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RESEARCH

Changes in carbon stocks according to stand development stages in oriental beech forests in the Marmara Region of Türkiye

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Abstract This study was conducted to determine the changes in carbon stocks of oriental beech (*Fagus orientalis*) according to stand development stage in the Marmara Region of Türkiye. For this purpose, sample plots were taken from a total of 32 areas encompassing four stand development stages (young, middle age, mature and overmature stand). The diameter at breast height and height of all trees in the sample plots were measured, and only three dominant trees's ages per plot were determined. Aboveground carbon stock was calculated using equations developed for beech forests, while the coefficients in the Agriculture, Forestry and Other Land Use guide were used to determine belowground carbon stocks. A soil pit was dug in each plot and soil samples were taken at different depths (0–10, 10–30, 30–60, 60–100 cm). In addition, litters were sampled from four different 25 × 25 cm sections in each plot, and then the physical and chemical properties of the soil and litters were analysed. The variations in carbon stocks in above- and below-ground tree mass, litter and soil, and in ecosystem carbon stocks according to development stage were examined by analysis of variance and Duncan test, and the relationships between the carbon stocks were investigated by correlation analysis. Aboveground (AG) and belowground (BG) tree, soil and ecosystem carbon stocks showed significant differences between the four stand development stages ($P < 0.05$), but not the litter carbon stocks ($P > 0.05$). AG and BG tree and ecosystem carbon stocks increased with progressive stand development stages, while the soil carbon stock was the highest at the young stage. These findings will contribute to the preparation of forest management plans and the national greenhouse gas inventory.

Keywords *Fagus orientalis* · Ecosystem carbon stock · Soil · Forest floor

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Introduction

International agreements to mitigate the effects of global climate change have obliged countries to report their carbon emissions and carbon pools. To ensure that inventory data is comparable between countries, an Agriculture, Forestry and Other-Land Use guide (AFOLU) for calculating these parameters has been developed (IPCC, 2006, 2013). This guide explains in detail how to calculate the annual change in carbon stocks in forest ecosystems. The guide divides forest ecosystem carbon pools into three classes: living belowground and aboveground biomass, dead organic matter (dead wood and litter), and organic carbon in soil. In addition, the guide includes some empirical coefficients in terms of climate zone, forest type and tree species to be used in the calculations of the pools in question, but suggests that these coefficients should be revealed through research on tree species at the local level for more accurate calculations (IPCC, 2003, 2006). Research has shown that the rate of carbon accumulation in carbon pools varies depending on environmental factors, tree species and tree organs (Bert & Danjon, 2006; Çömez, 2012; Laiho & Laine, 1997; Lamlom & Savidge, 2003; Thomas & Malczewski, 2007).

Türkiye's forest area is 22.9 million hectares; of this, the oriental beech (*Fagus orientalis* Lipsky) constitutes 8.2% of the country's forests, with a spread of 1.9 million hectares, and ranks second after oak genus (*Quercus* spp.) in terms of distributional area among broad-leaf species (GDF, 2021). Therefore, oriental beech is one of the priority species that needs to be researched (Güner, 2021). Native to Türkiye, the oriental beech spreads to Bulgaria, Romania, Greece, Crimea, the Caucasus and Northern Iran. It is widely distributed in Türkiye in the middle- and high elevations of the mountains running parallel to the Black Sea coast, and tends to establish along north-facing aspects, especially in pure and mixed forests. It is also seen occasionally in the Marmara, Central Anatolia and Eastern Mediterranean Regions. Oriental beech is distributed in regions with some temperate climate rich in moisture and with balanced precipitation (Anşin & Özkan, 1997; Atalay, 1992).

The aboveground biomass of oriental beech forests in the Eastern Black Sea Region of Türkiye was previously determined by Saraçoğlu (1998), while Güner et al. (2010) revealed both aboveground and belowground biomass in young oriental beech forests in the Eastern Black Sea Region (Artvin). Some researchers also studied the amount of belowground biomass in oriental beech forests in the Black Sea Region (Tüfekcioglu et al., 2005; Mısır & Mısır, 2013; Özbayram & Güvendi, 2016). Furthermore, the studies were carried out to investigate carbon stocks of Turkish forest soils (Tüfekcioglu et al., 2005), litters (Sargıncı et al., 2021) and ecosystems (Erkut, 2013). Additionally, aboveground carbon stocks in oriental beech forests in the Central Black Sea Region (Sinop) were determined by Kahyaoğlu (2017) and Kahyaoğlu et al. (2019). In general, these studies focused on the Black Sea Region and determined only one of the carbon pools in the ecosystem (such as aboveground tree mass, root mass, soil or litter). However, our study differs from previous studies because it covers all carbon pools in the oriental beech forest ecosystems, takes into account development stages and was conducted in the Marmara Region.

In this study, we aimed to investigate the carbon stocks and the relationships between these carbon pool stocks according to their development stages in oriental beech forests in the Marmara Region of Türkiye. The study hypothesised that there would be variations in the carbon pools among the stages of stand development and that there was a relationship between the carbon pools. The results of the study can be used in forest management plan development and greenhouse gas inventory reporting.

Materials and methods

Study area

The research was carried out in pure oriental beech forests in the Marmara Region of Türkiye (Fig. 1). The research areas were located on granite, granodiorite and quartz diorite bedrock (GDMRE, 2021). The soil type commonly found in the research areas was Luvisol (IUSS Working Group WRB, 2015). In addition, the beech forests in the research area were spread on different soil texture classes, without carbonate and salt.

The annual mean temperature in the sample plots ranged from 6.8 to 10.2 °C, with high temperatures from 26.5 to 29.9 °C, and low temperatures from -9.2 to -5.8 °C. Mean temperature of the coldest month was -3.4 °C, while mean temperature of the hottest month was 20.1 °C. Furthermore, mean annual rainfall varied between 903 and 1276 mm, with rainfall range of 24–34 mm in the driest month, 241–340 mm in the spring months (March + April + May), and 161–227 mm in the summer months (June + July + August) (GDM, 2020). According to the Erinç method, the climate types of the research areas were semi-humid and humid (Özyuvacı, 1999).

The dominant tree species in the research area was *Fagus orientalis*, and the *Trachystemo*

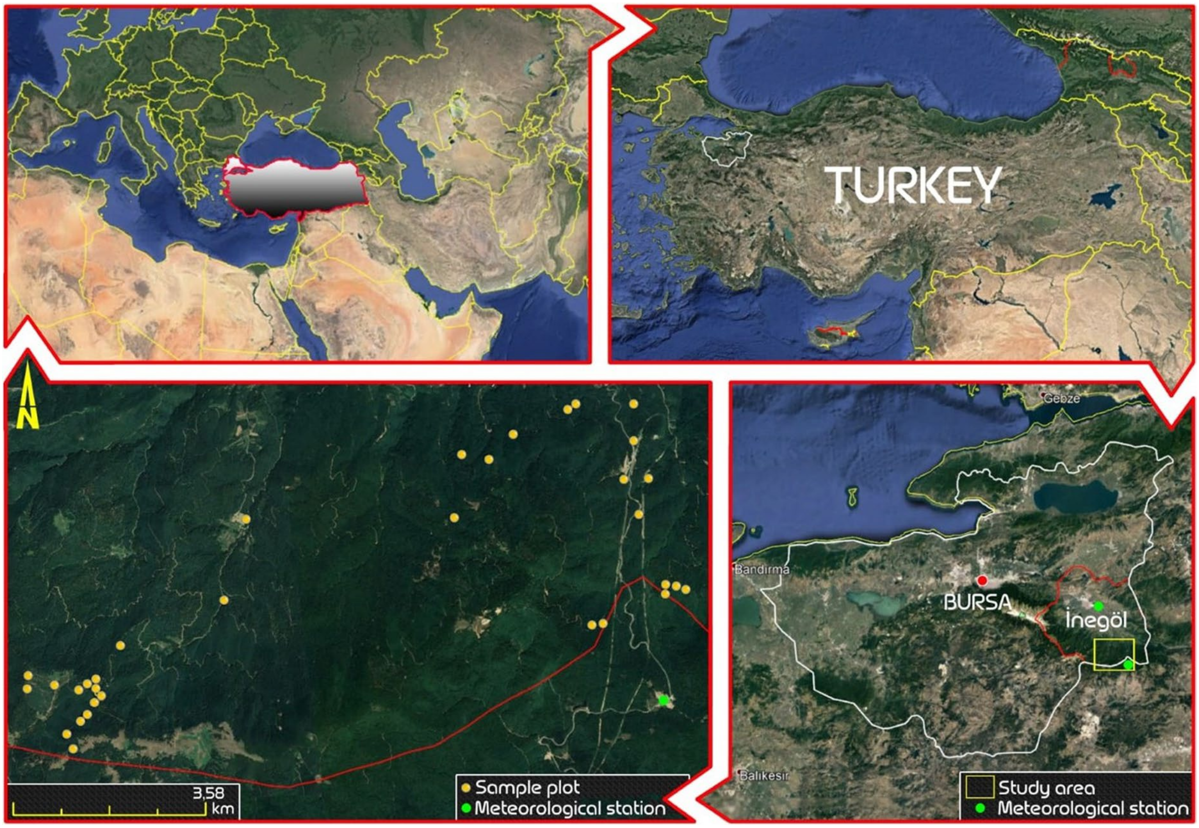

Fig. 1 Location of the study area

orientalis–Fagetum orientalis plantassociation was widespread at 600–1100 m. Its distinctive species included *Trachystemon orientalis* (G.Don), *Cardamine bulbifera* (L.) Crantz and *Campanula rotundifolia var. olympica* (Boiss). While 54.5% of the plant taxa included in its floristic composition belong to the Euro-Siberian region, 1.8% belong to the Mediterranean flora. Plant taxa with multiple or unknown regions constitute 43.7% of the total flora in the area (Akman et al., 1979; Türe et al., 2005).

Experimental design and sampling procedure

The research was conducted in a total of 32 sample plots, within 8 areas for each of 4 development stages: young (diameter at breast height, dbh = 0–7.9 cm), middle age (dbh = 8–19.9 cm), mature (dbh = 20–35.9 cm) and overmature stands (dbh ≥ 36 cm). Sampling plots were generally selected among 3 dense-cover (canopy cover = 70–100%; one mature and two overmature sampling plots) and among 2 moderate-cover (canopy cover = 40–70%) plots to ensure that different growing environments were represented. The sample plots were square or rectangular in shape and large enough to include at least 15 trees (Çepel et al., 1977). The slope, elevation, aspect and slope position characteristics of the sample plots were recorded, the diameter at breast height and total height of all trees were measured, and the age of three dominant trees was measured with increment borer in per sample area (Table 1). Then, a soil pit was dug in each of the sample plots, and soil samples were taken using a steel cylinder with a volume of 1000 cm^3 at the following depth levels: 0–10, 10–30, 30–60 and 60–100 cm. Litter were sampled from 4 different points representing the sample plots and in areas of 0.0625 m^2 (25 × 25 cm) in size (32 sample plots × 4 replications = 128 litter samples). All litter was collected in these areas, placed in bags and transported to the laboratory.

Table 1 Site descriptions of the sample plots

Sample plots	DS	CC	Coordinates		Elevation (m)	İnclination (%)	SP (%)	Aspect	SA (year)	MH (m)	MD (cm)
			East	North							
1	Middle age	3	35S 0727584	4,421,805	1000	18	72.7	ne	62	23.1	36.1
2	Mature	3	35S 0726261	4,421,721	983	20	93.4	nw	93	20.0	36.3
3	Mature	3	35S 0726316	4,421,002	1125	25	16.3	nw	63	23.0	27.1
4	Mature	2	35S 0724578	4,420,279	1078	18	48.5	se	85	30.5	32.8
5	Overmature	2	35S 0724108	4,420,294	1098	24	37.3	se	72	27.0	51.9
6	Middle age	3	35S 0727531	4,419,626	1097	15	47.3	se	43	21.5	25.5
7	Overmature	3	35S 0723834	4,417,682	1272	30	52.8	e	106	33.0	42.9
8	Middle age	3	35S 0727962	4,418,237	1160	8	31.0	nw	34	16.5	15.6
9	Overmature	3	35S 0725110	4,418,242	1122	18	46.3	n	94	37.0	54.1
10	Middle age	3	35S 0726123	4,418,122	1136	20	63.7	nw	39	18.0	24.8
11	Mature	3	35S 0719444	4,421,740	1011	28	64.9	ne	60	26.0	24.8
12	Middle age	3	35S 0717548	4,417,693	1272	24	54.8	nw	66	25.0	31.5
13	Overmature	3	35S 0717089	4,420,945	1120	38	93.9	nw	102	30.5	30.5
14	Overmature	3	35S 0716871	4,421,069	1170	27	83.0	n-nw	102	32.0	42.3
15	Mature	3	35S 0716519	4,420,316	1087	23	42.3	se	70	28.0	34.7
16	Mature	3	35S 0716619	4,419,895	1240	11	89.6	n	75	25.5	32.5
17	Middle age	3	35S 0719996	4,418,160	1173	21	87.6	ne	44	22.0	19.7
18	Middle age	3	35S 0717094	4,421,377	1076	29	37.7	n- nw	24	16.5	15.9
19	Mature	3	35S 0717101	4,417,680	884	35	85.8	nw	62	26.0	25.1
20	Overmature	2	35S 0717034	4,418,799	1141	34	90.5	nw	120	36.0	63.7
21	Mature	3	35S 0716769	4,418,210	1398	35	12.2	e-se	88	27.0	35.7
22	Overmature	3	35S 0715784	4,417,662	1534	27	33.8	se	102	26.0	35.0
23	Young	3	35S 0715910	4,417,038	1566	36	62.0	w-nw	21	12.0	3.2
24	Young	3	35S 0727584	4,416,743	1600	33	24.3	nw	15	7.0	1.9
25	Overmature	3	35S 0726261	4,416,488	1631	38	20.2	nw	117	28.0	45.5
26	Middle age	3	35S 0726316	4,420,283	1098	30	63.7	se	30	16.0	4.1
27	Young	3	35S 0724578	4,417,487	1567	11	16.7	nw	19	10.0	2.5
28	Young	3	35S 0724108	4,417,401	1565	5	8.3	nw	24	12.0	3.2
29	Young	3	35S 0727531	4,417,254	1568	30	83.3	nw	26	12.0	4.8
30	Young	3	35S 0723834	4,417,496	1548	8	51.9	s	19	8.0	2.2
31	Young	3	35S 0727962	4,417,691	1504	5	6.3	se	13	4.4	2.9
32	Young	3	35S 0725110	4,417,848	1515	25	7.7	e	14	4.8	2.1

DS: development stages, CC: canopy closure (2 = %41–70, 3 = %71–100), SP: slope position, SA: stand age, MH: mean height, MD: mean diameter at breast height, n: north, ne: northeast, nw: northwest, e: east, s: south, se: southeast, sw: southwest, w: west.

Laboratory analysis

The litter samples were dried to constant weight at 70 °C, weighed, and then the amount per unit area was calculated. The dried litter samples were ground and analysed for carbon content using a CNH elemental analyser (Leco Corporation, St. Joseph, Michigan, USA). The soil samples were air dried, the soil clods (aggregates) were crushed in a porcelain mortar and sieved through sieves of 2 mm mesh, and the weights of the fine earth and coarse fragments were determined. The fine earth was dried to a constant weight at 105 °C, weighed, and its moisture content determined (Carter & Gregorich, 2008). For the soil samples, pH-values were determined in pure water at a v/5v ratio (TS ISO 10390, 2013), soil texture was analysed by the Bouyoucous hydrometer method (Kroetsch & Wang, 2008) and organic carbon content was determined using the Walkley–Black wet combustion method (TS8336, 1990).

Calculations and statistical analysis

Equation 1, developed by Erkut (2013), was used to calculate the aboveground carbon stocks of trees in the sample plots. Then, the aboveground carbon stocks in a one-hectare area were calculated using the values obtained for the sample plots and the conversion coefficients to hectares. The coefficients in the AFOLU guide (IPCC, 2006) were used to determine belowground carbon stocks. For this purpose, coefficients of 0.46 were used in areas with aboveground tree mass < 75 t ha^{-1}, 0.23 in areas with 75–150 t ha^{-1} and 0.24 in areas with > 150 t ha^{-1}. By adding the aboveground and belowground carbon stocks of the sample plots, the carbon stocks of all trees in a hectare area were found.

$$AGCS = 0.025672 \times d^{2.775} \quad (1)$$

where AGCS is aboveground carbon stock (kg), and d is diameter at breast height (cm).

Equation 2, developed by Atıcı (1998), was used to calculate the bark trunk volumes in the sample plots.

$$\ln V = (-1.773944715) + (1.348733625 \times \ln d) + (0.148947009 \times \ln^2 d) + (0.360600105 \times \ln h) + (0.114774826 \times \ln^2 h) \quad (2)$$

where ln is logarithm, V is the volume of trunk with bark (dm^3), d is diameter at breast height (cm), and h is tree height (m).

The carbon stocks in the forest litter (forest floor) at the sample plot were estimated by multiplying the amount of litter in the sample plot and the carbon rates found as a result of the analysis, and then these values were converted into hectares.

The carbon stock per volume of 1000 cm^3 was determined by multiplying the percentage of carbon values in the soil by the amount of fine earth in a volume of 1000 cm^3. Then, these values were multiplied by the thickness of the depth layers to calculate the carbon amount of 1 m depth and 1 m^2 area (i.e. 1 m^3), and this value was converted to hectares by multiplying by 10,000.

The total carbon stock in one hectare of each sample area was measured by adding up the amount of carbon stocked in the trees, litter and soil. The relationships between the soil, litter, tree and ecosystem carbon stock and stand characteristics (age, mean diameter at breast height of the stand, mean height of the stand, age, basal area and bark trunk volume) were examined by Pearson correlation analysis. Normal distribution of the data set was controlled by Shapiro–Wilk tests, while homogeneity of the variances was evaluated by Levene's test. All data were normally distributed ($P > 0.05$) and homogeneous variance ($P > 0.05$). Then the differences between stand characteristics and tree, litter, soil and ecosystem carbon stock at different development stages were examined by analysis of variance. (ANOVA). Duncan's multiple-range test was used for comparison of the means. The results were considered statistically different at the $\alpha = 0.05$ level. The SPSS package program was used for statistical analysis (SPSS, 2015).

Results and discussion

Stand parameters

In this study, significant differences were found between the stand development stages in terms of stand age, mean diameter at breast height of the stand, mean height of the stand, number of trees, basal area and bark trunk volume ($P < 0.05$). Four similar groups were formed in terms of the stand age, stand mean diameter at breast height and stand mean height; three similar groups were formed in terms of the number of trees and bark trunk volume; and two similar groups were formed in terms of basal area. While the stand age, stand mean diameter at breast height, stand mean height and bark trunk volume increased with increasing development stage, the number of trees decreased. The stand basal area was found to be highest (48.6 m^2 ha^{-1}) in stands at the mature stage and lowest (30.6 m^2 ha^{-1}) in stands at the young stage (Table 2). Similarly, Makineci et al. (2015) showed for oak that stand age, stand mean diameter at breast height, stand mean height and basal area increased with successive development stages, while the number of trees decreased. The stand volume was found 122, 356, 793, and 1108 m^3 ha^{-1} in the development stages young, middle age, mature, and overmature respectively, depending on the progression of the stand development stage. Similar findings have been found in studies on the subject (Çömez, 2012; Güner

Table 2 Stand characteristics according to development stage (mean ± SE)

Stand parameters	Development stages				F	P
	Young	Middle age	Mature	Overmature		
Stand age (year)	18.8 ± 1.6^{A}	42.7 ± 5.2^{B}	74.5 ± 4.5^{C}	101.8 ± 5.2^{D}	67.746	< 0.001
Mean diameter (dbh-cm)	5.1 ± 0.8^{A}	17.7 ± 1.9^{B}	30.4 ± 2.4^{C}	48.7 ± 2.1^{D}	94.918	< 0.001
Mean height (m)	7.1 ± 0.9^{A}	18.6 ± 1.1^{B}	24.6 ± 0.9^{C}	30.2 ± 0.9^{D}	97.760	< 0.001
Number of trees (ha)	$29{,}000 \pm 12386^{C}$	1981 ± 754^{B}	675 ± 105^{A}	218 ± 26^{A}	5.120	< 0.01
Basal area (m^2 ha^{-1})	30.6 ± 2.9^{A}	36.7 ± 4.9^{AB}	48.6 ± 5.7^{B}	45.1 ± 6.6^{AB}	2.432	< 0.05
Stand volume (m^3 ha^{-1})	122 ± 20^{A}	356 ± 44^{B}	793 ± 75^{C}	1108 ± 149^{C}	25.703	< 0.001

The same letters on the same lines indicate no difference (P > 0.05), SE: standard error, P: significant level, dbh: diameter at breast height

& Çömez, 2017; Karataş et al., 2017; Tolunay et al., 2017).

Tree carbon stock

Significant differences ($P < 0.05$) were determined between the stand development stages in terms of the aboveground, belowground and whole-tree carbon stocks. Three similar groups were established in all three carbon stocks, and the lowest carbon stock was found in stands in the young stage. The aboveground, belowground and whole-tree carbon stocks were found to be highest in the stands at the mature and overmature stages, and the differences between these stands were found to be statistically insignificant ($P > 0.05$) (Table 3). The high level of the aboveground, belowground and whole-tree carbon stocks in the stands in the mature and overmature development stages can be explained by the fact that they have more stand volume and tree mass compared to the other development stages. As seen in the Table 2, the average stand volumes in stands at the young, middle age, mature and overmature development stages were 122, 356, 793 and 1108 m^3 ha^{-1}, respectively. Likewise, a study for oak, the aboveground tree carbon stocks of the young, middle age and mature development stages (Makineci et al., 2015) were reported 13, 54 and 89 t ha^{-1}, respectively. Furthermore, for black pine (*Pinus nigra* Arnold. subsp. *pallasiana* (Lamb.) Holmboe) afforestation sites, the carbon stock of all trees varied significantly between the stand development stages, with the lowest carbon stock in the young stands and the highest in the mature stands (Güner & Çömez, 2017). Another study for *Pinus strobus* L. plantations aged at 2, 15, 30 and 65-year-old, mean aboveground tree carbon stocks were 0.5, 66, 92 and 176 t ha^{-1} respectively (Peichl & Arain, 2006). Aboveground carbon stock in young, middle age, mature and overmature stages are found at 42.8; 122.6; 253.6 and 344.4 t ha^{-1} respectively. All sample plots have been evaluated together, and an average of 190.9 t C ha^{-1} was found. A similar study in the eastern beech forests in the Eastern Black Sea Region (middle age, mature, and overmature development stage) was found 175.9 t ha^{-1} (Erkut, 2013), which lower than our research findings. Belowground carbon stock in young, middle age, mature and overmature development stages were 12,6; 29,3; 60,9 and 82,7 t ha^{-1} respectively, and the average of all sample areas was 46.4 t C ha^{-1}. There are studies

Table 3 Tree carbon stocks according to development stage (mean ± SE)

Tree carbon stocks (t ha^{-1})	Development stages				Mean	F	P
	Young	Middle age	Mature	Overmature			
Aboveground	42.8 ± 8.8^{A}	122.6 ± 15.1^{B}	253.6 ± 24.1^{C}	344.4 ± 57.5^{C}	190.9 ± 25.9	17.177	< 0.001
Belowground	12.6 ± 1.8^{A}	29.3 ± 3.6^{B}	60.9 ± 5.8^{C}	82.7 ± 13.8^{C}	46.4 ± 6.1	16.364	< 0.001
Whole tree	55.4 ± 10.4^{A}	151.9 ± 18.8^{B}	314.5 ± 29.9^{C}	427.1 ± 71.3^{C}	237.3 ± 32.1	17.033	< 0.001

The same letters on the same lines indicate no difference (P > 0.05), SE: standard error, P: significant level investigating belowground mass and carbon stock in eastern beech forests in Türkiye (Tüfekcioglu et al., 2005; Mısır & Mısır, 2013; Özbayram & Güvendi, 2016). In these studies, the cylinder method was used, and the mass of belowground in a certain diameter class (such as Ø ≤ 10 mm or Ø > 50 mm) was determined. Although no study has been found revealing the entire belowground mass and carbon stock in eastern beech, belowground mass and carbon stock of the broad-leaf species ash (*Fraxinus angustifolia* Vahl.) and alder (*Alnus glutinosa* L.) were studied (Sariyildiz et al., 2023). In this study, belowground carbon stock was found 80.3 t ha^{-1} for ash and 25.2 t ha^{-1} for alder (Sariyildiz et al., 2023). These values determined for ash and alder are similar to values we determined for eastern beech.

Litter carbon stock

Differences between the stand development stages in terms of litter mass, carbon content and carbon stock were insignificant ($P > 0.05$). When all sample areas were evaluated together, the average litter mass was 12.5 t ha^{-1}, the carbon content was 43.9% and carbon stock was 5.5 t ha^{-1} (Table 4). It is reported that many factors such as location, climate characteristics, landform, tree type, forest age, canopy closure, soil properties and soil organisms influence litter mass (Kantarcı, 2000). In general, as stand development progresses, the tree mass per unit area and, as a result, the litter mass increases. A study in Iran for oriental beech forests showed that litter thickness (cm) and carbon content (%) increased with advancing development stages (Kooch et al., 2021). Likewise, for oak, litter mass showed significant differences among the young, middle age and mature development stages with the values of 4.5, 6.4 and 10.6 t ha^{-1} respectively (Makineci et al., 2015). Similar results were reported for coniferous tree species; *Pinus nigra* Arn. (Güner & Çömez, 2017), *Cedrus libani* A. Rich. (Karataş et al., 2017), *Pinus pinea* L. and *Pinus pinaster* Ait. (Makineci, 2021). For brutia pine (*Pinus brutia* Ten.), a significant relationship was found between a number of parameters such as basal area per hectare, total volume and canopy cover, and the amount of litterfall (Erkan et al., 2018). However, in our study, differences between the stand development stages in terms of litter mass, carbon content and carbon stock were insignificant. This can be explained by the addition of high amounts of cutting residue to the litter as a result of natural regeneration studies (seeding, overhead release and final cutting). When all data were evaluated together, the average litter mass was 12.5 t ha^{-1}, carbon content was 43.9% and carbon stock was 5.5 t ha^{-1}. Similar to our findings, for oriental beech forests in the middle age, mature and overmature development stages in the Eastern Black Sea Region, the litter mass was 4.8–27 t ha^{-1}, litter carbon content was 34.9% and litter carbon stock was 2–7 t C ha^{-1} (Erkut, 2013). The results of another study from oriental beech forests in Türkiye also showed similar findings to our study, with litter mass of 8.7 (2.6–36.6) t ha^{-1} and litter carbon stock of 3.2 (1.0–9.4) t C ha^{-1} reported (Tolunay & Çömez, 2008). Similarly, for oriental beech forests in Iran, the carbon content of litter was 36.2% for the young stands and 52.5% for the old stands (Kooch et al., 2021).

Soil carbon stock

The changes in soil properties in the research area at different depth levels are given in Table 5. Differences between depth levels in terms of bulk density, amount of fine earth (Ø < 2 mm), percent sand, silt, clay, pH-values and organic carbon were significant ($P < 0.05$). In general, bulk density, fine earth, percent sand and pH-values increased with soil depth, while silt, clay and organic carbon values decreased (Table 5).

Table 4 Litter properties according to development stage (mean ± SE)

Litter properties	Development stages				Mean	F	P
	Young	Middle age	Mature	Overmature			
Litter mass (t ha^{-1})	12.7 ± 0.4^{A}	11.6 ± 0.5^{A}	12.4 ± 0.9^{A}	13,3 ± 0.9^{A}	12.5 ± 0.4	0.887	> 0.05
Litter C content (%)	43.9 ± 1.4^{A}	46.1 ± 0.5^{A}	42.3 ± 0.9^{A}	43,5 ± 0.8^{A}	43.9 ± 0.5	2.728	> 0.05
Litter C stock (t C ha^{-1})	5.6 ± 0.2^{A}	5.4 ± 0.2^{A}	5.3 ± 0.5^{A}	5,8 ± 0.4^{A}	5.5 ± 0.2	0.409	> 0.05

The same letters on the same lines indicate no difference ($P > 0.05$), SE: standard error, P: significant level.

Table 5 Soil properties according to soil depth (mean ± SE)

Soil properties	Soil depth (cm)				F	P
	0–10	10–30	30–60	60–100		
BD (g cm^{-3})	1.002 ± 0.039^{A}	1.151 ± 0.032^{B}	1.255 ± 0.033^{C}	1.312 ± 0.04^{C}	15.253	< 0.001
FE (g l^{-1})	842 ± 33^{A}	981 ± 31^{B}	1059 ± 31^{B}	1076 ± 37^{B}	10.021	< 0.001
Sand (%)	55.1 ± 1.1^{AB}	52.0 ± 0.9^{A}	53.5 ± 1.4^{A}	57.9 ± 2.2^{B}	2.955	< 0.05
Silt (%)	23.0 ± 0.8^{B}	22.5 ± 0.7^{B}	21.6 ± 0.8^{AB}	19.9 ± 1.0^{A}	2.661	< 0.05
Clay (%)	21.9 ± 0.7^{A}	25.4 ± 0.6^{B}	24.9 ± 0.8^{B}	22.1 ± 1.38^{A}	3.944	< 0.01
pH	4.97 ± 0.04^{A}	5.17 ± 0.04^{B}	5.31 ± 0.04^{C}	5.36 ± 0.04^{C}	18.648	< 0.001
OC (%)	3.73 ± 0.29^{D}	1.74 ± 0.15^{C}	0.90 ± 0.08^{B}	0.35 ± 0.04^{A}	77.485	< 0.001

The same letters on the same lines indicate no difference (P > 0.05), SE: standard error, P: significant level, BD: bulk density, FE: fine earth (Ø < 2 mm), OC: organic carbon.

The amount of fine earth (t ha^{-1}), soil organic carbon content (%) and soil carbon stock (t ha^{-1}) showed statistically significant differences between the stand development stages (P < 0.05). The amount of fine earth was the lowest in the young stands (8,96 t ha^{-1}), and the highest in the middle (11,22 t ha^{-1}) and mature (10,98 t ha^{-1}) age stands (Table 6). The fact that the amount of fine earth was lowest in young stands is likely because these stands are generally located on upper elevation land (Table 1). The amount of fine earth and carbon content affect the soil carbon stock. In addition, it is reported that organic matter input, the decomposition rate of organic matter (Tolunay & Çömez, 2007) and fine root decomposition in the soil (Berg & McClaugherty, 2003) influence the carbon content of the soil. In this study, soil organic carbon content and soil carbon stock were the highest at the young stage, followed by a decrease at the middle age and mature stand development stages. Soil organic carbon content and soil carbon stock increased after the mature development stage and reached 1.09% and 105 t C ha^{-1}, respectively, in the overmature development stage (Table 6). The fact that the soil organic carbon stock and organic carbon content were highest in young stands, then decreased, reaching their lowest level in mature stands, before increasing again in overmature stands, can be explained by the addition of high amounts of cutting residue to the litter as a result of natural regeneration studies. Due to the reduction in canopy closure via the overhead release and final cutting, the amount of precipitation and temperature within the stand increased. Therefore, abundant cutting residues decomposed faster, increasing the organic carbon content of the soil. As a result of regeneration activities, the cutting residues added to the litter decreased with decomposition and reached a balance in mature stands, and then, due to the increase in tree mass, both litterfall and fine root decomposition provided organic matter to the soil, causing an increase in the soil organic carbon stock. Likewise, in a study conducted on the sessile oak (*Quercus petraea* (Matt.) Liebl.), the carbon stock in 0–30 cm deep soil was found to be 31.5, 10.6, 24.7 and 55.0 t ha^{-1} in stands at young, middle age, mature and overmature development stages, respectively. The carbon stock decreased from the young stage to the middle age stage, reached a balance in the middle age stage, and increased again,

Table 6 Soil organic carbon stocks according to development stage (mean ± SE)

Soil properties	Development stages				Mean	F	P
	Young	Middle age	Mature	Overmature			
Fine earth (Ø < 2 mm) mass (t ha^{-1})	8957 ± 463^{A}	11,219 ± 508^{B}	10,982 ± 354^{B}	9999 ± 594^{AB}	10,289 ± 282	4.483	< 0.05
Soil organic carbon content (%)	1.45 ± 0.15^{B}	0.92 ± 0.14^{A}	0.70 ± 0.04^{A}	1.09 ± 0.16^{AB}	1.04 ± 0.08	5.596	< 0.01
Soil organic carbon stock (t ha^{-1})	126.5 ± 10.2^{B}	98.1 ± 12.2^{AB}	76.6 ± 3.1^{A}	104.5 ± 11.2^{AB}	101.4 ± 5.7	4.330	< 0.05

The same letters on the same lines indicate no difference (P > 0.05), SE: standard error, P: significant level.

reaching the highest level in the overmature stage (Savacı & Aktaş-Tümer, 2022). In our study, when all sampling areas were evaluated together, the average soil organic carbon stock was 101.4 t ha^{-1}. Likewise, the value of 77.9 (27.8–227.3) t ha^{-1} given by Tolunay and Çömez (2008) as the average carbon stock in Türkiye's beech forests is consistent with the findings of this study. Again, in a study conducted in eastern beech forests (middle age, mature and overmature development stage) in the Eastern Black Sea Region, soil organic carbon stock was found 81.1 t ha^{-1}, which is similar to our research findings (Erkut, 2013).

Ecosystem carbon stock

Differences between stand development stages in terms of ecosystem carbon stock were found to be significant ($P<0.05$). The lowest ecosystem carbon stock was in the young (187.5 t C ha^{-1}) and middle age (255.4 t C ha^{-1}) stands development stages, followed by mature (396.4 t C ha^{-1}) and overmature (537.4 t C ha^{-1}) stages (Table 7). This difference between stand development stages in terms of ecosystem carbon stock was largely due to tree carbon stock (Fig. 2); similar findings have been reported in many studies on the subject (Çömez, 2012; Güner & Çömez, 2017; Karataş et al., 2017; Makineci et al., 2015; Tolunay et al., 2017). The carbon stocks in the components of the ecosystem (trees, litter, soil) varied according to development stage. While tree mass carbon stock constituted 30% of the ecosystem carbon stock in stands at the young stage, this rate increased up to 80% in the overmature development stage stands. While the ratio of soil carbon stock to ecosystem carbon stock was 67% in stands at the young stage, this ratio decreased to 19% in stands at the overmature stage. The ratio of litter carbon stock to ecosystem carbon stock was 3%, 2%, 1% and 1% in stands of the young, middle age, mature and overmature development stages, respectively (Fig. 3). According to the average values, the ecosystem carbon stock in the oriental beech forests in the Marmara Region was found to be 344 t ha^{-1}. The ecosystem carbon stock (average of 257 t C ha^{-1}) reported in a study conducted on oriental beech forests (middle age, mature and overmature development stages) in the Eastern Black Sea Region (Giresun) was found to be lower than that in our study since belowground

Table 7 Ecosystem carbon stocks according to stand development stage (mean ± SE)

	Development stages				Mean	F	P
	Young	Middle age	Mature	Overmature			
Ecosystem C stock (t ha^{-1})	187.5 ± 15.7^{A}	255.4 ± 17.9^{A}	396.4 ± 32.8^{B}	537.4 ± 78.4^{C}	344.2 ± 32.0	12.401	< 0.001

The same letters on the same lines indicate no difference ($P>0.05$), SE: standard error, P: significant level.

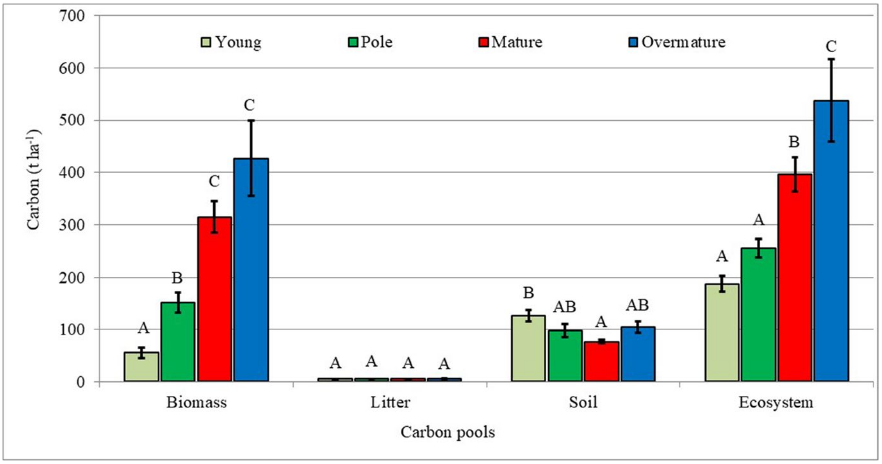

Fig. 2 Comparison of carbon stocks by development stage for different carbon pools (each column representing the mean value of the carbon stock for the related development stages). Error bars indicate ± SE. Carbon stocks sharing the same letter in columns are not significantly different from each other at the α = 0.05 level, according to the ANOVA results for the biomass, litter, soil and ecosystem

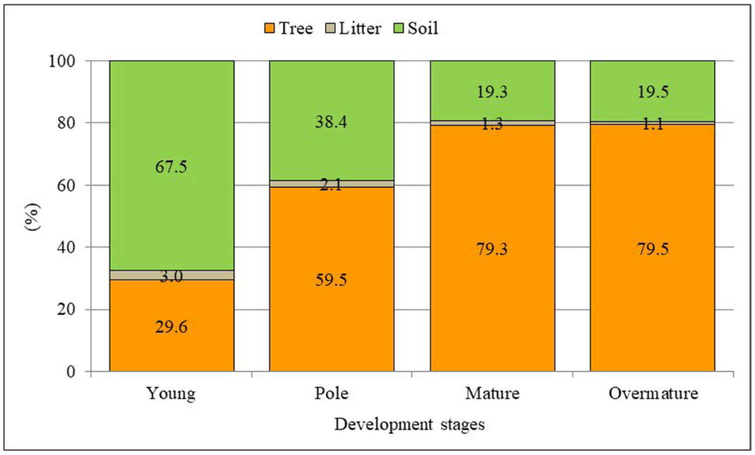

Fig. 3 Distribution rates of carbon stocks in ecosystem components of oriental beech forests at different development stages

Table 8 Relationships between carbon pools

Carbon pools (t C ha^{-1})	Tree C stock	Litter C stock	Soil C stock
Tree C stock	1.000	0.114 ^{ns}	-0.104 ^{ns}
Litter C stock		1.000	0.372*
Soil C stock			1.000

^{ns}: non-significant, **: P < 0.01

biomass was not included in the ecosystem carbon stock (Erkut, 2013).

Relationships between carbon stocks

The relationships between tree, litter and soil carbon stocks are given in Table 8. A positive relationship was seen between the litter carbon stock and the soil carbon stock at the 0.05 significance level, while the relationships between other carbon stocks were statistically insignificant (P > 0.05). As one of the sources of soil carbon was litter, the positive relationship between litter carbon stock and soil carbon stock was an expected outcome. Previous studies found positive relationships between tree carbon stock and litter carbon stock (Bradford et al., 2009; Çömez, 2012; Güner & Çömez, 2017). The fact that no significant relationship was detected between the tree carbon stock and litter carbon stock in our study can be attributed to the introduction of high amounts of cutting residue into the stands in the development stage through regeneration studies. In a study conducted on Taurus cedar (*Cedrus libani* A. Rich.) afforestation area, a positive relationship was found between tree carbon stock and soil carbon stock. This situation has been explained as more carbon input into the soil due to litterfall and fine root decomposition resulting from the increase in tree mass (Karataş et al., 2017).

Relationships between carbon stocks and stand parameters

A positive relationship was found between stand age, stand mean diameter at breast height, stand mean height, basal area and bark trunk volume, and tree carbon stock and ecosystem carbon stock at a significance level of 0.01. Furthermore, negative relationships were found between the number of trees and tree carbon stock and ecosystem carbon stock at the 0.05 significance level, as well as between the medium stand height and soil carbon stock at the 0.05 significance level (Table 9). The basis of these relationships is the mass of trees per unit area; with the increase in tree mass, tree carbon stock and ecosystem carbon stock increased. Similar results were obtained in studies conducted on Taurus cedar (Karataş et al., 2017) and black pine afforestation area (Güner & Çömez, 2017).

Conclusions

This study investigated to the variations in carbon stocks in different ecosystem components of the oriental beech forests of the Marmara Region, Türkiye, with stand development stages. Tree carbon stocks

Table 9 Relationships between stand parameters and carbon stocks

Stand parameters	Carbon stocks (t C ha^{-1})			
	Tree C stock	Litter C stock	Soil C stock	Ecosystem C stock
Stand age (year)	0.767^{**}	0.122^{ns}	-0.260^{ns}	0.723^{**}
Mean diameter (dbh-cm)	0.816^{**}	0.061^{ns}	-0.252^{ns}	0.773^{**}
Mean height (m)	0.719^{**}	0.049^{ns}	-0.392^{*}	0.651^{**}
Number of trees (ha)	-0.413^{*}	-0.110^{ns}	0.134^{ns}	-0.391^{*}
Basal area (m^2 ha^{-1})	0.775^{**}	0.160^{ns}	0.007^{ns}	0.779^{**}
Stand volume (m^3 ha^{-1})	0.987^{**}	0.100^{ns}	-0.151^{ns}	0.963^{**}

^{ns}: non-significant, *: $P<0.05$, **: $P<0.01$

showed significant differences between the stand development stages, reaching 55, 152, 315 and 427 t ha^{-1} in the young, middle age, mature and overmature stages, respectively. No differences were found between the development stages in terms of litter mass, litter carbon content and litter carbon stock. For oriental beech forests in the Marmara Region, mean litter mass was 12.5 t ha^{-1}, the litter carbon content and stock were 43.9% and 5.5 t ha^{-1} respectively. The obtained values can be used in future calculations for the same region and similar habitats. Mean soil carbon stock showed significant differences between the four development stages, as 127, 98, 77 and 105 t ha^{-1} for the young, middle age, mature and overmature stages, respectively. Since many factors such as stand characteristics, soil properties, litter decomposition rate and climate characteristics influence soil carbon stock, more comprehensive modelling studies are needed. Despite this, the soil carbon data presented in this study can be used until more detailed studies are conducted. Ecosystem carbon stock showed differences between development stages and was found to be 188, 255, 396 and 537 t ha^{-1} at the young, middle age, mature and overmature stages, respectively. The data revealed by this research can be used in forest management plan development and greenhouse gas inventory reporting.

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Author contribution Şükrü Teoman Güner: Conceptualization, Methodology, Data collection, Formal analysis, Data curation, Writing—original draft, Writing—review & editing, Visualization. Özgür Kiracıoğlu: Writing—review & editing. Abdullah Sarımehmetoğlu: Writing—review & editing.

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Data availability The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "ethical responsibilities of authors."

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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