

Ecosystem carbon pools of coppice-originated oak forests at different development stages

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Received: 24 September 2014/Revised: 11 November 2014/Accepted: 18 November 2014/Published online: 25 November 2014
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Abstract The carbon (C) pools of aboveground tree components (leaf, stem, branch, and stem bark), ground cover, organic, and mineral soil were examined and compared with three stand development stages based on the mean tree diameters [diameter at breast height (dbh) in which small-diameter forests (SDF) = 0–8 cm, medium-diameter forests (MDF) = 8–20 cm, and large-diameter forests (LDF) = 20–36 cm] in pure coppice-originated oak stands located in the northwestern Turkey. In tree components, only the stem C concentration differed significantly among the development stages. The total C pools of the total tree biomass changed between 13 and 89 Mg ha⁻¹ from SDF to LDF. The C content of tree biomass was strongly correlated with dbh ($R^2 = 0.83$). The C contents of the ground cover differed significantly while the C contents in both organic soil layers were also markedly different and increased from SDF to LDF. The amount of C stored in the soil pedon was 84, 123, and 103 Mg ha⁻¹, and

the total ecosystem (without belowground tree parts) C pools were 97, 177, and 192 Mg ha⁻¹, for the SDF, MDF, and LDF, respectively. Total ecosystem C content was significantly correlated ($R^2 = 0.46$) with dbh despite soil pedon C showed very weak correlation. The ratio between the C pool of the total aboveground tree components and total ecosystem C was 13 % in the SDF, 30 % in the MDF, and 46 % in the LDF. These results show that the soil was the main pool of C in the forests for all of the development stages.

Keywords Biomass · dbh · Ground cover · Mineral soil · Tree components

Introduction

Forests represent the largest carbon (C) pools on Earth (Walle et al. 2001; Bruckman et al. 2011), and they play an important role in the global C cycle (Hoff et al. 2002). Considering that forest ecosystems have an irreplaceable

Communicated by Christian Ammer.

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role in regulating the C balance and maintaining the global climate (Jasal et al. 2010), there is a significant amount of interest in estimating the C sequestration in forests (Gibbs et al. 2007; Laumonier et al. 2010; Gratani et al. 2011). However, more ground-based observations of C pools and C pool changes in forest ecosystems are needed to improve our understanding of the global C cycle (Yuste et al. 2005).

The different compartments of forest ecosystems serve vital functions in the global C cycle since they are capable of sequestering C (Turrión et al. 2009). The greatest potential for the aboveground biomass and C storage in forest ecosystems is usually found within the tree biomass components (stems, branches, and leaves) while the biomass of the understory and ground vegetation may also make a considerable contribution. Apart from the aboveground vegetation, the organic soil and mineral soil have also large C pools. In addition, the upper soil horizons (epipedons) accumulate soil organic matter (SOM). Nearly 75 % of the C in ecosystems is found in the soil, and there is still a great potential for C sequestration by soils (Turrión et al. 2009). The allocation of biomass and C storage among tree C pools also changes as forests age (Balboa-Murias et al. 2006; Peichl and Arain 2006). Detailed inventories of C are available for many regions of the world, but not for major forest types in Turkey (Tolunay 2009).

The effects of forest management on C sequestration have been widely discussed (Seidl et al. 2007; Nabuurs et al. 2008; De Vries et al. 2009; Foley et al. 2009; Bruckman et al. 2011), but there is a lack of information related to the impact of C storage on species substitution in a large range of realistic situations of site productivity and silvicultural options (Vallet et al. 2009). Furthermore, the C balance of a forest is determined by the dynamics resulting from the present age class distribution, and therefore, by its past and present-day man-made and natural disturbances. Thus, previous management and disturbances determine the present-day class distribution if a forest is in a growing or a declining stage and that can impact the likely C balance for the next several decades (Nabuurs et al. 1997).

This study was conducted at different development stages which were identified according to the forest management plans of the Turkish General Directorate of Forestry on coppice-originated pure oak forests in the northern European part of Turkey in which oaks are spread over a wide area as the dominant tree species. These oak forests have been managed as coppice for decades to meet the demand of wood for fuel.

Coppice management has been applied for many years via clear cuttings in 20-year rotations. Coppice management was mostly abandoned in Turkey in 2006, and the plan of the Turkish General Directorate of Forestry was to convert old coppice forests to high forests. Although

almost of coppice management was abandoned at that time, some formerly forested areas under coppice management before this date had been partially separated for conversion to high forests.

The main objectives of the present study were twofold: (1) to characterize the variations of the carbon concentrations and pools in aboveground tree components (leaf, stem, branch, and stem bark), ground cover, organic, and mineral soil at different stand development stages in which SDF = 0–8 cm, medium-diameter forests (MDF) = 8–20 cm, and large-diameter forests (LDF) = 20–36 cm, (2) to determine the changes of mean stand diameter with carbon content at different tree component and ecosystem compartments in coppice-originated oak forests located in the northwestern Turkey.

Materials and methods

Research area and sampling design

We examined patterns in C accumulation in ecosystem pools across seven regions, spanning large gradients in climatic and site characteristics (Fig. 1; Table 1). The current climatic data were obtained from the Turkish State Meteorological Service, and the long-term estimated data were derived from the study by Irmak et al. (1980). According to these evaluations, the mean annual precipitation ranged from 550 mm in the Kırklareli region to 1,053 mm in the Demirkoy1 (D1) region, and the mean annual temperature ranged from 10.1 °C in D1 to 14.5 °C in the Catalca region. The highest annual water deficit was 274 mm in Kırklareli while the lowest was 84 mm in D1 which were determined by using calculations of Thornthwaite water balance system (Table 1) (Makineci et al. 2011).

Soil types vary within each of the seven regions, so we chose two dominant soil types (based on parent material) in each region. On each soil type in each region, we established two replicated sample plots (20 m × 20 m) in three different stands, thus, six sample plots in a small-diameter forests (SDF, 0–8 cm dbh), six in medium-diameter forests (MDF, 8–20 cm dbh), and six in large-diameter forests (LDF, 20–36 cm dbh) (Fig. 2). This set of 18 plots on each of two parent materials within each of the seven regions was selected. Then, eight of the sample plots from the SDF were eliminated because stems were shorter than breast height. Thus, the number of total sample plots was 244 (7 regions × 2 dominant parent materials × 3 development stages × 6 replications (2 replicated in three stands) = 252 – 8 eliminated SDF stands = 244) (Table 1). In addition, the characteristics of the sampled stands at the different

Fig. 1 Sampling regions on coppice-originated oak forests, 1 Demirkoy1 (D1), 2 Demirkoy2 (D2), 3 Demirkoy3 (D3), 4 Demirkoy4 (D4), 5 Kırklareli, 6 Vize, 7 Catalca

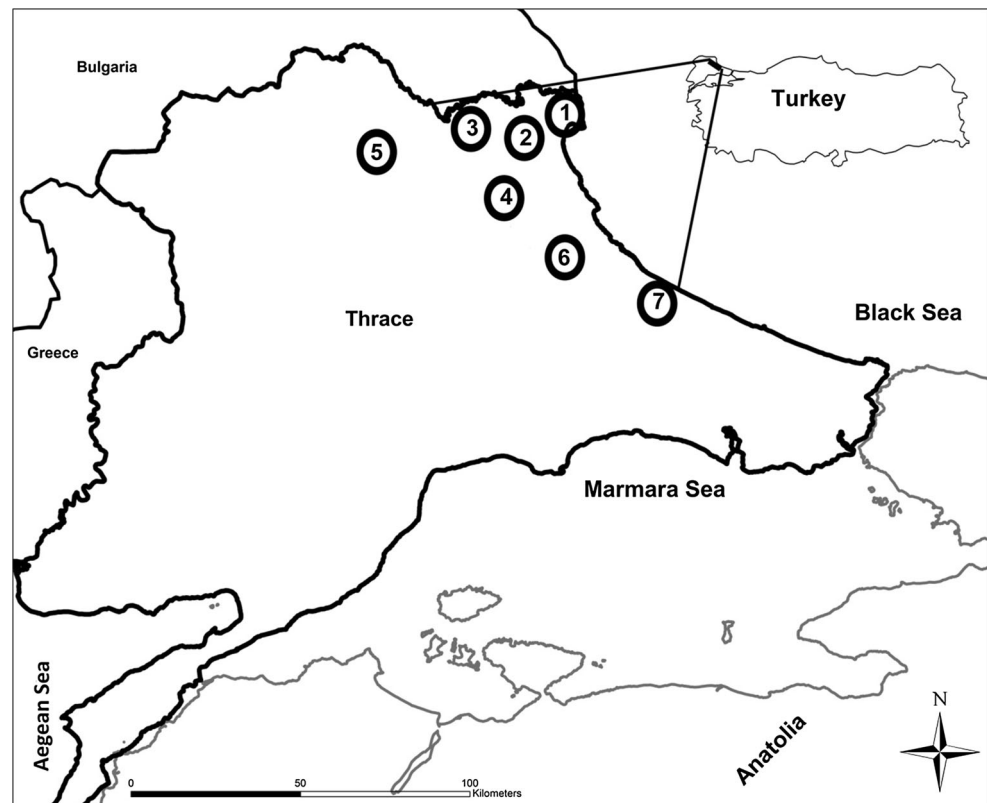


Table 1 Experimental layout and site characteristics of study area (Makineci et al. 2011)

Region	Altitude (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)	Mean annual water deficit (mm)	Parent Materials
Demirkoy1 (D1)	682	1,053	11	84	Schist-calcschist Metagranitoid
Demirkoy2 (D2)	381	837	12	158	Granitoid Metagranitoid
Demirkoy3 (D3)	125	867	13	181	Pebble-sandstone-mudstone Volcanic sedimentary- shelf
Demirkoy4 (D4)	391	838	12	158	Granitoid Schist-calcschist
Kırklareli	493	550	14	274	Marble Schist-calcschist
Vize	322	720	12	244	Limestone Augen gneiss-metagranitoid
Catalca	290	844	14	212	Quartzite-quartzschist Augen gneiss-metagranitoid

development stages are summarized in Table 2. The sites and possible stands were determined before the field studies using geological maps supplied by the Turkish General Directorate of Mineral Research and Exploration, forest management plans of the Turkish General Directorate of

Forestry and local foresters, and then, this information was checked and confirmed on field. In every site (stand), plots which represent different development stages were possibly chosen as closely as to each other within similar on general local site characteristics.

Fig. 2 Stand structure of coppice-originated oak forests at different development stages



SDF (dbh:0-8 cm)



MDF (dbh:8-20 cm)



LDF (dbh:20-36 cm)

Tree biomass samplings

The stands are characterized as pure oak stands, with varying dominance of three major species: Sessile oak (*Quercus petraea* (Mattuschka) Liebl.), Hungarian oak (*Quercus frainetto* Ten.), and Turkey oak (*Quercus cerris* L.). A complete inventory was taken of each stand to characterize the tree development stage distribution in the summers (mostly July and August) of 2008, 2009, and 2010. The species, height, and diameter at breast height (dbh) of all trees were recorded. Destructive biomass harvesting was carried out for the construction of equations for predicting tree biomass (Makineci et al. 2011). One tree with a mean diameter from each species in each sampled plot was then selected and felled. Given the consistent morphology among the oak species, we developed a composite representation of the C pools without separation by oak species. The age of the sampled trees was determined from a section taken at the base of the stem. The mean stand ages were determined as SDF = 14, MDF = 65, and LDF = 83

(Table 2). The total number of harvested trees was 657 (189 from SDF, 226 from MDF and 242 from LDF).

Each harvested tree was divided by their stems, branches, and leaf. The stems were separated into sections by length (0 + 0.3, 0.3 + 2, 2.3 + 2, 4.3 + 2 m, etc.), and the leaf and branches were then separated from the stem. All of these components were weighed fresh in the field immediately after they were sorted, and five-cm-wide discs were taken from the middle of each section as subsamples. Five or 10 discs were randomly removed from the collected branches from the different diameters, and some representative parts of the leaf were collected as subsamples and were also immediately weighed in the field (Alemdağ 1982; Çömez 2010; Durkaya 1998; Onyekwelu 2004, 2007; Saraçoğlu 1998). The representative composite subsamples of tree components were dried at 70 °C to arrive at a constant moisture level for dry weight determination. The bark was separated from the stem discs in the laboratory, and the bark biomass of the entire tree was calculated based on the bark/wood weight ratio obtained

Table 2 Mean stand characteristics at different development stages of coppice-originated oak

Characters	SDF (dbh = 0–8 cm)	MDF (dbh = 8–20 cm)	LDF (dbh = 20–36 cm)
Stand density (tree ha ⁻¹)	7,676a ± 979	1,161b ± 101	561c ± 32
dbh (diameter at breast height) (cm)	3.2a ± 0.4	15.1b ± 0.3	24.1c ± 0.5
Height (m)	3.8a ± 0.3	12.1b ± 0.4	16.1c ± 0.4
Age (year)	14.0a ± 1.5	65.0b ± 1.5	83.0c ± 4.0
Basal area (m ⁻² ha ⁻¹)	7.2a ± 1.1	19.9b ± 1.3	24.7c ± 1.2
<i>Biomass</i> (Mg ha ⁻¹)			
Tree			
Leaf	3.8a ± 0.6	5.6b ± 0.5	6.7b ± 0.6
Branch	4.6a ± 0.8	16.5b ± 1.4	33.1c ± 2.6
Bark	4.7a ± 0.8	15.7b ± 1.2	19.7c ± 1.3
Stem	14.1a ± 2.7	72.3b ± 6.1	121.7c ± 8.3
Total	27.1a ± 4.6	110.1b ± 8.2	181.2c ± 11.5
Ground cover			
Organic soil	1.0a ± 0.04	0.6b ± 0.02	0.9c ± 0.03
O _L + O _F	4.0a ± 0.07	5.7b ± 0.08	9.3c ± 0.15
O _H	0.5a ± 0.02	0.7b ± 0.02	1.3c ± 0.02
Total	4.5a ± 0.08	6.4b ± 0.08	10.6c ± 0.21
<i>Mineral soil bulk density</i> (<2 mm) (g/l)			
Soil depths (cm)			
0–5	720.1b ± 15.0	667.7a ± 14.9	676.5a ± 19.9
5–15	946.1a ± 28.3	897.7a ± 30.5	965.0a ± 29.5
15–30	976.2a ± 25.9	933.1a ± 29.8	972.3a ± 31.1
30–50	951.4a ± 28.5	894.1a ± 40.3	925.1a ± 32.9
50–70	885.9a ± 30.3	827.8a ± 42.5	849.7a ± 36.4
70–100	845.6a ± 32.5	809.4a ± 40.2	841.5a ± 38.6

Biomass is dry matter. SDF, MDF and LDF are development stages of coppice-originated oak forests. O_L + O_F: litter + fermentation, O_H: humus, ± is standard error. Means within rows following by the same letter are not statistically different at 0.05 significance level in Duncan post hoc test

Table 3 Carbon concentrations and contents of different tree components and ecosystem compartments

Carbon concentrations (%)			
Characters	SDF (dbh = 0–8 cm)	MDF (dbh = 8–20 cm)	LDF (dbh = 20–36 cm)
Tree			
Leaf	48.5a ± 0.003	48.1a ± 0.002	48.2a ± 0.002
Branch	48.1a ± 0.003	49.0a ± 0.002	48.9a ± 0.002
Bark	47.6a ± 0.002	47.7a ± 0.002	47.4a ± 0.003
Stem	48.2a ± 0.002	49.8b ± 0.002	49.3b ± 0.003
Ground cover	43.2a ± 0.157	43.2a ± 0.127	43.8b ± 0.114
Organic soil layers			
O _L + O _F	39.3b ± 0.191	39.2b ± 0.175	37.7a ± 0.179
O _H	30.4c ± 0.314	28.1a ± 0.325	29.0b ± 0.266
Mineral soil depths (cm)			
0–5	3.8a ± 0.293	5.1b ± 0.350	6.1b ± 0.483
5–15	1.8a ± 0.150	2.6a ± 0.266	2.3a ± 0.258
15–30	1.0a ± 0.083	1.6b ± 0.194	1.2ab ± 0.167
30–50	0.7a ± 0.050	1.2b ± 0.199	0.9ab ± 0.134
50–70	0.6a ± 0.041	1.2b ± 0.199	0.6a ± 0.065
70–100	0.6a ± 0.034	1.1b ± 0.183	0.6a ± 0.059
<i>Mean carbon contents (Mg ha⁻¹)</i>			
Tree			
Leaf	1.8a ± 0.3	2.7b ± 0.2	3.2b ± 0.2
Branch	2.2a ± 0.4	8.0b ± 0.7	16.1c ± 1.2
Bark	2.2a ± 0.4	7.5b ± 0.5	9.4c ± 0.6
Stem	6.8a ± 1.3	35.9b ± 3.0	60.3c ± 4.2
Total	13.1a ± 2.2	54.1b ± 3.9	88.9c ± 5.7
Ground cover	0.4c ± 0.02	0.3a ± 0.01	0.4b ± 0.01
Organic soil layers			
O _L + O _F	1.6a ± 0.03	2.2b ± 0.03	3.5c ± 0.05
O _H	0.2a ± 0.005	0.2b ± 0.005	0.4c ± 0.007
Total	1.7a ± 0.03	2.4b ± 0.03	3.9c ± 0.05
Mineral soil depth (cm)			
0–5	13.3a ± 0.9	17.1b ± 1.2	19.9b ± 1.4
5–15	16.1a ± 1.2	21.5a ± 1.7	21.2a ± 2.2
15–30	14.4a ± 1.1	21.2b ± 2.3	16.2ab ± 1.8
30–50	13.1a ± 0.8	21.3b ± 3.0	16.6ab ± 2.0
50–70	10.6a ± 0.6	17.6b ± 2.3	10.5a ± 0.9
70–100	14.3a ± 1.0	21.7b ± 2.8	14.3a ± 1.1
Soil pedon	83.5a ± 4.3	122.8b ± 11.4	102.6ab ± 6.6
Ecosystem total	97.1a ± 5.3	177.2b ± 13.0	191.9b ± 7.0

SDF, MDF and LDF are development stages of coppice-originated oak forests. OL + OF: litter + fermentation, OH: humus, ± is standard error. Soil pedon includes organic soil and mineral soil carbon mass. Means within rows following by the same letter are not statistically different at 0.05 significance level in Duncan post hoc test

from each section. The assessment of the biomass of the tree components at the sample plot level was performed by multiplying the dry values of the sampled trees by the tree number in the unit area, and these were then converted to Mg ha⁻¹.

Ground cover and organic soil

Five ground cover samples (1 m²) were randomly selected from each plot. The complete aboveground

ground cover layer was removed and weighed, and then some representative parts from the ground cover were separated as subsamples were also immediately weighed in the field. Organic soil samples were taken from an area of 0.25 m² with five replications in each sample plot at the same sampling points as the ground cover samples. The representative composite subsamples of all of ground cover and the organic soil were dried at 70 °C to arrive at a constant weight. The organic soil samples were

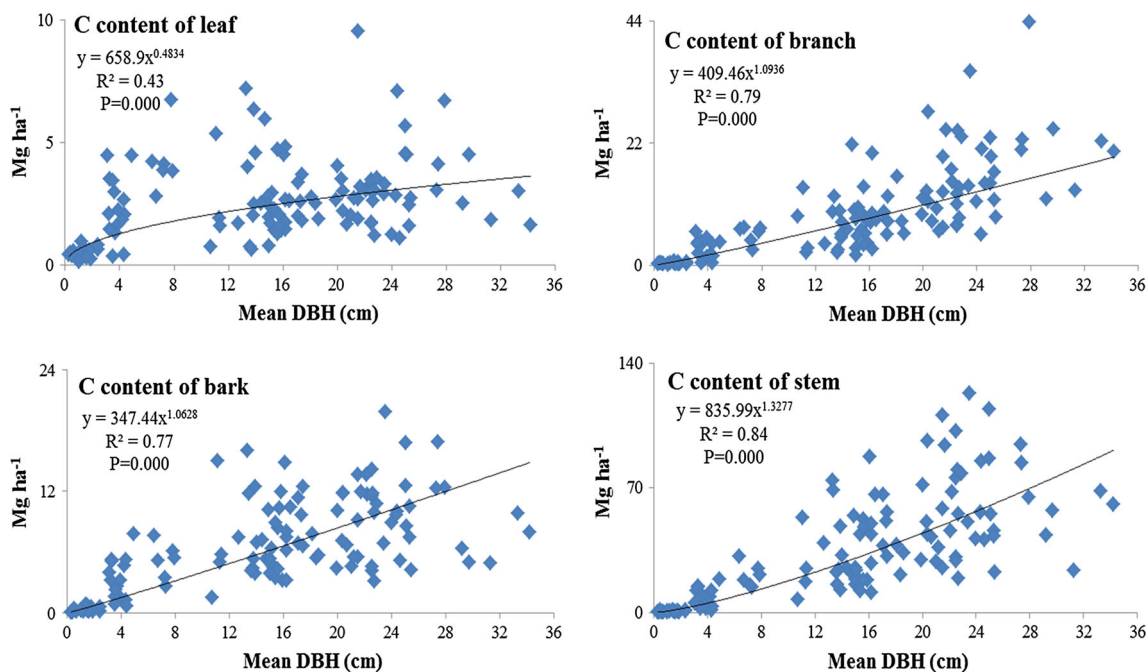


Fig. 3 Mean carbon contents of tree components, values are the mean of plots, $n = 122$

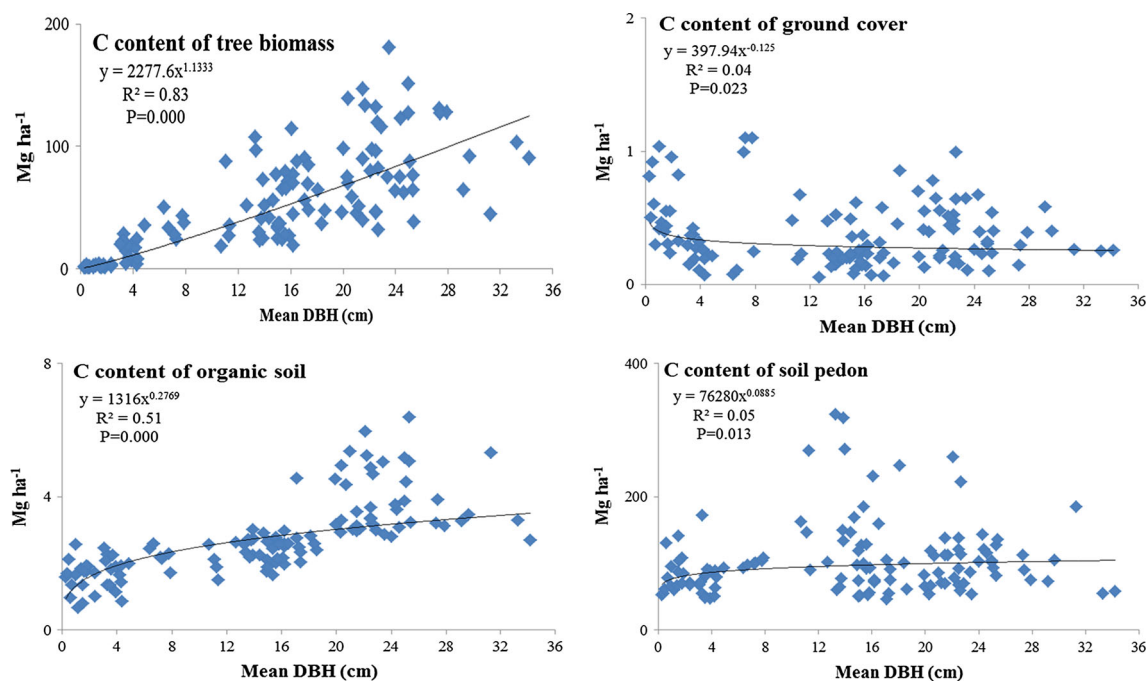


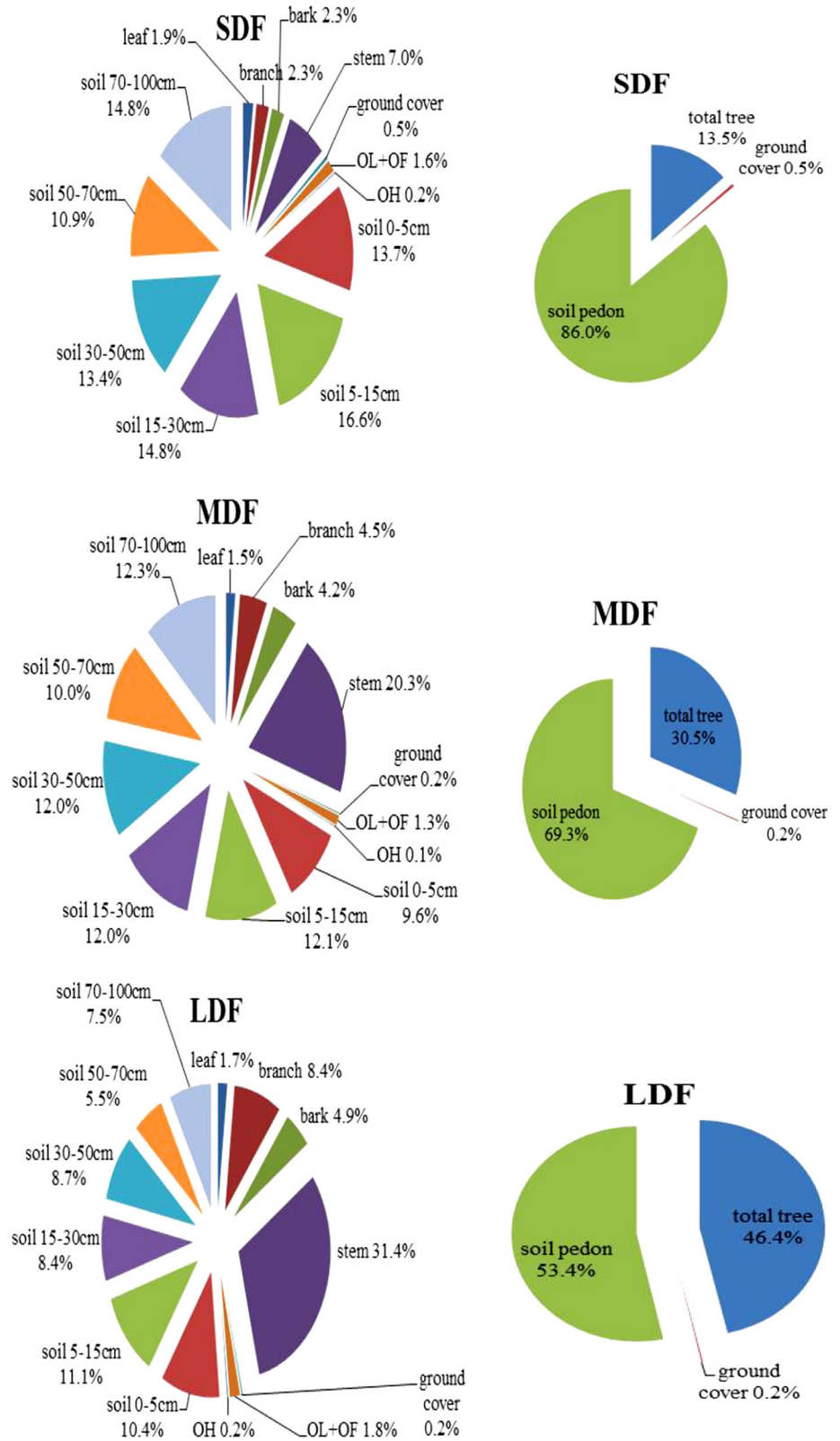
Fig. 4 Mean carbon contents of the ecosystem compartments, values are the mean of plots, $n = 122$. Soil pedon includes carbon content of organic and mineral soil (1 m)

passed through a one-mm sieve, and the remaining parts above and below the sieve were classified as the litter + fermentation (OL + OF) and humus (OH) layers, respectively.

Mineral soil

Soil pits were dug at random points in the sample plots with three replications. The total number of soil pits was

Fig. 5 Distribution rates of carbon contents in ecosystem compartments of coppice-originated oak forests at different development stages [SDF (dbh = 0–8 cm), MDF (dbh = 8–20 cm), LDF (dbh = 20–36 cm)]



122, which was half the total of the sample plots. To determine bulk density, samples were taken from different depths of up to one meter (0–5, 5–15, 15–30, 30–50,

50–70, and 70–100 cm) with 100 cm³ steel soil corers. In each soil pit, three soil samples were collected from each depth layer, and these later formed a composite sample. In

the laboratory, soil samples were air-dried, weighed, ground, and sieved over two-mm screen to remove stones and root materials. Subsamples were oven-dried at 105 °C to constant weight to calculate moisture. Mineral soil mass was calculated as oven-dried soil weight minus root and stone masses.

C analysis

The plant and organic soil subsamples were ground for C analysis. To calculate the C content of the samples, the ground subsamples were mixed together to obtain a composite sample. The C concentrations of the subsamples were measured using a LECO TruSpec 2000 Analyzer (LECO Corporation, St. Joseph, MI, USA) (Leco 2000), and the C contents from each of tree components and samples were calculated by multiplying the concentration by the dry weight calculated for the respective fraction.

The mineral soil subsamples were then ground and sieved (0.5 mm) again before C analysis. To determine the organic C concentration of the soil, the calcium carbonate (CaCO₃) concentration of all of the soil samples was determined using a Scheibler calcimeter, and the C concentration of this was subtracted from the total C concentration. All of the results were expressed on an oven-dried (105 °C) weight basis. The total organic C content (Mg ha⁻¹ of carbon) of each soil depth was calculated from the C concentration, bulk density, and layer thickness, and the total C content of the pedon was determined by summing the C contents of all of the soil depths (Makineci et al. 2011).

Statistics

The statistical evaluation of the data was done using the IBM SPSS STATISTIC 20 for Windows computer software package (SPSS 2010), and descriptive statistics were used to reveal the overall characteristics of the data. In

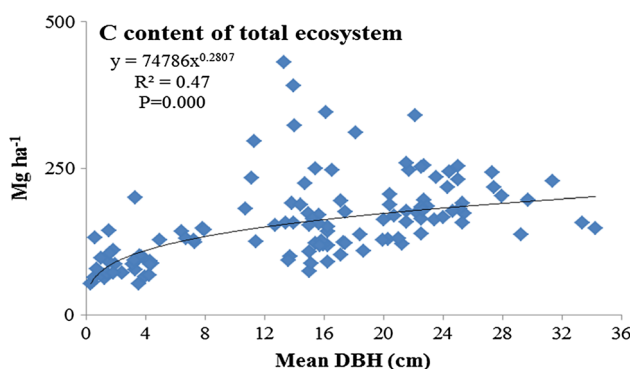


Fig. 6 Mean carbon content of total ecosystem (without below-ground parts of trees), values are the mean of plots, $n = 122$

addition, the means of all of the variables within the sample plots were calculated by averaging the values within each of the development stages, and analysis of variance (ANOVA) was used to evaluate the dependent variables according to the independent variables and factors in the development stages. Levene's test of equality showed that there was homogeneity of the variances at the 0.05 level. As a result, the Duncan post hoc test was performed to determine the homogeneous subgroups. The correlations were calculated to examine the relationship between C content at different tree components, ecosystem compartments, and mean plot dbh. The replications' averages in each site (total 122) were used in regressions models.

Results

C in tree components

The mean C concentrations in the tree components varied between 47.4 and 49.8 % and did not differ significantly with development stage. Patterns in the biomass of pools across stand diameter led to strong trends in C content. The C content of leaf increased by more than 50 % from SDF (1.8 Mg ha⁻¹) to MDF stands (2.7 Mg ha⁻¹), showing little C increase in LDF (3.2 Mg ha⁻¹) (Table 3). The leaf carbon content was significantly ($p = 0.000$) correlated ($R^2 = 0.43$) with mean dbh (Fig. 3).

The mean C concentrations of the branches did not vary significantly among the stages, but significant differences were seen on carbon contents of branches because the branch biomass changed markedly (Table 2), branch carbon content increased eightfold from SDF to LDF stage (Table 3) and strongly correlated ($R^2 = 0.79$) with dbh (Fig. 3).

The C concentrations of the bark were approximately 47 % and did not vary significantly among the different stages of growth. However, the large variety in the bark biomass yielded that bark C contents significantly increased from SDF to LDF (Table 3) and increases in strong correlation ($R^2 = 0.77$) with dbh (Fig. 3).

The stem C concentration of the SDF stands (48.2 %) was significantly lower than MDF (49.8 %) and LDF (49.3 %) stands. Furthermore, the stem biomass was also markedly different and was higher in the larger development stages, and it was about ten times higher in LDF than SDF (Table 3). The stem C contents were strongly correlated ($R^2 = 0.84$) with dbh (Fig. 3).

Carbon contents of total aboveground tree biomass significantly increased from SDF to LDF (Table 3), and a greater proportion of the variance in aboveground tree biomass C contents ($R^2 = 0.83$) was explained by dbh (Fig. 4). Total aboveground tree biomass increased from

13.1 Mg ha⁻¹ in the SDF stage to 54.1 Mg ha⁻¹ in MDF stage, to 89.0 Mg ha⁻¹ in LDF stage. Stems accounted for 52, 66, and 68 % of total aboveground tree C across the tree stages. These results demonstrated that the ratio of accumulated C in the stem/C ratio in the total aboveground tree biomass differed significantly by as much as 16 % between SDF and LDF (Table 3).

C in ground cover

LDF had significantly the highest C concentration (43.8 %) in the ground cover. The content of ground cover C ranged from 0.3 (MDF) to 0.4 Mg ha⁻¹ (SDF) depending on the highest ground cover mass in the SDF (1.0 Mg ha⁻¹) and the lowest in MDF stands (0.6 Mg ha⁻¹) (Tables 2, 3). Ground cover C contents were significantly ($p = 0.023$), however, not strongly ($R^2 = 0.04$) correlated with dbh (Fig. 4).

Organic and mineral soil C

The mass of both organic soil (OL + OF and OH) layers significantly rose as the stand development stage increased (Table 2). The C concentration of the OL + OF layer ranged from 37.7 to 39.3 %, and the LDF had the lowest. The C concentration of the OH layer was the highest in the SDF (30.4 %) stands (Table 3).

The C contents of both layers and the total organic soil increased from SDF to LDF (Table 3). The total organic soil was significantly correlated with dbh ($R^2 = 0.51$) (Fig. 4).

The mean mineral soil C concentrations decreased as the soil depth increased and varied from 0.6 to 6.1 %. In addition, the C concentrations of all of the soil depths in the SDF were significantly the lowest (Table 3).

The soil bulk densities of depths lower than five cm did not show any significant differences (Table 2). Approximately 50 % of the total soil C in the soil was located in the first 30 cm of the soil in all of the stages (Table 3). The soil C contents in the pedon (including organic soil C + total C in mineral soil at a depth of 100 cm) varied significantly at 83.6, 122.8, and 102.6 Mg ha⁻¹ for the SDF, MDF, and LDF, respectively. C contents of the soil pedon showed significant but weak correlation with dbh ($R^2 = 0.05$) (Fig. 4).

Ecosystem C pools (without belowground tree parts)

The C content in the aboveground tree biomass, soil pedon, and total ecosystem C increased with dbh from SDF to LDF (Table 3; Fig. 5).

In the tree components, the portion of the stem C within the total tree C increased despite the leaf and bark C

portions decreased from SDF to LDF. Branch C accounted for 14, 16, and 18 % of total aboveground tree C in MDF, SDF, and LDF, respectively. The ratio of the total tree C mass to the total ecosystem C content was between 13.5 and 46.4 % with an increasing trend from SDF. Ground cover generally only played a small role in the total ecosystem C, with rates of 0.5 % in the SDF stands and 0.2 % for the MDF and LDF stands (Fig. 5).

Despite the fact that the OH layer of the organic soil had a small percentage (0.1–0.2 %) on the total ecosystem C, the total organic soil was valuable, constituting 1.8, 1.4, and 2.0 % of the total ecosystem C in the SDF, MDF, and LDF, respectively. The total soil C was the primary C compartment of the ecosystem, even though its ratio decreased with increasing stand dbh. The ratio of the total soil C to the total ecosystem C pool was approximately 86 % in the SDF stands while it was 69 % in the MDF stands and 53 % in the LDF stands (Fig. 5).

The total ecosystem C pools were determined as 97.1, 177.2, and 192.0 Mg ha⁻¹, for the SDF, MDF, and LDF, respectively (Table 3). Carbon content of the total ecosystem showed significant correlation with dbh ($R^2 = 0.47$) (Fig. 6). Results can be interpreted with a simple estimation based on the carbon content change between the youngest and the oldest stage, the net annual change in C storage over 69 years from SDF to LDF, was about 1.4 Mg ha⁻¹ year⁻¹ in total ecosystem (without belowground parts of trees) and 1.1 Mg ha⁻¹ year⁻¹ in tree biomass.

Discussion

Temperate broadleaf forests of the Northern Hemisphere have been identified as an important sink for storing carbon (Powell et al. 2006). However, forest management, which implies changes in stand structure and ecosystem components, can subject to substantial modifications. In present study as discussed below, coppice forest management with former clear cut rotations could have possibly been the cause of intrinsic variability on the C concentrations and pools of these forest ecosystems and might have caused alterations in the vegetation cover, litterfall, quality and quantity of forest floor, SOM, and biological characteristics of the forest floor and soil.

C in tree components

The similar or relatively similar C concentration in tree components has also been observed in other studies, ranging from 47.9 to 48.7 % in the stem and branches of the *Quercus mongolica* Fisch. (Zhang et al. 2009), 43–51.9 % (Löwe et al. 2000), and 45–51.9 % in different

tree components in European forests (Nabuurs et al. 1997). Furthermore, Vallet et al. (2006) reported C percentages of 52.9 % for coniferous and 50.8 % for broadleaf species, and Lamblom and Savidge (2003) stated that the C concentration in the wood of 41 different tree species varied between 46.27 and 55.20 %.

We found significant differences in the C concentration of the stems in the three development stages, however, no significant variations in the ratio of C in the leaf, branches, or bark. Similar to our results, Bert and Danjon (2006) observed that the C concentration of needles was not related to forest age.

The C contents of the aboveground tree biomass of the SDF and MDF stands in our study were not within the ranges of previous cohorts. For example, Balboa-Murias et al. (2006) found that the average C accumulation in the aboveground tree biomass of the *Quercus robur* in Spain was 118 Mg ha⁻¹ (range 62–194 Mg ha⁻¹), and the C amounts in the biomass of their study were consistent with those reported by Walle et al. (2001) for oak/beechn stands in Belgium.

Coppice management can have an effect on the biomass and C contents for ecosystems in a study area. For instance, Bruckman et al. (2011) found that the living biomass was strongly influenced by forest management, which led to clear differences between the oak-dominated high forest (HF) and oak/hornbeam coppice, which featured a coppice with standards (CS). Moreover, they found that the average biomass of the C pool (standing woody plants + roots) was higher in the CS.

In general, an increase in the age of the stand as well as the forest development stage leads to higher amounts of C at the stand level, as we determined that above ground C content significantly ($R^2 = 0.83$) increased with increasing stand dbh. Peichl and Arain (2006) reported total aboveground tree C (stem, foliage, live, and dead branches) levels of 0.2, 30.1, 44.2, and 82.6 trees ha⁻¹ in 2-, 15-, 30-, and 65-year-old stands, respectively.

C in ground cover

The C concentration of ground cover was approximately 43 % in our study. Similarly, Makineci (2004) found that the C concentration of ground cover was 40 % under the *Q. petraea* while Akburak (2013) noted that it was 44 % under the *Q. frainetto*. Moreover, Falkengren-Grerup et al. (2006) identified rates of between 41.5 and 44.2 % under a *Q. robur* forest, and Peichl and Arain (2006) reported higher ground cover C concentrations of between 46 and 53 %.

There are different results on the literature with regard to C content of ground cover. Makineci (2004) stated that the C mass of ground cover varied between 0.3 and

0.6 Mg ha⁻¹ under different densities of sessile oak, and Makineci (1999) determined as 1.07–1.53 Mg ha⁻¹ while the amount was found as 0.4 Mg ha⁻¹ by Akburak (2013) under *Q. frainetto* coppices.

We determined that the C mass of the ground cover was significantly altered in the stand stages, and this was dependent on the changes in mass; however, C content of ground cover showed very weak correlation ($R^2 = 0.04$) with stand dbh. In addition, many researchers have found that the variations in species composition of ground cover in oak forests are related to coppice and forest management (Small and McCarthy 2005; Strandberg et al. 2005; Aikens et al. 2007; Tárrega et al. 2007). Furthermore, Peichl and Arain (2006) found that the higher levels of ground vegetation biomass and C storage in the youngest stand in their study resulted from the large amount of forbs and grasses. These results demonstrate that lower canopy closures at early stages lead to more ground cover.

Organic soil C

Similar to the present study, André and Ponette (2003) determined that the C concentration of the organic soil was 380 mg kg⁻¹ in a *Q. petraea* forest. However, some researchers found higher concentrations of close to 43 % associated with the *Q. petraea* (Çakır 2013) and roughly 44 % in a *Q. frainetto* organic soil (Akburak 2013) in Turkey.

We found that older forest stages have lower C concentrations in the organic soil. But Peichl and Arain (2006) reported that the C concentrations of the organic soil (LFH layer) ranged from 26 % in a two-year-old stand to approximately 36 % in older stands; however, they concluded that organic soil C did not clearly correspond to the age of the stand. Furthermore, Pregitzer and Euskirchen (2004) found that organic soil C increases with stand age in temperate forests, and it has been reported to be highly susceptible to disturbances and variations in stand treatment, litter input, and decomposition rates (Yanai et al. 2000; Pregitzer and Euskirchen 2004; Peichl and Arain 2006).

The total organic soil C content differed significantly among the development stages. Also, C content of organic soil showed significant correlation ($R^2 = 0.51$) with stand dbh. Akburak (2013) identified 2.6 Mg ha⁻¹ of carbon in a *Q. frainetto* organic soil, which is similar to our findings, but Çakır (2013) found a higher amount (4.7 Mg ha⁻¹) in a *Q. petraea* organic soil. Furthermore, Tolunay and Çömez (2008) reviewed the C contents of organic soil in Turkey and reported that the C content varied between 0.3 and 42 Mg ha⁻¹. Hence, the data suggest that the C content of the organic soil is more variable and changes depending on the tree species and decomposition rate.

Mineral soil C

Within temperate forest ecosystems, soils are typically the dominant pools of organic C (Liski et al. 2002), and the quantity and quality of SOM is again considerably influenced by forest management (Chen and Xu 2005) and environmental conditions. Similar to our results, in the study by Verma et al. (2012) involving an oak forest, the soil organic carbon (SOC) varied between 0.9 and 4.2 %. Benham et al. (2012) also determined that the SOC concentrations decrease significantly with increased horizons and depth under a *Q. robur* forest.

There are many different results related to SOC in oak forests. Regina (2000) found 4.4–105.0 mg g⁻¹ of SOC in a *Quercus pyrenaica* forest in Spain, and André and Poinette (2003) identified 19–58 mg kg⁻¹ of SOC in a *Q. petraea* forest in Belgium. In addition, Son et al. (2004) determined SOC concentrations of between 0.69 and 2.76 % under *Q. mongolica* and *Q. variabilis* forests in South Korea, and Turrión et al. (2009) found 0.2–71.0 g kg⁻¹ of SOC in a *Q. pyrenaica* forest in Spain.

Similar to SOC concentrations, soil organic C contents vary in literature. Balboa-Murias et al. (2006) declared values close to our results, with the average C storage in the mineral soil amounting to 131 Mg ha⁻¹ (range 73–144 Mg ha⁻¹) in *Q. robur* stands. We found no clear tendency between the stand development stage and total soil C content in the pedon. Besides, C content of mineral soil showed very weak correlation ($R^2 = 0.05$) with stand dbh. But contrary to our results, the soil C of oak forests increased depending on the age of the stand in the study by Benham et al. (2012). Small and McCarthy (2005) also reported significant changes in soil C that were dependent on the age of an oak forest stand in Ohio-USA. On the other hand, Matos et al. (2010) reported that SOC stocks decreased as oaks got older, which was probably the result of the faster decomposition rates of the organic layer. Furthermore, Peichl and Arain (2006) observed no age-related patterns across the stands in their study, whereas other studies have reported an increase in soil C in early stand stages (Hooker and Compton 2003; Pregitzer and Euskirchen 2004; Peichl et al. 2006). Many other studies have also suggested that there is no significant increase in mineral soil C with increased stand age (Richter et al. 1999; Schlesinger and Lichter 2001; Paul et al. 2002; Peltoniemi et al. 2004). These contradictory reports in the literature may be due to numerous factors that can influence soil C, such as climate, soil properties, and forest floor and forest type, all of which may overshadow the effect of stand age on soil C accumulation (Paul et al. 2002; Pregitzer and Euskirchen 2004; Sun et al. 2004).

In this study, approximately 50 % of the total soil C in the mineral soil was found in the first 30 cm of the soil in

all of the stages because of the higher C concentrations in the upper soil layers. Similarly, Jobbagy and Jackson (2000) reported the percentage of C content of total mineral soil in the top 20 cm was 50 %.

Ecosystem C pools

Carbon content of total ecosystem without belowground tree parts showed significant correlation ($R^2 = 0.47$) with stand dbh and development stage. Total carbon stock in coppice oak ecosystem changed about 1.4 Mg ha⁻¹ year⁻¹ in total and 1.1 Mg ha⁻¹ year⁻¹ in tree biomass depending on the development stages (over 69 years from SDL to LDF). In the present study, mineral soil was the primary C pool in all of the development stages. In addition, the total C in the soil pedon rose with increased stand diameter, but there was no clear tendency, with the middle stage (MDF) having highest and the youngest stage (SDF) having the lowest amounts of mineral soil C. Banfield et al. (2002), Gallardo and González (2004) and Dupouey et al. (1999) found similar results. The soil C stock may comprise as much as 85 % of the terrestrial C stock in boreal forests and 60 % in temperate forests (Lal 2005). These results indicate that C partitioning in forest ecosystems can differ dramatically.

Very different C mass and C partitioning also exists in the total ecosystem compartments. In a *Q. robur* forest in Spain, Balboa-Murias et al. (2006) found that the average C stock of the total tree biomass at the stand level amounted to 150 Mg ha⁻¹ (range 82–243 Mg ha⁻¹), which accounted for 50 % of the C accumulated in the whole system (tree biomass, litter layer and total mineral soil). On the other hand, Vallet et al. (2009) estimated that the portion of soil C was about 50 % of total C stock in a sessile oak stand. Walle et al. (2001) noted in the oak-beech stand, 41.5 % of the total C was found in the SOM, 11 % in the litter layer, and 47.5 % in the vegetation.

Similar to our results, Peichl and Arain (2006) also declared that the aboveground and total ecosystem biomass and C pools increased with stand age and that the mineral soil was the dominant C pool in the two youngest stands in their study; however, the aboveground tree biomass became the major C pool in two older stands. They compared their results with Martin et al. (2005) and determined that the total ecosystem C was 50 and 28 % higher in the 18- and 30-year-old stands, respectively. In contrast, Verma et al. (2012) found that a comparatively younger stand of *Quercus semecarpifolia* had marginally higher C sequestration rates, and Genet et al. (2009) indicated that the C balance between growth and storage remained constant between age classes in sessile oaks.

Stand age and site characteristics seem to play an important role in the distribution of C over the different

compartments (Walle et al. 2001). When forests become more mature, a number of structural and physiological changes occur. In temperate regions, aboveground tree biomass may serve as the major control on total ecosystem C development. However, in order to verify ecosystem C pool dependence on stand age, further data are needed from replicated chronosequence studies (Peichl and Arain 2006).

Compared with high forests, the increased amounts of energy and rapid growth of new sprouts in coppices can cause a rise in the aboveground tree and stem biomasses, especially in the early development stages. Bruckman et al. (2011) investigated C pools in two *Q. petraea* dominated chronosequences under different forest management techniques (HF-high forest and CS-coppice with standards) and found that the total C and SOC pools (belowground C pools excluding the roots and organic residues) were lower in the HF stand and that the ratio of aboveground to belowground pools steadily increased with age as indicated by the aboveground biomass accumulation. Contrary to our results, they also found that the SOC pools seemed to be very stable and that silvicultural interventions had no impact.

Conclusions

In conclusion, the ecosystem C pools increased along with the development stages of coppice-originated oak forests. Furthermore, in each development stages, the mineral soil C was the main C component of the ecosystem, even though its ratio in the total ecosystem C decreased in conjunction with the stages. Approximately 50 % of the total soil C in the mineral soil was in first 30 cm of soil depth in all of the stages. In addition, the forest ground vegetation and organic soil contributed only a little to the total ecosystem C pool. However, the contribution of the organic soil C pools may become more significant as the stand matures; thus, it should not be excluded from the total C pool.

Coppicing might have the advantage of a fully functional root system, which facilitates rapid resprouting, but the rotations and intensive harvesting in the research area will likely lead to degradation. Further studies are needed to improve and complement our results, especially those that would involve belowground compartments (root systems and soil C dynamics) since they would provide accuracy regarding the accounting of C pools. Finally, the total ecosystem C and biomass change depended on tree age-development stage, and this can be interpreted using age-sensitive biomass estimations to acquire reliable estimates of C accounts in forest ecosystems.

Acknowledgments We thank to Prof. Dr. Dan Binkley from Department of Ecosystem Science and Sustainability and Natural Resource Ecology Laboratory, Colorado State University, USA, for his valuable suggestions on the manuscript. The authors are grateful to Istanbul Regional Forestry Directorate for their corroboration in the field. This work was supported by The Scientific and Technological Research Council of Turkey (TUBITAK), Project Number: TOVAG-107O750.

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