aizawa, S., Kaneko, S. and Takahashi, M. (2010) Accuracy criteria for measuring carbon and nitrogen concentrations in forest soil and litter samples. *Soil Sci. Plant Nutr.*, 56, 466–475.
- Van Wagner, C. E. (1968) The line intersect method in forest fuel sampling. *For. Sci.*, 14, 20–26.
- Warren, W. G. and Olsen, P. F. 1964. A line intersect technique for assessing logging waste. *For. Sci.*, 13, 267–276.
- Wild, S. A. (1971) Forest humus: its classification on genetic basis. *Soil Sci.*, 111, 1–12.
- Woodall, C. W., Heath, L. S. and Smith, J. E. (2008) National inventories of down and dead woody material forest carbon stocks in the United States: challenges and opportunities. *For. Ecol. Manag.*, 256, 221–228.
- Yang, Y. H., Fang, J. Y., Guo, D. L., Ji, C. J. and Ma, W. H. (2010) Vertical patterns of soil carbon, nitrogen and carbon: nitrogen stoichiometry in Tibetan grasslands. *Biogeosciences Discuss.*, 7, 1–24.

## 日本の森林における枯死木、堆積有機物、土壌の炭素蓄積量： 森林土壌インベントリの第1報

鵜川 信<sup>1)\*</sup>、高橋 正通<sup>2)</sup>、森貞 和仁<sup>3)</sup>、竹内 学<sup>4)</sup>、松浦 陽次郎<sup>5)</sup>、吉永 秀一郎<sup>6)</sup>、  
荒木 誠<sup>1)</sup>、田中 永晴<sup>1)</sup>、池田 重人<sup>1)</sup>、三浦 覚<sup>1)</sup>、石塚 成宏<sup>6)</sup>、小林 政広<sup>1)</sup>、  
稲垣 昌宏<sup>6)</sup>、今矢 明宏<sup>1)</sup>、南光 一樹<sup>1)</sup>、橋本 昌司<sup>1)</sup>、相澤 州平<sup>3)</sup>、平井 敬三<sup>7)</sup>、  
岡本 透<sup>8)</sup>、溝口 岳男<sup>9)</sup>、鳥居 厚志<sup>9)</sup>、酒井 寿夫<sup>10)</sup>、大貫 靖浩<sup>1)</sup>、金子 真司<sup>1)</sup>

### 要旨

本研究では、日本の森林における枯死木、堆積有機物および土壌（深さ 0–30 cm）の炭素蓄積量を明らかにすること、炭素蓄積量の空間分布を都道府県単位で示すこと、深さ 0–100 cm の土壌炭素蓄積量に占める深さ 0–30 cm の土壌炭素蓄積量の割合を示すことを目的とした。これらの目的を達成するため、2006–2010 年度に実施した林野庁森林吸収源インベントリ情報整備事業（日本全国の森林における枯死木、堆積有機物および土壌の炭素蓄積量調査）のデータを解析した。枯死木、堆積有機物および土壌（深さ 0–30 cm）の炭素蓄積量（平均 ± 標本標準偏差）は、それぞれ  $0.42 \pm 0.67$ 、 $0.49 \pm 0.32$ 、 $6.94 \pm 3.25 \text{ kg m}^{-2}$  であった。各都道府県の枯死木および堆積有機物の炭素蓄積量は、緯度方向の分布傾向を示さなかった。しかしながら、統計解析では、年平均気温が高い都道府県ほど堆積有機物炭素蓄積量が低くなる傾向が検出された。土壌炭素蓄積量は、北日本で高く、南西日本で低くなる傾向がみられ、年平均気温が高い都道府県ほど土壌炭素蓄積量が低くなることが確認された。他方、火山帯に位置する南西日本の都道府県で土壌炭素蓄積量が高くなる傾向がみられた。このことから、深さ 0–30 cm の土壌炭素蓄積量は、気温のみならず、火山灰の分布によっても規定されることが窺われた。加えて、深さ 0–100 cm の土壌炭素蓄積量は  $14.29 \pm 8.38 \text{ kg m}^{-2}$ （平均 ± 標本標準偏差）であり、これに占める深さ 0–30 cm の土壌炭素蓄積量の割合は  $0.59 \pm 0.31$ （平均 ± 標本標準偏差）であった。この割合は、世界の平均値よりも高かった。

キーワード：炭素蓄積量、枯死木、堆積有機物、土壌、インベントリ、システムティックサンプリング、京都議定書

- 
- 1) 森林総合研究所立地環境研究領域
  - 2) 森林総合研究所企画部
  - 3) 森林総合研究所北海道支所
  - 4) 林野庁中部森林管理局
  - 5) 森林総合研究所国際連携推進拠点
  - 6) 森林総合研究所九州支所
  - 7) 森林総合研究所東北支所
  - 8) 森林総合研究所木曾試験地
  - 9) 森林総合研究所関西支所
  - 10) 森林総合研究所四国支所

\* 森林総合研究所立地環境研究領域 〒305-8687 茨城県つくば市松の里 1 e-mail: ushin@ffpri.affrc.go.jp