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Carbon concentration changes in biomass components of black pine forests: Case study from Sündiken Mountains, Eskişehir

Karaçam ormanlarının bitkisel kütle bileşenlerinde karbon içeriklerindeki değişimler: Sündiken Dağları örneği, Eskişehir

Aydın Çömez[1]
Mustafa Oğuz Soydan[2]
Hatice Ay[2]

[1] Ege Ormancılık Araştırma Enstitüsü Müdürlüğü, İzmir
[2] Bartın Üniversitesi, Bartın

Sorumlu yazar (*Corresponding author*)
Aydın Çömez
acomez@hotmail.com

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Şükrü Teoman Güner
stguner@bartin.edu.tr

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Abstract

Understanding carbon concentration in different tree components is essential for accurate forest carbon accounting and climate change mitigation efforts. This study investigated the carbon concentrations of wood, bark, needles, and roots in natural black pine (*Pinus nigra* subsp. *pallasiana*) forests located in the central part of Türkiye. Samples were collected from ten pure mature stands between 1000 and 1600 m elevation, considering both aspect and slope position. Carbon content was analyzed using an elemental analyzer. Results showed significant differences in carbon concentration among tree components, with the highest mean carbon concentration found in wood (54.96%), followed by bark (53.90%) and needles (52.89%), while the lowest was found in roots (51.75%). Above-ground and total tree biomass-weighted carbon concentrations were calculated to be 54.68% and 54.19%, respectively. Carbon content in needles and roots was significantly influenced by aspect and slope position. The study highlights the importance of using component-based and site-specific carbon coefficients, rather than default coefficients, to improve the precision of national carbon inventories and forest-based carbon credit projects.

K***eywords:*** *Pinus nigra*, biomass, carbon inventory, climate

Öz

Ağaç bileşenlerinde karbon içeriklerinin bilinmesi, doğru orman karbon hesaplaması ve iklim değişikliğiyle mücadele çalışmaları açısından büyük önem taşımaktadır. Çalışmada, Türkiye'nin iç kesimlerinde doğal olarak yetişen karaçam (*Pinus nigra* subsp. *pallasiana*) ormanlarında odun, kabuk, iğne yaprak ve köklerin karbon içerikleri incelenmiştir. Örnekler, yükseltisi 1000 ile 1600 metre arasında değişen, bakı ve yamaç konumu dikkate alınarak seçilmiş on adet saf ve ağaçlık çağındaki meşcereden toplanmıştır. Karbon içeriği, laboratuvarda elementel analiz cihazı kullanılarak belirlenmiştir. Sonuçlar, ağaç bileşenleri arasında karbon yoğunluğunun önemli farklılık gösterdiğini ortaya koymuştur. En yüksek ortalama karbon oranı odun bileşeninde (%54,96) bulunmuş, bunu kabuk (%53,90) ve iğne yaprak (%52,89) izlemiş, en düşük oran ise köklerde (%51,75) tespit edilmiştir. Toprak üstü ve toplam ağaç biyokütlesine göre ağırlıklı ortalama karbon oranı sırasıyla %54,68 ve %54,19 olarak hesaplanmıştır. İğne yaprak ve köklerin karbon içeriği, bakı ve yamaç konumundan da önemli düzeyde etkilenmiştir. Bu çalışma, ulusal karbon envanterlerinin ve orman temelli karbon kredi projelerinin doğruluğunu artırmak için genel katsayılar yerine, bileşen bazlı ve saha özelliklerine özgü karbon katsayıları kullanılmasının önemine dikkat çekmektedir.

Anahtar Kelimeler: *Pinus nigra*, biyokütle, karbon envanteri, iklim

1. Introduction

Forest trees sequester atmospheric carbon dioxide (CO_2) through photosynthesis to build tissues and grow. CO_2, along with other gases such as water vapor, methane, and nitrous oxides in the atmosphere, plays a critical role in maintaining Earth's temperature suitable for life (Kurnaz, 2019). However, increased CO_2 concentration has been identified as a primary driver of global warming (Nunes, 2023). Reducing greenhouse gas emissions, particularly CO_2, and enhancing CO_2 removal from the atmosphere are regarded as prominent approaches in alleviating the climate change impacts (IPCC, 2018). One of the most effective strategies for reducing atmospheric CO_2 is expanding carbon sink areas through afforestation (Nunes, 2023).

While oceans represent the largest carbon sink globally, forests, spanning approximately 4 billion hectares of terrestrial ecosystems, have the highest carbon sequestration capacity among terrestrial ecosystems (Janzen, 2004). In forest ecosystems, carbon is primarily stored in four pools: biomass, deadwood, litter, and soil. Among these, biomass and soil constitute the most significant carbon reservoirs. Biomass, which ultimately contributes to soil carbon, is predominantly derived from trees in forest ecosystems. Tree taxa exhibit varying carbon content, and even within the same tree, carbon content differs across components, such as leaves, stem, bark, and roots. Thus, accurately estimating the carbon stocks of forests requires detailed knowledge of species-specific mean carbon content.

Global initiatives like the Kyoto Protocol (unfccc.int/kyoto_protocol), the United Nations Framework Convention on Climate Change (UNFCCC; unfccc.int), and the Paris Agreement have accelerated efforts to develop national carbon inventories while also improving data quality. To ensure consistency and comparability of carbon calculations across countries, guidelines have been developed for estimating carbon stocks in forest ecosystems (IPCC, 2006). These guidelines provide coefficients for biomass and carbon content derived from extensive research, typically as averages for plant genera or species groups. Although these generalized coefficients may be suitable for regional and global assessments, they can reduce the precision of carbon inventories at the country and local scales. Consequently, the IPCC recommends developing species-specific coefficients at local levels for more accurate calculations (IPCC, 2003; IPCC, 2006).

More precise carbon inventory is essential not only for national carbon inventory assessments but also for carbon projects, primarily aimed at generating carbon credits (Lamlom and Savidge, 2003; Malmsheimer et al., 2011). Research indicates that tree carbon content varies by species, organ (e.g., leaves, branches, trunk, bark, roots), and habitat (Laiho and Laine, 1997; Lamlom and Savidge, 2003; Bert and Danjon, 2006; Thomas and Malczewski, 2007; Çömez, 2012). Determining the carbon content of individual tree components is also vital for understanding changes in carbon pools resulting from forest management interventions.

Black pine (*P. nigra*) is distributed across Southern Europe, Northwest Africa, and Türkiye (Vidaković, 1991). The species includes five subspecies: *nigra*, *salzmannii*, *laricio*, *dalmatica*, and *pallasiana* (Tutin et al., 1993). Among these, Anatolian black pine (*P. nigra subsp. pallasiana* var. *pallasiana*) is naturally spreading in Türkiye, Thrace, Crimea, the Balkans, Southern Carpathians, Cyprus, Western Caucasus, and Western Syria (Davis, 1965; Anşin and Özkan, 1993). In Türkiye, black pine grows at elevations of 165 m to 2,150 meters, either in pure stands or mixed with other tree species such as oak (*Quercus*), fir (*Abies*), pine (*Pinus*), and juniper (*Juniperus*). It is widespread in the Marmara, Black Sea, Aegean, Mediterranean, Central Anatolia, and Upper Euphrates regions (Kandemir and Mataracı, 2018).

According to 2020 data, the forest area of Türkiye covers 22.9 million hectares, of which approximately 18.3% (4,199,623 ha) comprises black pine forests (OGM, 2021). Due to its extensive distribution and economic significance, black pine is a critical species for carbon estimation studies. Comprehensive studies on belowground and aboveground biomass and carbon content for black pine plantations in Türkiye have been conducted (Güner and Çömez, 2017). Carbon concentration in plant tissue largely depends on species, climate, stand, and environmental properties (Poroshy et al. 2021; Güner et al. 2025). Additionally, research on aboveground biomass and carbon content in natural black pine forests was carried out in the Zonguldak Forest Region in Türkiye (Çakıl, 2008). However, based on Serengil's (2018) classification, the study by Durkaya et al. (2015) is situated in the Euxine-Colchic deciduous forest ecozone. In contrast, the present study focuses on the Northern Anatolian mixed forest ecozone, distinguishing it from previous work. On the other hand, knowledge on belowground biomass and carbon content of roots, as well as weighted carbon concentration, in natural black pine forests is still lacking, although existing studies suggest that differences may exist between afforested and natural stands (Soto-Cervantes et al. 2023; Li et al. 2024).

This study aims to determine the carbon content of tree components, the weighted carbon content of aboveground biomass, and the total biomass in natural black pine forests located within the Northern Anatolian mixed forest ecozone.

2. Materials and Methods

2.1. Description of the study area

The study was conducted in the natural black pine forests of the Sündiken Mountain Ranges, located in the Central Anatolia Region, near Eskişehir, Türkiye (Figure 1). The Sündiken Mountains extend in an east-west direction, forming a mass approximately 25 km wide and 120 km long, bordered by the Eskişehir-Alpu plains to the south and the Sakarya River to the north (Kaymak, 2020).

The lowest part is located at an elevation of 250 m above sea level (a.s.l) in the north, while the highest elevation reaches 1800 m a.s.l. The southern part has an elevation of 800 m a.s.l. Geologically, the western and higher regions of the Sündiken Mountains are composed of Paleozoic mica schists and marbles, while the eastern sections consist of Neogene limestone and calcareous sedimentary materials. Oligocene-aged rocks and Neogene limestone formations exist on the southern aspects (Gözler et al., 1996).

The southern part of the Sündiken Mountains has a continental semi-arid steppe climate, while the northern part is affected by Black Sea Hinterland Climate, characterized by low humidity due to the distance from the sea (Koray et al., 2012), which corresponds to the Northern Anatolian mixed forest ecozone described by Serengil (2018). The average annual temperature varies with elevation, ranging from 8.2°C in the high mountainous areas (Çatacık) to 15.9°C in the lower elevations (Sarıcakaya). Similarly, annual precipitation also varies with elevation, from 315 mm in lowland areas (Sarıyar Dam, Nallıhan/Ankara) to 582 mm in higher (Mihalıççık/Kızıltepe) regions (Kaymak, 2020).

The Sündiken Mountains encompass a total forested area of approximately 146,365 hectares, of which about 33% is covered by black pine forests (Koray et al., 2012). Other tree species in the region include Turkish red pine (*Pinus brutia Ten.*), Scots pine (*Pinus sylvestris L.*), stinking juniper (*Juniperus foetidissima Willd.*), Crimean juniper (*Juniperus excelsa Bieb.*), Aleppo oak (*Quercus infectoria Oliv.*), Turkey oak (*Quercus cerris L.*), and sessile oak (*Quercus petraea* (Mattuschka) Liebl.). In the southern aspects of the Sündiken mountain range, forests degraded by human activity are found at elevations of 900-1,100 m, consisting of black pine, oak, and juniper. Between 1,100 and 1,500 m, black pine dominates the landscape, while mixed stands of black pine and Scots pine are observed at 1,500-1,600 m. Above 1,600 m, pure Scots pine forests prevail. On the northern aspects, Turkish red pine is reported to dominate between 300-800 m, black pine between 800-1,200 m, and Scots pine above 1,300 m (Çömez, 2004).

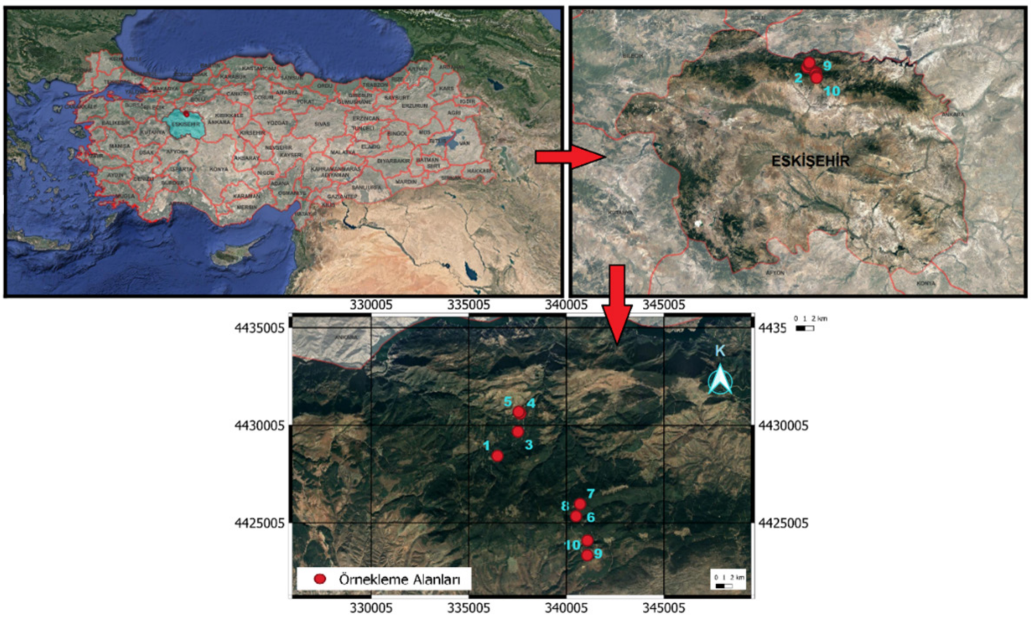

Figure 1. Study site (upper left) and sample plots (upper right and below)
Şekil 1. Araştırma sahası (üst sol) ve deneme alanları (üst sağ ve alt)

2.2. Selection of sampling sites and sampling method

To ensure adequate representation of ecological heterogeneity, a stratified purposive sampling design was employed. Sampling was carried out in pure black pine stands at the mature stage, with a mean diameter at breast height between 20.0 and 51.9 cm, as this diameter range covers larger areas compared to juvenile and over-mature stands. To encompass the carbon content variations across different environmental conditions, ten sampling locations with elevations varying from 1000 m to 1600 m, northern and southern aspects, and upper and lower slope positions were selected. Each sampling plot measured 20×20 m (= 400 m²).

The slope of sample plots was measured with a clinometer, while the elevation was recorded with an altimeter, and the aspect was determined with a compass. The slope position was calculated as a percentage, representing the ratio of the plot's distance from the top of the slope to the total slope length. Sampling was carried out during the dormant season, between November and March, when the nutrient fluctuations in tree tissue were minimal.

At each sampling site, foliage, wood, bark, branches, and root samples were collected from three healthy trees in the dominant canopy layer. Needle samples were collected from a height of approximately 9 m using a telescopic pruning shears. Needles were taken equally from four cardinal directions within the crown, considering different needle ages, and then combined to form a composite sample. Wood cores were extracted at tree breast height, 1.3 m above the ground, using an increment borer to minimize damage to the trees.

Bark samples were taken at breast height, using a knife to cut down to the cambium layer carefully. For root sampling, a section was excavated near the base of each sampled tree using a pickaxe, and the roots with a diameter smaller than 4 cm were collected (Durkaya et al., 2019), considering the prevailing root diameter. The root samples were thoroughly washed to remove soil particles.

2.3. Laboratory analyses

Tree component samples (needles, wood, bark, and roots) collected from the field (10 sampling plots ×3 replicates ×4 components= 120 samples) were dried in an oven at 65°C until reaching a constant weight. Subsequently, the samples were ground into fine particles and prepared for analysis. The carbon content of the tree components was determined using a LECO CNH TruSpec elemental analyzer.

2.4. Data evaluation

The proportions of aboveground biomass components in total aboveground biomass for black pine can vary depending on stand development stage, stand structure, and site conditions, as reported by various studies (Table 1). To calculate weighted carbon ratios, the component biomass-to-aboveground biomass ratios for the study area were adopted from Koray (2017) due to its proximity to the study area. For total tree biomass calculations, the root-to-shoot (r/s) ratio was taken as 0.20, based on the IPCC (2006), as there were no data available on the belowground biomass of natural black pine forests.

Table 1. Proportions of biomass components in black pine across different studies
Tablo 1. Karaçamdaki biyokütle bileşenlerinin farklı çalışmalardaki oranları

Needles (%)	Branches (%)	Stem (%)	Bark (%)	Region	Source
1-10	3-9	50-95	-	Zonguldak	Çakıl (2008)
5-20	30-15	15-70	25-10	Kastamonu-Taşköprü	Şenyurt (2016)
28	31	28	13	Ankara-Kızılcahamam	Saranay (2017)
7	21	59	11	Eskişehir	Koray (2017)
11	13	64	12	Çankırı	Ercanlı et al. (2023)
2-7	10-19	66-76	7-10	Samsun	Kahveci (2024)

The weighted carbon ratio for aboveground and total tree biomass was calculated using Equation 1 (Erkan and Güner, 2018).

$$wcc = \sum \left(\frac{ccc_i \times cb_i}{100} \right) \quad (1)$$

Where,

wcc: Weighted carbon concentration for aboveground or total tree biomass (%),

ccc_i: Carbon content of component i (%),

cb_i: Proportion of component (i) in aboveground or total tree biomass (%).

2.5. Statistical analysis

The differences in carbon content among tree components were assessed using analysis of variance (ANOVA). Before conducting the ANOVA, the normality of the data distribution was checked through the Shapiro-Wilk test. Homogeneity of variances was verified using Levene's test.

All data showed normal distribution and homogeneous variances. Results were considered statistically significant at the α= 0.05 level. SPSS software (SPSS, 2015) was used for the statistical analyses.

3. Results

The carbon concentrations of needles showed a minor variation, with a mean of 52.89%, compared to other components. In contrast, a wider variation in carbon was found in the wood, with a range from 52% to 60%, compared to the other components. The lowest carbon was found in the roots with a mean of 51.75%, while the highest was obtained in the wood, with a mean of 54.96% (Table 2). The differences in carbon concentrations among the tree components were significant. The bark carbon concentration was 1% lower than that of the wood. The weighted mean carbon content was calculated as 54.68% for the above-ground tree biomass and 54.19% for the whole tree, including below-ground biomass (Table 2).

Table 2. Carbon ratios (%) of tree components
Tablo 2. Ağaç bileşenlerinin (%) karbon oranları

Component	Mean	Min.	Max.	Standard Deviation
Needles	52.89 b	52.27	53.80	0.49
Wood	54.96 c	52.20	60.02	2.04
Bark	53.90 bc	52.19	55.44	0.92
Roots	51.75 a	49.91	52.81	0.86

Carbon concentration of tree components showed significant differences at the level of $P<0.001$. Identical letters in rows indicate similar groups without significant differences ($P>0.05$).

Carbon concentrations in the needles and roots significantly changed between the slope aspects, with higher concentrations on the southern aspects than on the northern. Likewise, the lower slope had higher carbon concentrations of needles and roots than the upper slope. Similar patterns of order among the carbon content of tree components were observed on both slope aspects and slope positions, with the order of wood>bark>needles>root (Figure 2). However, there was no significant relationship between the carbon concentration of tree components and altitude.

Carbon concentrations in the needles and roots showed significant differences according to both the aspects and the slope positions at a level of 0.05, indicated by * in Figure 2.

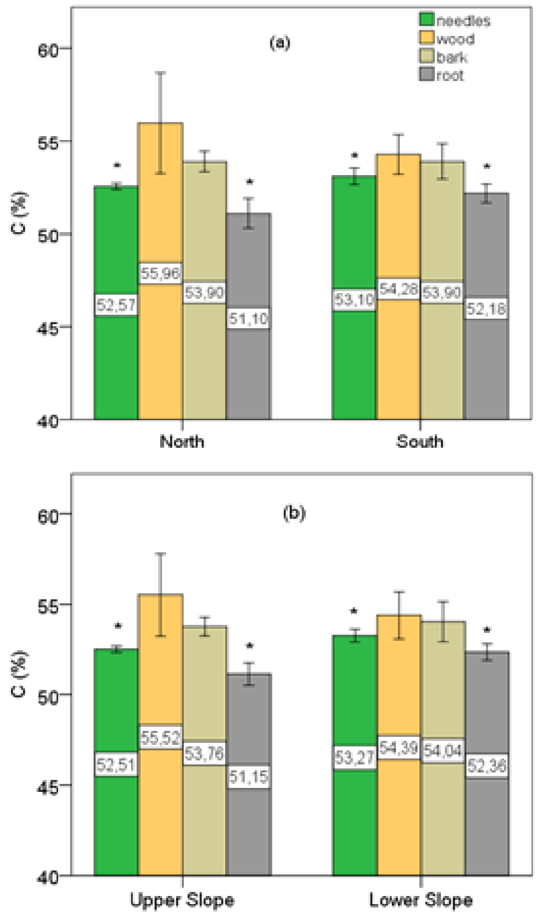

Figure 2. Changes in carbon concentration of tree components according to (a) aspects and (b) slope positions
Şekil 2. Ağaç bileşenlerinin karbon konsantrasyonundaki (a) yönlere (bakı) ve (b) yamaç konumlarına göre değişiklikler

4. Discussion and Conclusions

The highest variation in carbon concentration of the stem may arise from different heartwood and sapwood ratios and extractives. Heartwood was shown to have higher carbon content than sapwood by Herrero de Aza et al. (2011). Although extractives and heartwood-to-softwood ratio were not measured in this study, sample trees were chosen from various sites having various ecological conditions, likely leading to different biomass growth and wood properties.

Significant variation in carbon concentration among the tree components in this study, as well as earlier studies (Bert and Danjon, 2006; Çömez, 2012; Tolunay et al., 2017; Güner and Çömez, 2017;

Karataş et al., 2017; Erkan and Güner, 2018; Güner, 2019; Güner and Çömez, 2022; Tunçkol and Güner, 2022), highlights the critical role of tree components in influencing carbon dynamics within forest ecosystems. This variability can substantially affect the nutrient and carbon pools in forests, as tree components- such as leaves, branches, and roots- differ in their carbon storage capacities and decomposition rates (Sariyildiz and Anderson, 2003; Litton et al., 2007; Ma et al., 2018). Particularly, the forest floor, which comprises a mixture of organic materials such as litterfall and cutting residues, acts as a dynamic carbon reservoir. The decomposition processes on the forest floor are highly influenced by the chemical composition of these inputs, including nitrogen, lignin, and cellulose concentrations, which determine decomposition rates (Sarıyıldız, 2003; Sariyildiz and Anderson, 2003; Berg and McClaugherty, 2008).

Variability in tree components entering the forest floor can alter microbial activity and nutrient cycling, leading to spatial and temporal heterogeneity in carbon fluxes (Prescott, 2010). Consequently, changes in the quality and quantity of litterfall or harvesting residues, caused by silvicultural practices or climate change, may result in complex outcomes for carbon sequestration and ecosystem stability. This interaction between carbon dynamics and tree components underscores the need for detailed research to understand better the implications of forest management strategies on carbon storage and emissions, particularly in the context of climate change mitigation efforts (Pan et al., 2011).

In this study, the highest carbon concentration was observed in the wood, with a mean of 54.9%, which is higher than the mean of 46.5% reported by Herrero de Aza et al. (2011) for the sapwood of *P. nigra*. The lower carbon concentration in the sapwood was attributed to the generally higher carbon concentration found in heartwood compared to sapwood in pine species, noted by Herrero de Aza et al. (2011).

Unlike the study of Herrero de Aza et al. (2011), our wood samples included both sapwood and heartwood, which may explain the higher carbon content. On the other hand, Güner and Çömez (2017) reported a stem wood carbon content ranging between 52.6 and 54.1% which is very close to our results in black pine afforestation covering the Inner, western northern part of Türkiye. However, our results were higher than the stem wood carbon concentration of 52.1% which was reported by Durkaya et al. (2015) for natural black pine stands on the northern part of Türkiye with a humid climate.

The lowest carbon concentration among tree components in this study was detected in the roots, consistent with findings from previous studies (Bert and Danjon, 2006; Çömez, 2012; Tolunay et al., 2017; Güner and Çömez, 2017; Karataş et al., 2017; Erkan and Güner, 2018; Güner, 2019; Güner and Çömez, 2022; Tunçkol and Güner, 2022). However, a slightly higher root carbon concentration, with a mean of 52.6%, was reported by Güner and Çömez (2017) in a study conducted on *P. nigra* plantations in Türkiye. These variations may be explained by differences in sampling time, stand development stages, and site conditions, as highlighted in earlier studies (Erkan and Güner, 2018; Güner, 2019; Çömez, 2012; Makineci et al., 2015; Güner and Çömez, 2017; Karataş et al., 2017).

Slope position affected carbon concentration of roots, likely due to the rhizosphere properties as suggested by Zhang et al. (2023). Deeper and finer soils develop on lower slopes, which have higher content of moist conditions where tree roots can grow in larger dimensions (Day et al. 2010). In humid conditions, trees do not need more fine roots, which include a lower amount of lignin. That is why on lower slopes, roots might have coarser roots, with high lignin content and, consequently, high carbon content.

The carbon concentration in needles was higher on southern aspects compared to northern aspects. This finding aligns with the results of Yan et al. (2012), who reported greater needle carbon content on the south side of trees than on the north side. The higher carbon concentration may be attributed to increased light exposure on the southern aspects, which enhances photosynthetic capacity and leads to greater starch accumulation. Alternatively, the increase in lignin concentration in woody plant tissues under drought stress, particularly on southern aspects, may represent another explanatory mechanism, as suggested by Han et al. (2022).

In this study, the carbon concentration in stem wood was found to be higher than in other tree components. However, in contrast to our findings, several studies on coniferous species have identified bark as having the highest carbon concentration (Bert and Danjon, 2006; Çömez, 2012; Tolunay et al., 2017; Karataş et al., 2017; Erkan and Güner, 2018; Güner, 2019; Güner and Çömez, 2022; Tunçkol and Güner, 2022). This discrepancy might be attributed to the higher lignin and extractive content in bark (Güner and Çömez, 2017).

In coniferous species, the lignin content in wood typically does not exceed 30%, while in bark, it can reach up to 55%. Furthermore, the extractive content in bark can be up to three times higher than that of wood (Dönmez and Dönmez, 2013).

A study on natural black pine forests in Türkiye reported a bark carbon concentration of 51.9% (Durkaya et al., 2015), while in black pine plantations, it was found to be 54.7% (Güner and Çömez, 2017). This wide range of bark carbon concentrations (51.9%-54.7%) is likely due to differences in stand development stages, site characteristics, and forest establishment practices, indicating that natural and plantation forests should be evaluated separately.

For black pine, the needle carbon concentration was reported as 52.3% in natural forests (Durkaya et al., 2015) and 54.7% in plantation areas (Güner and Çömez, 2017). When examining needle carbon concentrations, findings from natural forests were relatively consistent, whereas values from plantations were higher than those from natural forests. This difference may stem from variations in forest establishment practices.

Studies on various tree species in Türkiye have reported the following weighted average carbon concentrations for total tree biomass: 51.96% for natural Scots pine forests (Tolunay, 2009), 52.46% (Çömez, 2012), and 52.37% (Erkan and Güner, 2018); 52.15% for Kazdağı fir (*Abies nordmanniana* subsp. *equi-trojani*) forests (Güner, 2019); 53.86% for black pine plantations (Güner and Çömez, 2017); 51.27% for Taurus cedar (*Cedrus libani*) plantations (Karataş et al., 2017); 50.32% for stone pine (*Pinus pinea*) plantations (Tolunay et al., 2017); 54.07% for natural stone pine forests (Tunçkol and Güner, 2022); and 51.77% for Turkish red pine forests (Güner and Çömez, 2022). In a study on black pine plantations in Türkiye, the weighted average carbon concentration was calculated as 54.1% for above-ground biomass and 53.8% for total tree biomass (Güner and Çömez, 2017).

The AFOLU (Agriculture, Forestry, and Other Land Use) guidelines suggest using a default carbon concentration of 51% for coniferous species in carbon inventory reporting in the absence of species-specific data (IPCC, 2006). However, we found 6% more carbon fraction than the one IPCC suggested in the present study. Our findings- as well as recent Turkish national studies- demonstrate that relying solely on stem wood values or general coefficients can lead to significant inaccuracies in carbon accounting. Incorporating component-based and weighted carbon values would improve the precision of national and project-level carbon inventories.

This study demonstrated that carbon concentrations in different tree components of *P. nigra* exhibit substantial variation, ranging between 51.75% and 54.96%. The highest values were observed in wood, while roots had the lowest carbon content. The weighted average carbon concentration was calculated as 54.68% for above-ground biomass and 54.19% for total tree biomass, suggesting that component-specific measurements offer a more accurate basis for carbon inventory assessments than generalized coefficients.

The findings highlight the importance of considering individual tree components- wood, bark, needles, branches, and roots- in carbon accounting. Variations in carbon content are not only species- and component-specific but are also influenced by environmental factors such as slope position, soil moisture, and forest establishment type (natural vs. plantation). For instance, slope-induced differences in root carbon content may stem from shifts in lignin allocation due to changing rhizosphere conditions.

The study also reveals that bark and needle carbon concentrations tend to be higher in plantation stands compared to natural forests, likely due to differences in management intensity and stand development stage (Soto-Cervantes et al. 2023; Li et al. 2024). These findings underscore the need to evaluate forest carbon stocks within their specific ecological and silvicultural contexts.

Given these insights, the adoption of component-based and site-specific carbon ratios is recommended over the use of default values, such as the 51% coefficient suggested by IPCC (2006) for conifers including *P. nigra*. Integrating such refined values into carbon budgeting and climate mitigation strategies will enhance the accuracy and credibility of national forest carbon inventories and carbon credit certification processes.

Moreover, forest management practices should aim to protect and optimize carbon-rich components, particularly bark and wood. Non-wood components like needles, often overlooked, can also contribute to long-term carbon storage through their role in litter input and nutrient cycling. Promoting the retention of organic residues (e.g., needle litter) can therefore offer co-benefits for soil fertility and carbon sequestration.

Pinus nigra forests, due to their high carbon density, hold significant potential for integration into locally adapted carbon credit projects. It is recommended that both above-ground and below-ground (root) carbon stocks be jointly considered in such initiatives. These findings support the use of black pine in afforestation efforts by the General Directorate of Forestry (ogm.gov.tr) and long-term climate policy implementation, especially in regions with similar ecological conditions.

Authors' contributions

Aydın Çömez: Study design, data collection, data analysis, interpretation of the results, writing, reviewing, and editing.

Mustafa Oğuz Soydan and Hatice Ay: Data analysis, writing, editing, and visualization.

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References

Anşin, R., Özkan, Z.C., 1993. Tohumlu Bitkiler. Karadeniz Teknik Üniversitesi, Orman Fakültesi Yayın No: 19, Trabzon

Berg, B., McClaugherty, C., 2008. Plant Litter: Decomposition, Humus Formation, and Carbon Sequestration. Springer-Verlag. Berlin- Heidelberg

Bert, D., Danjon, F., 2006. Carbon concentration variation in the roots, stem and crown of mature *Pinus pinaster* (Ait.). *Forest Ecology and Management* 222(1-3): 279-295

Çakıl, E., 2008. Zonguldak Orman Bölge Müdürlüğü Karaçam Biyokütle Tablolarının Düzenlenmesi. Zonguldak Karaelmas Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi. Zonguldak

Çömez, A., 2004. Sündiken Dağları Kütlesinin Batı Bölümünde (Çatacık İşletmesi) Hava Kirliliğinin Orman Ağaçlarına Etkisinin Yükselti ve Bakıya Göre İncelenmesi. İstanbul University, Institute of Science, Master of Science Thesis, İstanbul

Çömez, A., 2012. Sündiken Dağları'ndaki (Eskişehir) Sarıçam (*Pinus sylvestris* L.) Meşcerelerinde Karbon Birikiminin Belirlenmesi. Research Institute for Forest, Soil and Ecology Publications, Tech. Bulletin No: 2. Eskişehir

Day, S.D., Wiseman, P.E., Dickinson, S.B., Harris, J.R., 2010. Tree root ecology in the urban environment and implications for a sustainable rhizosphere. *Arboriculture & Urban Forestry*, 36(5): 193-205

Davis, P. H., 1965. Flora of Turkey and the East Aegean Islands. Volume 1, Edinburgh Univ. Press, Edinburgh

Dönmez, İ.E., Dönmez, Ş., 2013. Ağaç kabuğunun yapısı ve yararlanma imkanları. *Journal of Süleyman Demirel Üniversitesi Faculty of Forestry*, 14: 156-162

Durkaya, A., Durkaya, B., Makineci, E., Orhan, I., 2015. Aboveground biomass and carbon storage relationship of Turkish pines. *Fresenius Environmental Bulletin*, 24(11): 3573-3583

Durkaya, A., Durkaya, B., Yagci, H., 2019. Biomass equations in natural black pines. *Fresenius Environmental Bulletin*, 28(2A): 1132-1139

Ercanlı, İ., Şenyurt, M., Günlü, A., Çakır, M., Bolat, F., Bulut, S., 2023. ÇAKÜ Araştırma Ormanı karaçam meşcereleri için tek ve çift girişli toprak üstü ağaç biyokütle denklemlerinin geliştirilmesi. *Anatolian Journal of Forest Research*, 9(2): 126-134

Erkan, N., Güner, Ş.T., 2018. Determination of carbon concentration of tree components for Scotch pine forests in Türkmen Mountain (Eskişehir, Kütahya) Region. *Forestist*, 68(2): 87-92

Gözler, M.Z., Cevher, F., Ergül, E., Asutay, H.J., 1996. Orta Sakarya ve Güneyinin Jeolojisi. Mineral Research and Exploration General Directorate (MTA; mta.gov.tr). Report No: 9973, Ankara

Güner, Ş.T., Çömez, A., 2017. Biomass equations and changes in carbon stock in afforested black pine (*Pinus nigra* Arnold. subsp. *pallasiana* (Lamb.) Holmboe) stands in Turkey. *Fresenius Environmental Bulletin,* 26(3): 2368-2379

Güner, Ş.T., 2019. Changes in carbon concentration of tree components for Kazdağ fir (*Abies nordmanniana* subsp. *equi-trojani*) forests. *Fresenius Environmental Bulletin* 28(1): 116-123

Güner, Ş.T., Çömez, A., 2022. Carbon concentration in tree components of mature *Pinus brutia* Ten. forests in the Marmara transition zone. *Kastamonu University, Journal of Forestry Faculty* 22(3): 193-201

Güner, Ş. T., Özdemir, E. G., Çömez, A., Kaya, S., 2025. Bartın ve Kastamonu yöresi doğu kayını ormanlarında ağaç bileşenlerine ait karbon yoğunluklarının değişimi. *Anadolu Orman Araştırmaları Dergisi*, 11(1): 38–44. https://doi.org/10.53516/ajfr.1599059

Han, X., Zhao, Y., Chen, Y., Xu, J., Jiang, C., Wang, X., Zhou, R., Lu, M.Z., Zhang, J., 2022. Lignin biosynthesis and accumulation in response to abiotic stresses in woody plants. *Forest Research (Fayettev).* 2022. 2(1): 9. Doi: 10.48130/FR-2022-0009

Herrero de Aza, C., Turrión, M.B., Pando, V., Bravo, F., 2011. Carbon in heartwood, sapwood and bark along stem profile in three Mediterranean *Pinus* species. *Annals of Forest Science*, 68(6): 1067-1076

IPCC. 2003. Good Practice Guidance for Land Use, Land-use Change and Forestry, *In*: IGES. Penman, J., Gytarsky, M., Hiraishy, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.), IPCC/OECD/IEA/IGES, Hayama, Japan. ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html [Accessed on 17.02.2017]

IPCC, 2006. IPCC Guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme, *In*: IGES, Japan (Eds.: H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe). ipcc-nggip.iges.or.jp/public/2006gl/index.html [Accessed on 04.01.2016]

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Janzen, H.H., 2004. Carbon cycling in earth systems- A soil science perspective. *Agriculture*, *Ecosystems and Environment*, 104(3): 399-417

Kahveci, E., 2024. Samsun Yöresi Saf ve Karışık Doğal Karaçam (*Pinus nigra* Arnold. subsp. *pallasiana* (Lamb.)) Meşcerelerinin Toprak Üstü ve Toprak Altı Biyokütle ve Karbon Depolama Miktarlarının Belirlenmesi. Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Doktora Tezi. Trabzon

Kandemir, A., Mataracı, T., 2018. *Pinus* L. *In*: Güner, A., Kandemir, A., Menemen, Y., Yıldırım, H., Aslan, S., Ekşi, G., Güner, I., Çimen, A.Ö. (Ed.) Resimli Türkiye Florası 2: 324-354. ANG Vakfı, Nezahat Gökyiğit Botanik Bahçesi Yayınları. İstanbul

Karataş, R., Çömez, A., Güner, Ş.T., 2017. Sedir (*Cedrus libani* A. Rich.) ağaçlandırma alanlarında karbon stoklarının belirlenmesi. *Ormancılık Araştırma Dergisi* 4(2): 107-120

Kaymak, H., 2020. Morfo-klimatik özelliklerin Sündiken Dağları'nda (Eskişehir) bitki örtüsünün dağılışı üzerindeki etkileri. *Türk Coğrafya Dergisi*, 75: 17-32

Koray, E.Ş., Kantarcı, M.D., Çelik, N., Güner, Ş.T., Çömez, A., Karataş, R., 2012. Sündiken Dağlarındaki (Eskişehir) Sarıçam (*Pinus sylvestris* L.) Kuşağında Yetişme Ortamı Birimlerinin Belirlenmesi. Orman Toprak ve Ekoloji Araştırmaları Enstitüsü Müdürlüğü Teknik Bülten No: 3, Eskişehir

Koray, E.Ş., 2017. Türkmen Dağı Karaçam Meşcerelerinde İbre Dökümü ile Ekosisteme Giren Besin Maddesi Miktarları. İstanbul Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, İstanbul

Kurnaz, L., 2019. Son Buzul Erimeden-İklim Değişikliği Hakkında Bilmek İstediğiniz Her Şey. Doğan Egmond Yayıncılık, İstanbul

Laiho, R., Laine, J., 1997. Tree stand biomass and carbon content in an age sequence of drained pine mires in southern Finland. *Forest Ecology and Management,* 93(1-2): 161-169

Lamlom, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass and Bioenergy,* 25(4): 381-388

Li, B., Gao, G., Luo, Y., Xu, M., Liu, G., Fu, B., 2023. Carbon stock and sequestration of planted and natural forests along climate gradient in water-limited area: A synthesis in the China's Loess Plateau. *Agricultural and Forest Meteorology*, 333. https://doi.org/10.1016/j.agrformet.2023.109419

Litton, C.M., Raich, J.W., Ryan, M.G., 2007. Carbon allocation in forest ecosystems. *Global Change Biology*, 13(10): 2089-2109, Doi: 10.1111/j.1365-2486.2007.01420.x

Makineci, E., Ozdemir, E., Caliskan, S., Yilmaz, E., Kumbasli, M., Keten, A., Beskardes, V., Zengin, H., Yilmaz, H., 2015. Ecosystem carbon pools of coppice-originated oak forests at different development stages. *European Journal of Forest Research* 134(2): 319-333.

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., Fang J., 2018. Variations and determinants of carbon content in plants: a global synthesis, *Biogeosciences*, 15 (3): 693-702, Doi: 10.5194/bg-15-693-2018

Malmsheimer, R.W., Bowyer, J.L., Fried, J.S., Gee, E., Izlar, R.L., Miner, R.A., Munn, I.A., Oneil, E., Stewart, W.C., 2011. Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy. *Journal of Forestry* 109(Supplement 1). ISSN: 1938-3746

Nunes, L.J.R., 2023. The rising threat of atmospheric CO_2: A review on the causes, impacts, and mitigation strategies. *Environments*, 10: 66. Doi.org/10.3390/environments10040066

OGM, 2021. Orman Genel Müdürlüğü (ogm.gov.tr). Türkiye Orman Varlığı 2020. ISBN: 978-605-7599-68-1, Ankara

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Josep, G., Ciais, P., Jackson, R.B., Pacala, S., Mcguire, A.D., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. *Science*, 333(6045): 988-993. Doi: 10.1126/science.1201609

Prescott, C. E., 2010. Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry*, 101(1):133-149, Doi: 10.1007/s10533-010-9439-0

Saranay, S., 2017. Ankara Orman Bölge Müdürlüğü'ndeki Genç Doğal Karaçam (*Pinus nigra*) Meşcerelerinde Bitkisel Kütlenin Belirlenmesi. İstanbul Üniversitesi, Fen Bilimleri Enstitüsü. Yüksek Lisans Tezi, İstanbul

Sarıyıldız, T., 2003. Litter decomposition of *Picea orientalis*, *Pinus sylvestris* and *Castanea sativa* trees grown in Artvin in relation to their initial litter quality variables. *Turkish Journal of Agriculture and Forestry*, 27(4): 237-243

Sariyildiz, T., Anderson, J.M., 2003. Interactions between litter quality, decomposition and soil fertility: a laboratory study. *Soil Biology & Biochemistry*, 35(3): 391-399

Serengil, Y., 2018. İklim Değişikliği ve Karbon Yönetimi. Tarım/Orman ve Diğer Arazi Kullanımları. Orman Genel Müdürlüğü, Ankara

SPSS, 2015. SPSS 22.0 Guide to Data Analysis. Prentice Hall, Upper Saddle River, New Jersey, USA

Soto-Cervantes, J.A., Corral-Rivas, J.J., Domínguez-Calleros, P.A., López-Serrano, P.M., Montiel-Antuna, E., García-Montiel, E., Pérez-Luna, A., 2023. Comparison of carbon content between plantation and natural regeneration seedlings in Durango, Mexico. *PeerJ*, 11, e14774. Doi 10.7717/peerj.14774

Şenyurt, F., 2016. Taşköprü Orman İşletme Müdürlüğü Karaçam (*Pinus nigra* J.F. Arnold) Meşcereleri İçin Toprakϋstü Biyokütle Tablolarının Düzenlenmesi ve Uyumlu Biyokütle- Hacim Denklemlerinin Geliştirilmesi. Kastamonu Üniversitesi. Fen Bilimleri Enstitüsü. Yüksek Lisans Tezi, Kastamonu

Thomas, S.C., Malczewski, G., 2007. Wood carbon content of tree species in Eastern China: Interspecific variability and the importance of the volatile fraction. *Journal of Environmental Management,* 85(3): 659-662. Doi: 10.1016/j.jenvman.2006.04.022

Tolunay, D., 2009. Carbon concentration of tree components, forest floor and understory in young *Pinus sylvestris* stands in north-western Turkey. *Scandinavian Journal of Forest Research,* 24(5): 394-402

Tolunay, D., Makineci, E., Şahin, A. Özturna, A.G., Pehlivan, S., Abdelkaım, M.A., 2017. İstanbul-Durusu Kumul Alanlarındaki Sahil Çamı (*Pinus pinaster* Ait.) ve Fıstık Çamı (*Pinus pinea* L.) Ağaçlandırmalarında Karbon Birikimi. TÜBİTAK TOVAG Proje Nu: 114O797, İstanbul

Tunçkol, B., Güner, Ş.T., 2022. Determination of carbon concentration of tree components for stone pine forests in the Marmara Region. *Bartın Orman Fakültesi Dergisi,* 24(2): 315-323

Tutin, T.G., Burges, N.A., Chater, A.O., Edmondson, J.R., Heywood, V.H., Moore, D.M., Valentine, D.H., Walters, S.M., Webb, D.A., 1993. Flora Europaea. Second Edition Volume 1, Psilotaceae to Platanaceae, Cambridge University Press, Cambridge, England

Vidaković, M., 1991. Conifers Morphology and Variation. Grafički Zavod Hrvatske, Zagreb

Yan, C.F., Han, S.J., Zhou, Y.M., Wang, C.G., Dai, G.H., Xiao, W.F., Li, M.H., 2012. Needle-age related variability in nitrogen, mobile carbohydrates, and δ13C within *Pinus koraiensis* tree crowns. *PLOS ONE*, 7(4): e35076. Doi.org/10.1371/journal.pone.0035076

Zhang, Q., Zhou, Z., Zhao, W., Huang, G., Liu, G., Li, X., Wu, J., 2023. Effect of slope position on leaf and fine root C, N and P stoichiometry and rhizosphere soil properties in *Tectona grandis* plantations. *Journal of Forestry Research*, 34(6), 1997–2009. https://doi.org/10.1007/s11676-022-01582-2