

Estimating the age-dependent changes in carbon stocks of Scots pine (*Pinus sylvestris* L.) stands in Turkey

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Abstract

• **Key message** Simulated and observed carbon stocks in Scots pine forests varied considerably with stand age. The contribution of biomass to the total forest carbon stocks increased and that of dead organic matter decreased with increasing stand age.

• **Context** Understanding changes in forest carbon stocks over time is important to estimate carbon inventory. Although Scots pine (*Pinus sylvestris* L.) is a main species in Turkey, studies on such changes are still lacking.

• **Aims** We aimed to estimate the changes in carbon stocks, with stand age, of Scots pine stands in Turkey using field work data and a forest carbon model (FBDC model).

• **Methods** Biomass and dead organic matter carbon stocks were investigated to adjust the forest carbon model and to verify the model estimates. Forest carbon stocks with regards to stand age were simulated.

• **Results** The simulated carbon stocks were generally in clear agreement with the observed values on a stand scale. Changes in simulated and observed carbon stocks of biomass and dead

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Contribution of the co-authors Jongyeol Lee ran the data analysis, led discussion, and wrote the paper; Doğanay Tolunay, Ender Makineci and Aydın Çömez designed and conducted the field experiment and discussed the results; Yeong Mo Son and Raehyun Kim participated in model parameterization and discussion; and Yowhan Son wrote the paper, participated in discussion, and supervised the work.

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organic matter varied with stand age. The contribution of biomass to total forest carbon stocks increased, and that of dead organic matter decreased, with increasing stand age.

• **Conclusion** We found that the carbon stocks in each pool and their contribution to the total forest carbon stocks varied with stand age. Our results are expected to contribute to the understanding of annual changes in the carbon stocks of Turkish forests.

Keywords Forest carbon · Scots pine · FBDC model · Biomass · Dead organic matter · Verification

1 Introduction

Forest ecosystems contain a substantial amount of carbon (C) and make a significant contribution to the global C sink (Dixon et al. 1994; Pan et al. 2011). Maintaining forest C sinks has also become important to mitigate global climate change. In order to implement successful forest management policies, a scientific basis is required (Tewari 2015). Thus, forest C dynamics have been quantified at various spatial and temporal scales (Dixon et al. 1994; Luyssaert et al. 2010; Pan et al. 2011).

Forest C stocks and their changes have been estimated directly through field measurements. However, there are a number of limitations with this method, including uncertainties in data extrapolation at temporal and spatial scales, and high demands on labor and cost (Fang et al. 2014). Ecosystem modeling is a method frequently applied to estimate forest C stocks and their changes on regional and global scales (Kurz and Apps 1999; Luyssaert et al. 2010; Sitch et al. 2008). In addition, ecosystem models can estimate C cycles at different time and space more efficiently than direct measurement (Liski et al. 2002; Pilli et al. 2013). Considering these advantages, such models represent an effective alternative to field measurements.

Scots pine (*Pinus sylvestris* L.) is a main species in European forests and occupies 1.48 million ha of the total of 21.68 million ha of Turkish forests. Accordingly, understanding C dynamics in Scots pine forests is an important step toward estimation of the total C stock in Turkish forests. Previous studies have focused mainly on estimating C stocks in biomass using forest inventory data, allometry functions, and constant biomass expansion factors (Misir 2013; Sivrikaya et al. 2013; Tolunay 2011; Yolasiğmaz and Keles 2009). C stocks in dead organic matter (e.g., O horizon, dead wood, and mineral soil) have been poorly studied (Tolunay and Çömez 2008). The lack of measurement makes it hard to understand the C dynamics in Scots pine forests in Turkey.

Ecosystem models allow us to simulate the forest C cycle, including biomass and dead organic matter (Kim et al. 2015a). However, insufficient data on Turkish forests makes it hard to run most forest C models. The forest biomass and dead organic matter C (FBDC) model (previously known as the KFSC model) requires only few parameters and input data (Lee et al.

2014; Yi et al. 2013). For this reason, it seemed highly suitable to simulate C dynamics in the Scots pine forests of Turkey. The FBDC model has successfully estimated the forest C dynamics on a national scale over several decades in Korea (Lee et al. 2014, 2015; Park et al. 2013a; Yi et al. 2013).

In this study, we aimed to elucidate the annual changes in (1) the C stocks of above- and below-ground biomass, the O horizon, dead wood, and mineral soil; and (2) the distribution of C stocks among C pools in Scots pine stands. Field work was conducted to estimate the model input and parameters of the FBDC model and to measure the C stocks in each pool. The FBDC model was adjusted to fit the study site using empirical data and previous studies. The model estimates of biomass, O horizon, aboveground dead wood, and mineral soil were then verified by comparing them with the corresponding observed C stocks. The change in contribution of each pool to total forest C stocks with increasing stand age was also estimated.

2 Materials and methods

2.1 Site description and field work

In this study, the data of stand characteristics and C stocks of above- and below-ground biomass, O horizon, aboveground dead wood, and mineral soil reported in Çömez (2010) were used (Table 1). This study was conducted in Scots pine forests in the Sundiken Mountains, which are located in the central Anatolia region of Turkey (39° 56'–39° 59' N, 31° 03'–31° 11' E). According to the WorldClim 1.4 data set, the annual mean temperatures range between 7.2 °C and 9.2 °C and the annual mean precipitation was about 700–900 mm (Çömez 2010). The soil group and texture was almost Luvisol and sandy clay loam, and acidity (pH) ranged from 5.0 to 6.6 in the research area (Çömez 2010; IUSS Working Group WRB 2006).

A total of 63 sample plots was selected from Scots pine stands with different ages (8- to 177-year-old), diameters at breast height (DBH; 0–46.79 cm), tree heights (0.9–29.38 m), and canopy covers (10–90 %) in 2008. The areas of the sample plots varied between 100 m² and 400 m². The mean age of each plot was determined by counting the annual rings in samples taken with an increment borer from five trees. One tree with a mean DBH of each sample plot was excavated in order to weigh individual tree components (stem, foliage, and branch). The tree roots, the other tree component, were sampled and weighed in 24 sample plots due to limitations of labor and cost. Based on the data, a regression model of each tree component was developed according to the DBH and tree height. The mass

Table 1 Stand characteristics and carbon (C) stocks in the study site. *DBH* Diameter at breast height

	Minimum	Mean	Maximum
Stand characteristics			
DBH (cm)	0	29.24	46.79
Height (m)	0.85	16.22	29.38
Mean age (year)	8	85.46	177
Canopy cover (%)	10	56.45	90
Stand density (trees ha ⁻¹)	50	2658.51	40,000
C stocks (Mg C ha ⁻¹)			
Stem	0.91	71.34	202.65
Branch	0.44	12.56	37.54
Foliage	0.66	4.05	8.62
Aboveground biomass	2.21	87.95	247.93
Root	0.48	17.47	46.92
Total biomass	2.69	105.42	294.85
O horizon	2.15	15.37	34.91
Aboveground dead wood	0	0.94	4.62
Mineral soil (1 m depth)	53.79	99.65	160.84

of tree components in each plot was estimated using these regression models. The C stocks in 44 sample plots were selected to estimate growth models, and those in 19 plots were used to verify the models.

O horizon samples were taken randomly from an area of 0.25 m², with four replications in each sample plot. All dead wood materials in sample plots were collected and weighed. To estimate the C stocks in the mineral soil, one soil pit was dug at a random point in each sample plot. Soil samples were collected from the different mineral soil horizons up to 1 m in depth with 1-L soil corers. The soil samples were air-dried and sieved with a 2-mm screen. To estimate the soil bulk density, all roots and coarse material bigger than 2 mm were separated from the mineral soil.

Subsamples of tree components, O horizon, and aboveground dead wood were dried at 65 °C and soil samples were dried at 105 °C to constant weight. Then, C concentration was measured using a CHN analyzer (LECO TruSpec 2000 Analyzer; LECO Corporation, St. Joseph, MI). To measure the amount of C in trees, O horizon, aboveground dead wood, and mineral soil, the C concentration was multiplied by the dry weight. In particular, the C stock at each soil depth was measured from the C concentration, bulk density and layer thickness, and the total C stocks in the mineral soil were determined by summing the C contents at all soil depths. Consequently, the C stocks (Mg C ha⁻¹) in the total biomass, O horizon, mineral soil, and aboveground dead wood were 2.69–294.85, 2.15–34.91, 53.79–160.84, and 0–4.62, respectively.

2.2 FBDC model structure and parameterization

The FBDC model is a generic model, simulating the complex C dynamics of dead organic matter with simple biomass regression models and only a few parameters (Lee et al. 2014; Yi et al. 2013). The main feature of this model is the low level of required input data and its high applicability at various spatial and temporal scales. It was first called the Korean Forest Soil Carbon (KFSC) model (Lee et al. 2014; Yi et al. 2013). We changed the name to the FBDC model because it can simulate C dynamics for both biomass and dead organic matter. This model consists of a biomass compartment and a dead organic matter compartment (Yi et al. 2013). The biomass category includes five tree components: the stem, branch, foliage, coarse root, and fine root pools, and their growth rates were estimated using a yield table and allometric function. The dead organic matter compartment includes the five primary dead organic matter pools (aboveground woody debris from stems, aboveground woody debris from branches, aboveground litter, belowground woody debris, and belowground litter) and the three secondary dead organic matter pools (aboveground humus, belowground humus, and soil organic C) that were classified by their source and degree of decomposition and kinetics (Lee et al. 2014). The following C processes were simulated in this model: (1) C stocks in biomass increase by sequestering atmospheric C; (2) a proportion of stems, branches, foliage, and coarse roots input organic C into primary dead organic matter pools (the O horizon and dead wood); (3) the annual production of dead fine roots becomes input to the mineral soil pool; (4) C in the O horizon and dead wood decay to the mineral soil C pool; and (5) C in the mineral soil finally decays to atmospheric C. Because the FBDC model was not parameterized for Scots pine forests, an adjustment was required. To estimate the growth function of each tree compartment with stand age, field data were used. The Gompertz function was used to formulate non-linear growth of tree with stand age {Biomass = a * exp [b * exp (c * Stand age)]; a, b, and c are constants}. The best-fitting model for each compartment was estimated with the PROC NLIN procedure in SAS 9.4 due to the non-linearities (Table 2). Measurement data of biomass C from 44 plots were used in this procedure. The actual growth of the trees in each plot, unfortunately, did not exactly follow the best-fitting functions due to heterogeneity in productivity among the plots. In order to calibrate for this heterogeneity, the following factor was invented (Lee et al. 2014):

$$\text{Growth Modifier} = \frac{\text{Stem } C_{\text{obs}}}{\text{Stem } C_{\text{est}}} \quad (1)$$

where Stem C_{obs} is the observed stem C stock from field work,

Table 2 Regression model of each biomass compartment. The regression models were based on the Gompertz function. Biomass carbon (C) stock (Mg C ha^{-1}) for each compartment (age) = $a \times \exp [b \times \exp (c \times \text{age})]$. The annual increase of C stock was calculated by the first-order derivative of each function

Compartment	Parameter		
	a	b	c
Stem	163.0	-3.13	-0.016
Branch	50.0	-3.38	-0.010
Foliage	4.5	-2.47	-0.100
Coarse root	49.2	-2.83	-0.012

and Stem C_{est} is the estimated stem C stock from the best-fitting function at a certain stand age. The growth modifiers, as input data for the FBDC model, were multiplied by the best-fitting regression model of each biomass compartment in each plot. These modifiers determined the level of biomass growth and annual dead organic matter input to forest soils. Because fine roots were not investigated in this study, the following ratio of fine root to foliage with stand age was used to estimate the C stocks in fine roots (Vanninen et al. 1996):

$$\text{Fine root} : \text{Foliage} = \text{Stand age} + 0.1012 (r^2 = 0.67) \quad (2)$$

By multiplying these ratios with the C stocks in the foliage, the C stocks in the fine roots could be estimated.

The substitution of parameters was needed in the FBDC model in order to simulate the C cycle in the Scots pine plots (Table 3). Most parameters were substituted by parameters that represented the regional environment. A detailed description of the dead organic matter C processes in the FBDC model is given by Yi et al. (2013).

Table 3 Parameters of the forest biomass and dead organic matter carbon (FBDC) model. *AWDS* Aboveground woody debris from the stem, *AWDB* aboveground woody debris from branches, *ALT* aboveground litter, *BWD* belowground woody debris, *BLT* belowground litter, *AHUM* aboveground humus, *BHUM* belowground humus, *SOC* soil organic carbon

Parameter	Value	Reference
Turnover rate (year^{-1})		
Stem	0.0043	Liski et al. (2002)
Branch	0.027	Liski et al. (2002)
Foliage	0.25	Muukkonen (2005); Çömez (unpublished)
Coarse root	0.027	Liski et al. (2002)
Fine root	0.84	Landsberg et al. (2005)
Decay constant (k ; year^{-1})		
AWDS and AWDB	0.028	Liski et al. (2002)
ALT	0.341	Sariyildiz (2008)
BWD	0.028	Assumed to equal the decay constant of AWDS
BLT	0.462	Kim (2002)
AHUM and BHUM	0.012	Liski et al. (2005)
SOC	0.0012	Liski et al. (2005)

2.3 Initialization and simulation of C stocks

Due to the lack of data on C stocks in dead organic matter pools at plots with an age of 0, these pools needed to be initialized. The dead organic matter C pools in the study sites were initialized with a spin-up process (Kurz et al. 2009; Lee et al. 2014). Due to the maximum stand age (177 years old) and the management plans of Turkish General Directorate of Forestry, the spin-up process was conducted by 200-year interval clear cutting. That process was conducted until the quasi-steady state in which the difference in the C stocks in the mineral soil pool between two successive rotations was less than 1 %.

After the initialization process, the forest C dynamics in each plot was simulated over the stand age in 2008. The simulated average and standard deviation of the C stocks in the biomass, O horizon, aboveground dead wood, and mineral soil were estimated. Because the C dynamics in each plot from 1 to 200 years old could be simulated with the FBDC model, the continuous change in the simulated C stock over the stand age in each pool (up to 200 years old) was also provided. The changes in the simulated C stocks in the C pools were the averaged value among the sampling plots from 1 to 200 years of age.

2.4 Verification

The simulated C stocks in the tree biomass (stems, branches, foliage, and roots), O horizon, aboveground dead wood, and mineral soil at the stand age in 2008 were thoroughly verified by comparing them to the corresponding observed C stocks at the plot scale. For this verification procedure, we used the measurement data from 19 plots that were not used to estimate

the best-fitting models. The C stocks in the dead organic matter pools were verified with the measurement data from 63 plots. The accuracy of the model estimates was estimated as the slope and r^2 of the linear relationship between the simulated and observed C stocks with SAS 9.4 software. The simulated C stocks in each biomass pool (the stems, branches, foliage, and roots) were verified. The observed C stocks in the O horizon were compared to the sum of the simulated C stocks in the aboveground woody debris from branches and the aboveground fallen leaves. The C stocks in the aboveground woody debris from stems in the FBDC model corresponded to those of the aboveground dead wood. Finally, the observed C stocks in the mineral soil were compared to the sum of the simulated C stocks in dead fine roots, humus, and the other mineral soil.

3 Results

3.1 Verification of model estimates

The simulated C stocks in the biomass, O horizon, and mineral soil were in clear agreement with the corresponding observed C stocks at the stand scale (Table 4). The simulated C stocks in the stems, branches, foliage, and roots were accurate. The difference between the simulated and observed C stocks of each tree component was, on average, less than 10 % ($r^2 \geq 0.93$) and the slope of each pool was not significantly biased ($a = 1$; $P > 0.05$). The root mean square errors (RMSEs) of the simulated C stock of tree components were also less than 4 Mg C ha⁻¹. Compared to biomass C pools, the dead organic matter C pools showed a high level of uncertainty. The simulated C stocks in the O horizon and mineral soil

Table 4 Linear relationship between simulated and observed carbon stocks. Simulated value = $a \times$ Observed value (a = coefficient of slope). All P values of slopes in the regression models were significant ($a \neq 0$). RMSE Root mean square error

Pool	All sample plots		
	Slope	r^2	RMSE (Mg C ha ⁻¹)
Biomass			
Stem	1.00	1.00	0
Branch	0.90	0.93	2.94
Foliage	1.03	0.94	1.08
Roots	0.94	0.95	3.52
Dead organic matter			
O horizon	1.07	0.52	11.84
Mineral soil	1.02	0.77	68.74
Aboveground dead wood	4.26*	0.25	10.54

* $P < 0.05$ [slope of linear relationship is significantly different from 1 ($a \neq 1$)]

were 7 % and 2 % more than the observed values and these estimates were not significantly biased ($a = 1$; $P > 0.05$). However, they showed lower precision ($r^2 = 0.52, 0.77$) and high levels of root mean square errors (11.84 and 68.74 Mg C ha⁻¹). Especially, the simulated C stocks in the aboveground dead wood were overestimated by about 4.3 times, with low precision ($r^2 = 0.25$) and high RMSE (10.54 Mg C ha⁻¹). In addition, the slope of linear relationship for aboveground dead wood was also significantly biased ($a \neq 1$; $P < 0.05$).

3.2 Changes in forest C stocks with stand age

The simulated biomass C stocks gradually increased from 0.61 Mg C ha⁻¹ to 235.25 Mg C ha⁻¹, and the observed biomass C stocks also demonstrated an increase with increasing stand age (Fig. 1a). In contrast, the simulated C stocks in the O horizon had an inconsistent relationship with stand age (Fig. 1b). The simulated C stocks in the O horizon decreased to 17.35 Mg C ha⁻¹ on average at the early development stage, and then gradually increased to 29.65 Mg C ha⁻¹. The simulated C stocks in the aboveground dead wood also exhibited an inconsistent relationship with stand age (Fig. 1c). The simulated C stocks in aboveground dead wood decreased from 20.33 Mg C ha⁻¹ to 7.07 Mg C ha⁻¹, and then increased to 20.25 Mg C ha⁻¹. The observed C stocks in the O horizon and aboveground dead wood differed from the simulated C stocks. Compared to the other dead organic matter C pools, the simulated mineral soil C stocks were insensitive to stand age (Fig. 1d). The simulated C stocks in the mineral soil ranged from 108.60 Mg C ha⁻¹ to 123.36 Mg C ha⁻¹ during the early development stage.

The contribution of each C pool to the total C stock also varied with stand age. In general, the contribution of biomass increased while those of the dead organic matter pools decreased with increasing stand age (Fig. 2). The simulated results showed that the biomass pool explained between 0.22 % and 53.00 % of the total C stocks relative to stand age. The contributions of the O horizon, dead wood (including aboveground dead wood and dead coarse roots) and mineral soil decreased with increasing stand age while those of the O horizon and dead wood became constant. The contributions of the simulated C stocks in the O horizon, dead wood, and mineral soil pools decreased from a maximum of 32.57 %, 24.06 %, and 53.42 % to 6.97 %, 12.23 %, and 27.80 %, respectively.

4 Discussion

4.1 Reliability of the model estimates

Forest C models can be used to estimate forest C stocks but such models often require a number of input data and

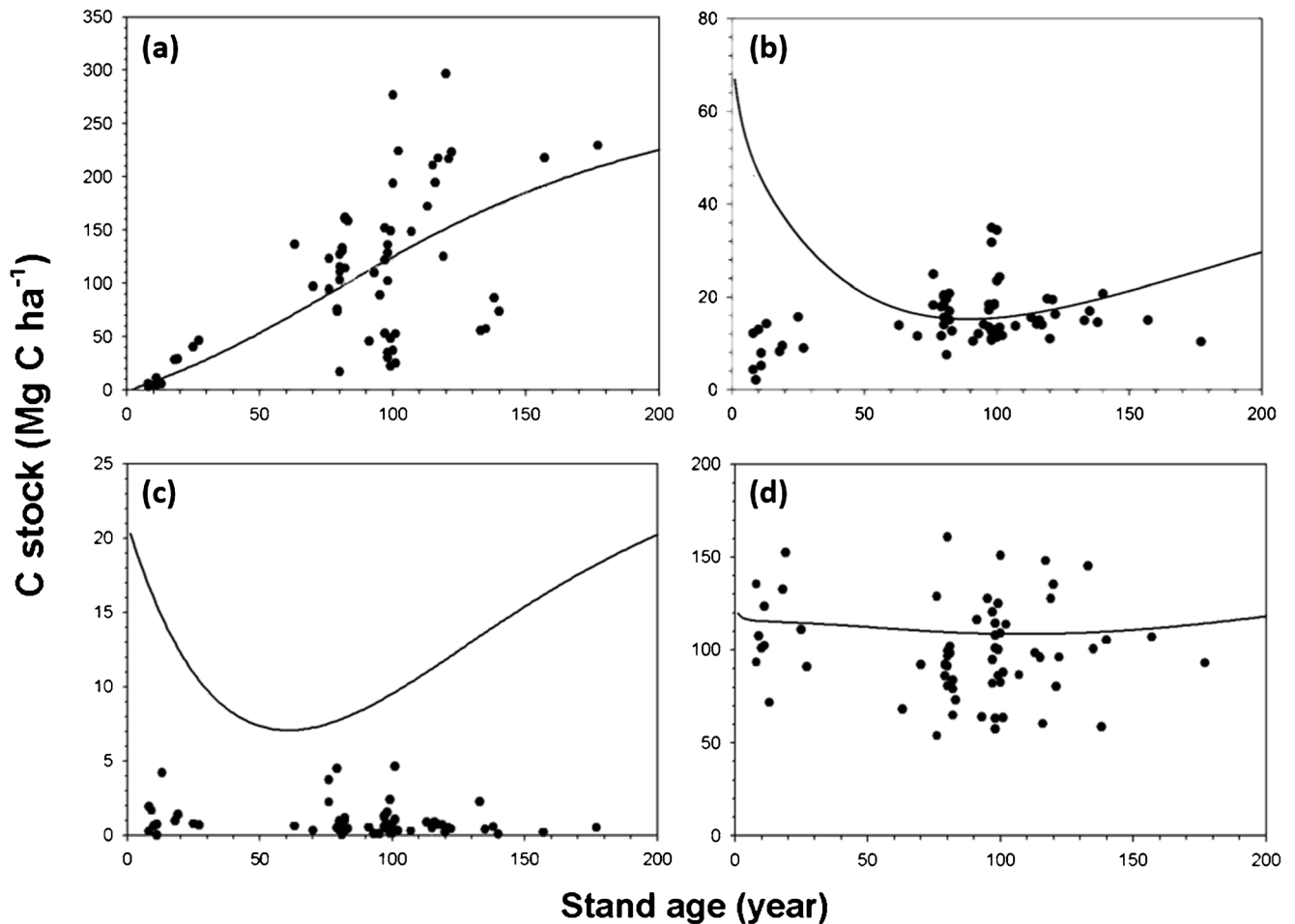


Fig. 1 Relationship between simulated (model simulation; *black solid line*) and observed (*black dots*) carbon (C) stocks with stand age in **a** biomass, **b** O horizon, **c** aboveground dead wood, and **d** mineral soil

parameters. For example, many forest C models (e.g., Yasso, Forest-DNDC, and RothC) require data on soil

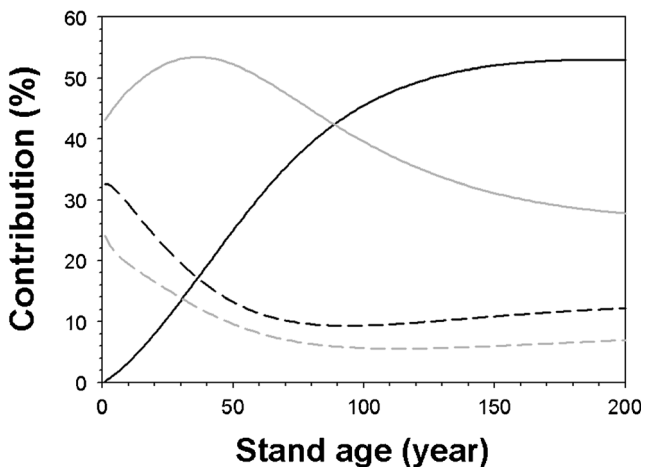


Fig. 2 Contributions of simulated carbon (C) stock in each pool to total forest C stock with increasing stand age. *Black solid and dashed lines* Contribution of biomass and dead wood (aboveground dead wood and dead coarse roots), respectively; *grey solid and dashed lines* contribution of the mineral soil and O horizon, respectively

properties and various climatic and vegetation conditions (Chertov et al. 2001; Coleman and Jenkinson 2008; Lee et al. 2010; Liski et al. 2005). However, our verification results showed that the model estimates agreed well with observations, especially for C stocks in the biomass (Table 4). An accurate estimation of C stocks in each tree compartment is crucial to estimate C stocks in the biomass and annual input to dead organic matter pools. In this study, the accurate estimation of C stocks in each tree compartment was attributed to the wide range of stand age in sample plots and the small variation in spatial scale. Allometric relationships between tree compartments vary with stand age (Jalkanen et al. 2005; Lehtonen et al. 2004) and climatic factors (Friedlingstein et al. 1999; Litton et al. 2007). The range of stand age in sample plots was wide enough to represent the growth pattern of each tree component during its life cycle. In addition, variation in allometric relationships by climatic factors might be constrained due to proximity of the geographical location of sample plots.

The simulated C stocks in the O horizon and mineral soil pools also seemed accurate because the simulated C stocks were not significantly biased. In addition, the simulated and observed C stocks in these pools were also similar on average. However, the relatively lower r^2 and high level of RMSE of the simulated C stocks in the O horizon and mineral soil indicated uncertainties. This phenomenon seemed to be attributed mainly to the parameter set (Peltoniemi et al. 2006). Most parameters used in this study were cited from studies conducted in other regions. These parameters thus did not perfectly represent the environment of the study site in this study. To improve model performance, using a local parameter set will be needed.

C stocks in the O horizon during the early development period and in aboveground dead wood, especially, were overestimated (Fig. 1; Table 4). During simulation, we assumed that only the stem was harvested and the other tree compartments were left. Branch became input to the O horizon pool due to limitations of model structure and assumption. This assumption could lead to overestimation of the simulated C stocks in O horizon during early period. The overestimation of aboveground dead wood was attributed mainly to Turkish forest management policies in Turkey, which attempt to suppress pest-borne disease or epidemics, as well as the use of harvest residue and dead wood for fire fuel by local villagers. Accordingly, consideration of forest management policies and practices can improve model accuracy (Kim et al. 2015c; Verkerk et al. 2011; Wang et al. 2013).

4.2 Comparison of the changes in simulated and observed C stocks with stand age

The changes in the simulated C stocks with increasing stand age were analyzed by model simulation. The relationship between simulated and observed C dynamics with stand age in dead organic matter differed greatly (Fig. 1). The differences between the simulated and observed C stocks in the O horizon and aboveground dead wood were especially substantial in the initial stages of stand development. These differences might be attributed to the initial C stocks in those pools (Peltoniemi et al. 2006). Initial C stocks in dead organic matter are affected by the history of land use and management (Jandl et al. 2007). For example, the initial C stocks in dead organic matter could decrease if the harvest interval was shortened (Park et al. 2013b). In this study, a 200-year harvest and no land-use change were assumed. Unfortunately, there were no available data with respect to management and land-use history for our study site. In addition, the C stocks in dead organic matter were measured at the same time in 63 plots that exhibited wide spatial heterogeneity (Fig. 1). This made it difficult to establish a clear pattern of changes in the observed forest C stocks

(Mohren et al. 2012; Rantakari et al. 2012; Yuan et al. 2013). Long-term monitoring and land-use data are required to enable a more accurate estimate of forest C dynamics with stand age.

Most previous studies have focused on the C stocks in Scots pine stands at certain stand ages (Helmissari et al. 2002; Lehtonen et al. 2004; Muukkonen 2007; Petersson and Ståhl 2006). Our integrative analysis, designed to understand changes in the contributions of C pools to the total forest C stocks with stand age, was thus worthwhile (Fig. 2). These changes in contributions could also be used as conversion factors for estimating C stocks in other pools based on the measurement of one pool. The contribution of biomass increased and that of dead organic matter decreased with increasing stand age. The rise in biomass C stocks overwhelmed that of dead organic matter as the stands matured. However, this relationship may be less accurate for Scots pine forests in other climatic zones. A different biomass growth rate or decay rate of dead organic matter could affect the ratio of each C pool to the total forest C stock (Khaine and Woo 2015; Vucetich et al. 2000; Zhu et al. 2010). Any difference in forest management could also affect those ratios (Kim et al. 2015b; Park et al. 2013b). Thus, the ratios should be adjusted to a regional scale in order to improve applicability and accuracy.

Forest C stocks generally increased with increasing stand age and decreasing frequency of harvest rotation (Jiang et al. 2002; Liski et al. 2001). In this study, the contribution of the biomass pool to the total C stocks becomes particularly dominant as stand age increases (Fig. 2). Harvests instantly reduce biomass C stocks and annual input of dead organic matters decrease with decreasing biomass C stocks. More frequent harvests suppress a level of biomass C stocks and increase in dead organic matter C stocks. Thus, forest C storage and sequestration could decrease under a harvest rotation that is shorter than 200 years.

5 Conclusions

We elucidated annual changes in C stocks of each pool using empirical data and model simulation. The C stocks in C pools and their contribution to total forest C stocks varied greatly with stand age. A forest C modeling method, simulating annual forest C dynamics with a small data set, was also developed. Our results will contribute to the understanding of the time series of C dynamics in Turkish forests.

Compliance with ethical standards

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