Environ Monit Assess (2024) 196:639
https://doi.org/10.1007/s10661-024-12783-z

RESEARCH

The effects of thinning on carbon and nutrient fluxes input into forest floor via litterfall in black pine afforestation sites

Furkan Atalar · Şükrü Teoman Güner · Rıza Karataş · Dilek Güner · Abdullah Sarımehmetoğlu

Received: 10 February 2024 / Accepted: 6 June 2024 / Published online: 21 June 2024

Abstract As a component of the biogeochemical cycle, litterfall contributes carbon and nutrients to forest ecosystems by transferring organic material to mineral soil. Litterfall therefore serves as an important indicator for soil fertility and ecosystem health. This study aimed to determine the impact of different levels of thinning (light, moderate, and heavy) on litterfall quantity (needles, branches, bark, cones, and miscellaneous parts) and on the amount of carbon and nutrients entering the ecosystem in black pine afforestation areas. Three levels of low thinning, namely light, moderate, and heavy thinning (15%, 25%, and 35% of breast height area, respectively), were applied as treatments. Additionally, a control plot was included in the experiment. Litterfall samples were collected four times per year (once per season) from 12 treatment plots for three years. In the laboratory, dry weight measurements and analyses of carbon and macro–micro nutrient elements (N, P, K, Ca, Mg, S, Na, Fe, Cu, Zn, and Mn) were performed on litterfall samples taken from the field. Differences between treatments in terms of litterfall and the amount of carbon and nutrient elements entering the ecosystem were evaluated through variance analysis and the Duncan test. According to the findings, the quantity of litterfall input into the forest floor was highest in the control treatment, at 6,543 kg ha^{-1} $year^{-1}$ and lowest in the heavy treatment, at 4,378 kg ha^{-1} $year^{-1}$, showing a significant variation in litterfall quantity. The input of C to the soil ranged between 2,233 kg ha^{-1} $year^{-1}$ and 3,347 kg ha^{-1} $year^{-1}$ depending on thinning treatment. Although thinning treatment reduced C input to the soil, there was no significant difference among treatments. This also applied to nutrient elements such as N, P, K, Mg, and S. Needles constituted the majority of litterfall components (60%) and had the highest C density among all components, at 51.2%. The weighted carbon ratio for litterfall was calculated at 50.8%. Considering carbon-focused planning, performing moderate thinning interventions in the study area or similar pine-afforested areas may be a suitable option for maintaining the sustainability and health of the forest.

Keywords Litterfall · Thinning · Carbon · Nutrient content · Silviculture · *Pinus nigra*

F. Atalar · A. Sarımehmetoğlu
Research Institute for Forest Soil and Ecology, 26160 Eskişehir, Türkiye

F. Atalar
Institute of Graduate Studies, Istanbul University-Cerrahpaşa, 34320 Istanbul, Türkiye

Ş. T. Güner (✉)
Ulus Vocational School, Department of Forestry, Bartın University, 74600, Ulus, Bartın, Türkiye
e-mail: stguner@bartin.edu.tr

R. Karataş · D. Güner
Research Institute for Forest Soil and Ecology, 26160 Eskişehir, Türkiye

Introduction

The organic matter that falls to the forest floor, known as litterfall, plays a vital role in maintaining healthy forest ecosystems. It is a critical component of the nutrient cycle, contributing to the accumulation of soil organic matter and nutrient input and output, as well as supplementing nutrients (Caldentey et al., 2001). Additionally, litterfall helps to preserve biological diversity by providing habitat for invertebrates and fungi and other essential ecosystem functions (Giweta, 2020). By connecting the canopy of trees to the underlying soil, litter materials enrich the soil with nutrients stored within their biomass, ultimately contributing to tree growth and boosting forest productivity (Pitman, 2013). In natural ecosystems, litterfall generates a significant quantity of organic material that undergoes a recycling process back into mineral soils (Qin et al., 2019).

Approximately one-third of the annual carbon sequestration is known to occur through the intermediary of litter materials, which constitute the forest floor and are transferred to the soil (Neumann et al., 2018). Monitoring litterfall provides a means to assess the health of the forest (Tobin et al., 2006; Ukonmaanaho et al., 2020). Therefore, understanding the nutrient flows of litter in forests across different ecosystems and their temporal variation is vital for ecological restoration and forestry practices (Shen et al., 2019; Wei et al., 2012). Determining the quantity of carbon accumulated in the ecosystem is also a crucial area of research in light of global climate change (Koray & Tolunay, 2020). Forest ecosystems are becoming increasingly important for policy makers due to their potential in carbon sequestration and thus in combating climate change (Beedlow et al., 2004; Bonan, 2008). Forests play a critical role in carbon sequestration and litterfall contributes to approximately 4–6% of the total forest carbon content at both the stand and global scales (Pan et al., 2011; Rodríguez-Ortiz et al., 2012).

As stipulated by the United Nations Framework Convention on Climate Change (UNFCCC), party countries are obliged to conduct greenhouse gas inventories for agriculture, forestry, and other sectors (Agreement, 2015). In these inventories, the amount of emissions from these sectors and the amount of greenhouse gases bound in these sectors are determined. In accordance with the agreements to which Türkiye is a party, Türkiye conducts greenhouse gas inventories at the national level and reports its emissions and carbon sinks areas by sector to the United Nations. In determining the carbon budgets of forest ecosystems, the focus has mostly been on methods based on the annual amounts of organic matter such as leaves, branches, bark, cones, and so forth, and the monitoring of their decomposition rates. For this reason, determining the carbon input to the soil through litterfall is important when calculating annual carbon accumulation (Çömez et al., 2019).

To assess the sustainability of forest management, information on the effects of silvicultural practices on carbon and nutrient cycling processes is needed (Kimmins, 2004). This is because silvicultural interventions that affect forest canopy density are thought to reduce the amount of litterfall and nutrients reaching the soil (Blanco et al., 2008). Depending on the intensity of these practices and the duration of the rotation period, they have been reported to lead to a long-term decrease in soil nutrient availability (Blanco et al., 2005).

Pinus nigra Arnold subsp. *pallasiana* (Lamb.) Holmboe (black pine) covers an area of 4,077,616 ha in Türkiye and has a 34.8% share in the distribution of coniferous species (GDF, 2022). It is the second most important pine species after *Pinus brutia* Ten. (Calabrian pine) in terms of distribution area and wood production and is widely used in afforestation works. In Türkiye, forestry practices for timber production are predominantly carried out in naturally growing areas and no action is taken to preserve or maintain the productivity of the site. Studies on how silvicultural practices in forest ecosystems affect the quantity and nutrient content of litterfall components are also scarce. Research on litterfall has been conducted according to stand type, in commercially important tree species and in natural forests (Çakır & Akburak, 2017; Çömez et al., 2019, 2021; Erkan et al., 2018, 2020; Kara et al., 2014; Kiracıoğlu et al., 2023; Koray & Tolunay, 2020; Kutbay & Horuz, 2001; Tüfekçioğlu et al., 2005). Studies investigating the effects of different thinning intensities on litterfall quantity have been carried out in various tree species, both in Europe and other parts of the world (Baek et al., 2022; Blanco et al., 2006a; Jiménez & Navarro, 2016; Kim, 2016; Lado-Monserrat et al., 2016; Navarro et al., 2013; Pérez-Alavez et al., 2021; Roig et al., 2005; Sarıyıldız et al., 2023; Segura et al., 2017). However, there is a lack of knowledge on the effect of different thinning intensities on litterfall quantity in black pine afforestation sites in Türkiye.

This study aimed to determine the impact of various thinning intensities on the amount of litterfall and the amount of carbon and nutrients entering the forest floor in areas afforested with black pine in Türkiye.

Materials and methods

Study area

The study was carried out between 2018 and 2021 in black pine plantations established in 1970 in Akdağ National Park (36.0239625–36.4250973° N and 36.0239725–36.4250873° E) located in the Central-Western Anatolia Region of Türkiye (Fig. 1). The elevation of the study area is 1,495 m above sea level.

The bedrock of the study area is sericite schist and the soil type is brown forest soil (Cambisol) (IUSS Working Group WRB, 2006). The shrub species found in the study area were *Juniperus oxycedrus* subsp. *oxycedrus* L., *Rosa canina* L., *Crataegus monogyna* subsp. *monogyna* Jacq., and *Berberis crataegina* DC. (Güner et al., 2016).

Annual total precipitation is 677 mm, annual average temperature is 8.4 °C, and annual average maximum temperature is 24.3 °C for the study area (GDM, 2022). According to the Thornthwaite method, the climate of the study area is humid, mesothermal, and has a large water deficit in summer (climate type B1 B1´ s2 b3´). Meteorological data were obtained from the meteorological station (1,490 m altitude) located in Akdağ National Park, 1 km from the experimental area.

Fig. 1 Location of the study area

Experimental design and sampling procedure

The study administered light, moderate, and heavy low thinning as treatments and included a control plot. The experiment was conducted in three replications with plot sizes of 20×20 m. Dendrometric measurements were performed in each plot as a prerequisite to the silvicultural operations. The treatment plots underwent interventions resulting in the removal of 15%, 25%, and 35% of the basal area in the light, moderate, and heavy treatments, respectively. Buffer areas of 10 m in width were left between the experimental plots, in which moderate treatment was applied. The research site comprised 12 treatment plots, within which we installed 60 traps (5 per plot) to capture litterfall material (needles, twigs, bark, cones, etc.) and estimate litterfall quantities in the experimental plots. These traps consisted of 0.5×0.5 m frames with 0.5 mm mesh polyester netting and were situated about 1 m above the ground level.

Litterfall materials were collected on the last day of each season, consisting of three-monthly periods (December to February, March to May, June to August, September to November) to adequately represent each season. The sampling was maintained for three years, from December 2018 to November 2021. This process yielded 720 litterfall materials acquired from a combination of treatments, replicates, seasons, and components (4 treatments × 3 replicates × 4 seasons × 3 years × 5 components = 720 samples).

Laboratory analysis

The litterfall material samples were collected from the field and brought to the laboratory, where they were separated into their components: needles, twigs, bark, cones, and other parts called as miscellaneous which included flowers, buds, resins, seeds, etc. The samples were dried at 65 °C to constant weight (approx. 24 h) and then weighed to determine mass. For the analysis, samples of litterfall collected from 5 traps in each treatment plot were merged to create a single combined sample for that particular treatment plot. The C content in the litterfall samples was analyzed using the dry combustion method by the LECO CNH elemental analyzer (Leco Corporation, St. Joseph, MI, USA), and N was determined using the Kjeldahl method (Foss Tecator, 2014) by the FOSS 8400. The S content was analyzed using the turbidimetric method and Na and K content was measured with a Jenway PFP 7 flame photometer. The Ca, Mg, Fe, Cu, Zn, and Mn content was determined with a Shimadzu 6601-F atomic absorption spectrometer (Kacar & İnal, 2008). Analyses were performed separately for each component of the litterfall material and for the periods of collection.

Data analysis

Seasonal changes in litterfall were assessed by collecting litterfall during each season. The annual litterfall was determined by calculating the average of litterfall amounts obtained in 2019, 2020, and 2021. The quantity of carbon and nutrients in the traps was determined by multiplying the litterfall collected in the traps in the sampled areas by the respective concentrations (%) of carbon and nutrients from the laboratory analysis. The calculated values were then converted to hectares using the hectare conversion factor to estimate the amount of litterfall in one hectare and thus the amount of carbon and nutrients added to the forest floor.

A specific Eq. (1) from Erkan and Güner's (2018) study was applied to determine the weighted carbon and nutrient densities of total litterfall for black pine plantations:

$$wcc = \sum_{i=1}^{5} \frac{(ccc_i * cb_i)}{100} \tag{1}$$

where *wcc* is the weighted carbon and nutrient content of total litterfall (%), ccc_i is the carbon and nutrient concentration (%), *i* is the associated litterfall component, and cb_i is the ratio of component mass to total litterfall mass (%).

Equation (2) was used to calculate the aboveground biomass of the trees in the experimental areas. The root biomass was determined using a root/shoot ratio of 0.179 and Eq. (3) was used to calculate the total tree biomass (Güner & Çömez, 2017). The values obtained were converted to hectares and the tree biomass in an area of one hectare was determined.

$$AGB = 4.9953 \times 1.1560^{dbh} \left(\mathrm{R}^2 = 0.952,\ \mathrm{SE} = 0.300\right) \tag{2}$$

$$TB = 5.9275 \times 1.1556^{dbh} \left(\mathrm{R}^2 = 0.951,\ \mathrm{SE} = 0.300\right) \tag{3}$$

where *AGB* is above-ground tree biomass (kg/tree), *TB* is total tree biomass (kg/tree), *dbh* is diameter at breast height (cm), R^2 is the coefficient of determination, and SE is the standard error.

The differences between treatments in terms of the amount of litterfall components, carbon and nutrient concentrations, and the amount of carbon and nutrients entering the forest floor, and the differences between sampling periods and sampling years in terms of the amount of litterfall, were evaluated by an analysis of variance (ANOVA). If significant differences were found as a result of the ANOVA, Duncan's test was applied, and similar groups were identified. The correlation analysis examined the relationship between stand characteristics and the amount of litterfall. Results showed a statistically significant difference at the $\alpha = 0.05$ level. Statistical analysis was performed using the SPSS software package (SPSS, 2015).

Results and discussion

Stand characteristics

Five years after implementing the thinning treatments, significant differences ($P < 0.05$) were found between treatments in terms of the number of trees, basal area, above-ground biomass, root biomass, and total biomass, while no significant differences ($P > 0.05$) were found in terms of stand average diameter and height. The number of trees, basal area, above-ground biomass, root biomass, and total biomass were highest in control plots and lowest in the heavy treatment plots (Table 1).

Relationship between litterfall and stand and climate characteristics

The relationships between the amount of litterfall components and stand and climatic characteristics are given in Table 2. A positive correlation was found at the 0.01 significance level between the quantity of litterfall components (needles, branches, bark, miscellaneous, and the total litterfall) and stand characteristics (basal area, volume, and above-ground biomass). In the correlation analysis in which litterfall components and climatic characteristics were analysed, a negative correlation at a 0.01 significance level was only found between the amount of needles and total precipitation, while insignificant correlation was found between maximum temperature, minimum temperature, and average temperature. No significant correlation was found between the amount of branches and climatic characteristics. Positive correlations were found between the amount of bark and other climatic characteristics (except for total precipitation) at a 0.01 significance level. The litterfall components, cones, miscellaneous material, and total litterfall quantity were negatively correlated with total precipitation and positively correlated with other climatic characteristics (Table 2).

We determined that the accumulation of forest floor was higher in black pine plantation areas with no thinning treatment (control) than in areas with treatment applied (light, moderate, and heavy) and found a positive correlation between basal area and the amount of annual accumulation of forest floor. Basal area is the main indicator of biomass

Table 1 Changes in stand characteristics according to treatments five years after thinning (Mean ± SE)

Stand characteristics	Thinning treatments				F values	P
	Control	Light	Moderate	Heavy		
Stand age (year)	52	52	52	52		
Average diameter (cm)	28.5 ± 0.8**a**	30.5 ± 1.1**a**	30.6 ± 0.6**a**	30.8 ± 1.5**a**	1.030	0.429
Average height (m)	17.1 ± 1.1**a**	17.5 ± 0.8**a**	17.2 ± 0.2**a**	16.7 ± 1.5**a**	0.132	0.938
Number of trees (tree ha^{-1})	858 ± 41.6**c**	600 ± 75**b**	492 ± 50.7**ab**	408 ± 8.3**a**	15.303	0.001
Basal area (m^2 ha^{-1})	55.7 ± 3.3**c**	43.9 ± 3.4**b**	36.6 ± 2.4**ab**	31.2 ± 2.4**a**	13.291	0.002
AGB (Mg ha^{-1})	353.4 ± 26.7**b**	314.6 ± 16.3**ab**	255.1 ± 11.9**a**	230.7 ± 40.8**a**	4.475	0.040
Root biomass (Mg ha^{-1})	63.3 ± 4.8**b**	56.3 ± 2.9**ab**	45.7 ± 2.1**a**	41.3 ± 7.3**a**	4.475	0.040
Total tree biomass (Mg ha^{-1})	414.8 ± 31.3**b**	369.1 ± 19.0**ab**	299.3 ± 14.0**a**	270.6 ± 47.8**a**	4.504	0.039

AGB above-ground biomass. Data are presented as the mean value ± standard error. The same letters in the rows indicate similar groups with no significant difference (*P* > 0.05). *P*: significance level

Table 2 Correlation coefficients and significance levels of the relationships between litterfall components and stand and climate characteristics

Stand and climate characteristics	Litterfall components (kg ha^{-1})					
	Needles	Branches	Bark	Cones	Miscellaneous	Total
Basal area (m^2 ha^{-1})	0.662**	0.540**	0.681**	0.075^{ns}	0.573**	0.467**
Volume (m^3 ha^{-1})	0.633**	0.551**	0.712**	0.091^{ns}	0.575**	0.465**
AGB (Mg ha^{-1})	0.589**	0.492**	0.560**	0.068^{ns}	0.582**	0.420*
Max. temperature (°C)	0.108^{ns}	-0.055^{ns}	0.279**	0.338**	0.504**	0.358**
Min. temperature (°C)	0.117^{ns}	-0.058^{ns}	0.314**	0.323**	0.460**	0.354**
Average temperature (°C)	0.094^{ns}	-0.055^{ns}	0.342**	0.352**	0.514**	0.360**
Total rainfall (mm)	-0.301**	-0.004^{ns}	-0.091^{ns}	-0.187*	-0.221**	-0.393**

AGB above-ground biomass, ns not significant, *: $P<0.05$, **: $P<0.01$

per unit area and increases in basal area per hectare lead to an increase in the amount of litterfall (Güner & Güner, 2021; Kiracıoğlu et al., 2023). Likewise, in Türkiye, Erkan et al. (2018) found significant relationships ($R^2=0.7583$) between stand basal area and litterfall for Calabrian pine. In other words, the total amount of litterfall decreased with the removal of above-ground biomass from the area and similar results were obtained in previous studies on different tree species (Blanco et al., 2006b; Novák & Slodičák, 2006; Roig et al., 2005). Furthermore, Clark et al. (2001) reported that in tropical forests, significant positive relationships were found between above-ground tree mass and the amount of annual litterfall. In the study conducted by Koray & Tolunay, (2020) in black pine forests, the relationship between above-ground tree mass and the amount of litterfall was $R^2=0.4071$, while this value was $R^2=0.1764$ in our study. In our study, we found a negative correlation between total litterfall and precipitation and a positive correlation between total litterfall and average temperature, which is in line with the values reported by Erkan et al. (2018). This can be explained by the combined effect of temperature and precipitation on litterfall. In other words, higher temperatures trigger litterfall, while higher precipitation reduces it. A relative increase in temperature and a relative decrease in precipitation together lead to litterfall increase. Drought stress may be the main reason behind the effect of temperature on litterfall.

Effect of thinning on litterfall quantity

Thinning treatments of varying intensity resulted in significant differences ($P<0.05$) in the amounts of litterfall components (except for cones). The heavy treatment plots recorded the lowest total litterfall of 4,378 kg ha^{-1} year^{-1}, while the control plots had the highest total litterfall, at 6,543 kg ha^{-1} year^{-1}. It was evident that the overall litterfall decreased with increasing thinning intensity. The control treatment plot had the highest amount of needle drop, while the treatment plots with heavy thinning had the lowest. Branch drop was most prevalent in the control treatment plots and least prevalent in the moderate treatment plots. There were significant differences in bark drop between the control treatment and the heavy and moderate treatments. The amount of cones did not differ significantly among treatments ($P>0.05$). The difference in litterfall of miscellaneous parts among the control, light, and heavy treatments was significant. Significant differences were found only between the control and heavy treatment plots ($P<0.05$) when comparing the total amount of litterfall among treatments. Needles showed the highest presence of all the litterfall components in all treatment plots, comprising 64%, 58%, 60%, and 58% of total litterfall material in the control, light, moderate, and heavy treatment plots, respectively (Table 3).

The basal area of the remaining stand after thinning manipulations ranged from 31.2 m^2 ha^{-1} to 55.7 m^2 ha^{-1}. In a study conducted by Lado-Monserrat

Table 3 Changes in annual litterfall by components according to the thinning treatments [Mean ± SE (%)]

Thinning	Litterfall components (kg ha^{-1} year^{-1})					
	Needles	Branches	Bark	Cones	Miscellaneous	Total
Control	4180 **b** ± 297 (63.9)	243 **b** ± 82 (3.7)	294 **b** ± 46 (4.5)	1179 **a** ± 356 (18.0)	644 **b** ± 63 (9.9)	6543 **b** ± 691
Light	3346 **a** ± 283 (57.9)	143 **ab** ± 41 (2.5)	194 **ab** ± 35 (3.4)	1447 **a** ± 505 (25.1)	641 **b** ± 35 (11.1)	5773 **ab** ± 810
Moderate	2900 **a** ± 290 (59.8)	41 **a** ± 12 (0.8)	146 **a** ± 29 (3.0)	1226 **a** ± 345 (25.3)	535 **ab** ± 43 (11.1)	4849 **ab** ± 633
Heavy	2530 **a** ± 198 (57.8)	98 **ab** ± 26 (2.2)	135 **a** ± 29 (3.1)	1135 **a** ± 412 (25.9)	479 **a** ± 35 (11.0)	4378 **a** ± 587
F values	6.908	3.133	3.640	0.114	3.185	1.977
P	< 0.01	< 0.05	< 0.05	> 0.05	< 0.05	< 0.05

Data are presented as the mean value ± standard error and (%) values show litterfall components in total litterfall. The same letters in the columns indicate similar groups with no significant difference ($P > 0.05$)

et al. (2016), an examination of litterfall in Aleppo pine (*Pinus halepensis* Mill.) showed that the total litterfall (excluding miscellaneous parts) was 2,057 kg ha^{-1} year^{-1} in the area where 60% thinning was applied and 2,912 kg ha^{-1} year^{-1} in the control, which was less than the litterfall in the control and heavy treatment plots in our study. The variability in the amount of litterfall may be due to differences in the intensity of treatments applied to the stands and the number of trees per hectare following manipulation. Kim (2016) conducted a study on Japanese red pine (*Pinus densiflora* Sieb. & Zucc.) that showed that as basal area increased, the amount of needles, bark, and total litterfall also increased, consistent with our findings. In our study, the quantity of branches and miscellaneous materials, such as flowers, seeds, and resin, increased as the basal area increased, but the quantity of cones showed no significant difference. This finding can be attributed to the possibility that the cone component is more susceptible to climatic events, such as storms or heavy winds, than the basal area. According to a research carried out in Spain, the impact of thinning on litterfall may vary between study sites depending on the intensity of thinning (Blanco et al., 2006a). Additionally, a study conducted in Türkiye found that the effect of thinning treatments on litterfall was more significant in mature stands than in overmature stands (Çömez et al., 2019). Various researchers have found that there is an annual litterfall rate ranging from 1,760 kg ha^{-1} to 4,100 kg ha^{-1} in stands of Scots pine (*Pinus sylvestris* L.) with a basal area ranging from 35 m^2 ha^{-1} to 65 m^2 ha^{-1} (Pausas, 1997; Santa Regina & Gallardo, 1989). Kim's (2016) study on Japanese red pine with basal area ranging from 21.4 m^2 ha^{-1} to 46.7 m^2 ha^{-1} reported a total litterfall rate ranging from 2,910 kg ha^{-1} year^{-1} to 4,528 kg ha^{-1} year^{-1}. Baek et al. (2022) found that total litterfall ranged from 3,653 kg ha^{-1} year^{-1} to 5,638 kg ha^{-1} year^{-1} in Japanese red pine with and without thinning (Basal area: 29 m^2 ha^{-1} and 42.5 m^2 ha^{-1}), respectively. In comparison to our findings, the amount of average annual litterfall obtained in both studies on Japanese red pine was found to be lower. According to Zhang et al. (2014), the annual litterfall amount varies between 3,000–11,000 kg ha^{-1} year^{-1} depending on the forest ecosystem type. The difference in the amount of litterfall in the studies can also be explained by the variability of forest types, forest management practices, and tree species (Erkan et al., 2020). Çakır and Akburak (2017) also noted that litterfall quantities can differ depending on the biome and specific location. However, in a distinct investigation conducted at an alternative site within a black pine forest, Çakır et al. (2023) documented the needle drop quantity as 2,484 kg ha^{-1} year $^{-1}$. This finding aligns with the observed needle drop quantity in corresponding stands, as evidenced by our study, which recorded a respective value of 2,530 kg ha^{-1} year $^{-1}$.

In our study, we found that black pine litterfall material was composed of 60% needles, 2% branches, 4% bark, 23% cones, and 11% miscellaneous litterfall types (Fig. 2). Needles were identified as the most prevalent litterfall component,

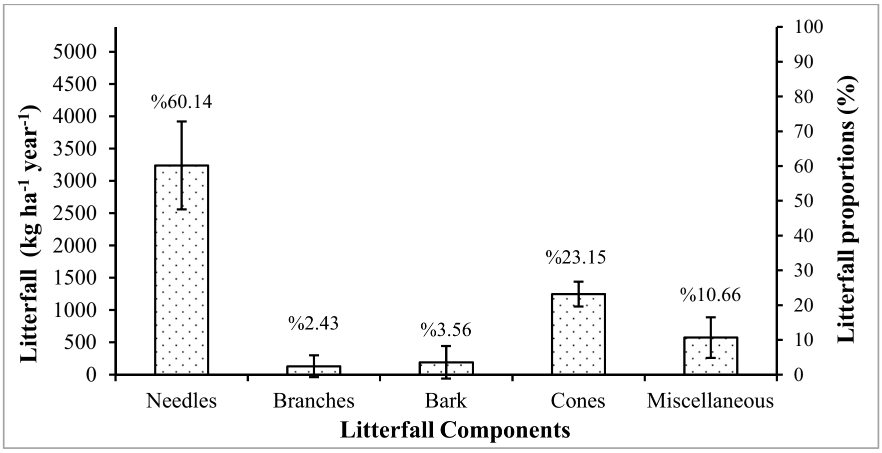

Fig. 2 Distribution of litterfall components in total litterfall (error bars indicate standard error)

representing for 60% of total litterfall, which is lower than the world average of 70% (Meentemeyer et al., 1982). Koray and Tolunay (2020) found that the fraction of needles in the total litterfall material in black pine was 53%, cone fraction 25%, and the miscellaneous fraction 11%; similar results were obtained in our study. In Aleppo pine, the proportion of needles to the total litterfall varied between 50–77% (García-Plé et al., 1995; Jiménez & Navarro, 2016). Erkan et al. (2020) found that the ratios of needles, branches, bark, cones, and miscellaneous materials were 71.4, 4.0, 9.1, 3.5, and 12.1% of the total litterfall, respectively, in a study of Calabrian pine. The needle ratios reported in these studies are effective in understanding and analyzing total litterfall. Additionally, variations in the ratios of litterfall components among species can be clarified by differences in genetic characteristics and growing conditions of the species.

Quantity of litterfall components across seasons

Significant differences in the amounts of litterfall components ($P < 0.001$) were observed during the sampling periods. The highest amount of litterfall was recorded in the fall season, at 1,942 kg ha^{-1} and the lowest amount of litterfall was determined in winter, at 952 kg ha^{-1} (Table 4). The total amount of litterfall components varied significantly between the fall and summer seasons and the winter and spring seasons. When analyzing the total amount of needle litterfall across seasons, it was determined that the highest amount occurred during the fall, while the lowest in spring. Significant differences in the branch

Table 4 Changes in litterfall by components according to the seasons [Mean ± SE (%)]

Seasons	Litterfall components (kg ha^{-1})					
	Needles	Branches	Bark	Cones	Miscellaneous	Total
Winter	716.8 **b** ± 60.1 (75.3)	38.1 **a** ± 7.3 (4.0)	40.5 **a** ± 3.3 (4.3)	56.3 **a** ± 14.3 (5.9)	100.7 **a** ± 8.7 (10.5)	952.0 **a** ± 75.3
Spring	132.9 **a** ± 12.1 (16.0)	28.7 **a** ± 6.7 (3.4)	33.3 **a** ± 4.1 (4.0)	494.2 **b** ± 93.2 (59.4)	142.8 **b** ± 10.8 (17.2)	831.7 **a** ± 108.4
Summer	674.3 **b** ± 53.2 (40.6)	28.2 **a** ± 10.3 (1.7)	86.3 **b** ± 11.5 (5.2)	627.5 **b** ± 99.6 (37.8)	243.8 **c** ± 16.1 (14.7)	1660.1 **b** ± 136.8
Fall	1715.7 **c** ± 94.6 (88.3)	36.7 **a** ± 12.1 (1.9)	32.4 **a** ± 5.2 (1.7)	69.8 **a** ± 17.9 (3.6)	87.7 **a** ± 6.4 (4.5)	1942.3 **b** ± 118.9
F values	111.935	0.307	14.167	17.884	40.849	23.111
P	< 0.001	> 0.05	< 0.001	< 0.001	< 0.001	< 0.001

Data are presented as the mean value ± standard error and (%) values show litterfall components in total litterfall. The same letters in the columns indicate similar groups with no significant difference (P > 0.05) component were observed across seasons. Similarly, significant differences were found in the bark component when comparing summer to other seasons. The amount of cones that fell during spring and summer was significantly higher than during other seasons. A comparison between the amounts of miscellaneous litterfall components according to the seasons (Table 4), indicates that the summer season had the highest litterfall amount, while the fall season had the lowest.

According to the seasonal results of litterfall in our study, the majority of litterfall occurred in the fall season (Table 4). Similar findings have been obtained for different tree species. For instance, the greatest quantity of litterfall was observed in smooth-bark Mexican pine (*Pinus pseudostrobus* Lindl.) during October–November (Pérez-Alavez et al., 2021), in Scots pine during September–October (Blanco et al., 2006a), and in maritime pine (*Pinus pinaster* Aiton) from August-October (Roig et al., 2005). However, seasonal litterfall patterns have shown varying results between different pine species. Scots pine exhibited litterfall between July and September (Bueis et al., 2017), while Aleppo pine exhibited it between August and September (Bueis et al., 2017; Jiménez & Navarro, 2016; Navarro et al., 2013). Mexican pine nut (*Pinus cembroides* Zucc.) demonstrated litterfall during June (Pérez-Suárez et al., 2009) and smooth-bark Mexican pine demonstrated it in April and May (González-Rodríguez et al., 2019). It is posited that the seasonal variation in litterfall by species may be due to differences in the study area or species-specific differences, even if species are located within the same general climate type (Pérez-Alavez et al., 2021). In temperate regions of the northern hemisphere, particularly in Europe and the Mediterranean climate zone, studies indicate that the summer season leads to an increased amount of litterfall. This is attributed to the drought-induced water stress period, which accelerates the fall of older needles in particular (Pausas, 1997; Zhang et al., 2014). Additionally, Çepel et al. (1988) observed that a significant proportion of litterfall occurs in the summer season due to high temperatures. However, proximity to higher elevation zones in our study area may have resulted in the highest amount of litterfall occurring during the fall season due to the end of the vegetation period and reduced water delivery to the trees. It is thought that the higher amount of cone fall in spring and summer may be related to the fact that black pine seeds mature in November–December and drop their seeds in February-May.

Over three years, our findings indicated that litterfall reached its peak during the fall of 2021, summer of 2021, and fall of 2019. In contrast, the lowest levels of litterfall occurred during the spring of 2020, winter of 2019, and spring of 2019 (Fig. 3). We assume that the variation in litterfall between seasons and years is a result of differences in soil quality, precipitation, and temperature recorded in the study area at those times.

Quantity of litterfall components across years

Significant differences were found in the quantities of litterfall components between the years in which samples were taken ($P < 0.001$). The highest amount of litterfall was recorded in 2021, at 7,712 kg ha^{-1}, while

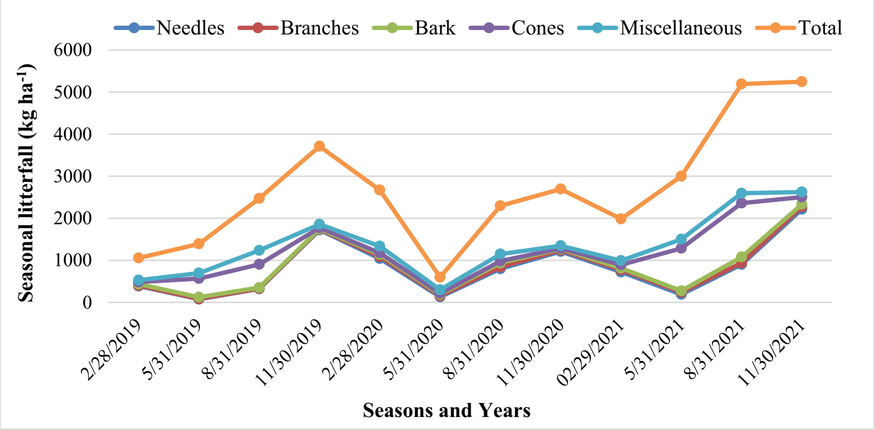

Fig. 3 Seasonal litterfall amounts by components

the lowest was recorded in 2020, at 4,130 kg ha^{-1}. We found that the total amount of litterfall showed a significant difference in 2021 compared to the 2019 and 2020 values. Regarding the quantity of needles in the total litterfall material between the years, the highest amount of needles was recorded in 2021, at 4,030 kg/ha and the lowest amount in 2019, at 2,507 kg/ha (Table 5).

There was a significant difference in the amount of litterfall by components between years ($P<0.05$). Previous studies also reported that the amount of litterfall generally showed significant differences between years (Çömez et al., 2019; Lado-Monserrat et al., 2016; Starr et al., 2005). Our study found that the increase in total litterfall and needle drop between 2019 and 2021 was similar to that in the studies conducted by Çömez et al. (2019) and Lado-Monserrat et al. (2016). The observed increase in total litterfall and needle drop over the years is hypothesized to be a result of increased light exposure due to the opening of the stand canopy. Additionally, higher biomass and needle production may also be contributing factors. Furthermore, despite the decrease in annual precipitation from 2019 to 2021, the observed increase in litterfall during the same period can be attributed to the significant negative correlation between annual precipitation and litterfall (Table 2).

Carbon and nutrient concentrations

Significant differences were detected in carbon and nutrient concentrations between the litterfall components ($P<0.001$). Notably, the needle material revealed the highest concentrations of C and Mn, the miscellaneous materials the lowest concentrations of C, and the cones the lowest concentrations of Mn among the litterfall components. Additionally, the cone material produced the highest concentration of K, while the bark material produced the lowest concentration of K. The concentrations of Ca and Na were highest in branches and lowest in cones. The miscellaneous materials had the highest concentrations of N, P, Mg, S, Fe, Cu, and Zn. Bark had the lowest concentrations of N, P, Mg, S, and Zn, while cones and branches had the lowest concentrations of Fe and Cu (Table 6).

A study investigating the entry of carbon into the forest floor via litterfall in Scots pine revealed that the carbon content in needles (51.6%), branches (51.5%), and miscellaneous (49.9%) was higher compared to our findings, while it was lower in cones (49.5%) and similar in bark (49.7%) (Çömez et al., 2019).

The concentrations of carbon in needles determined for black pine were in accordance with the findings of studies conducted on Calabrian pine by Erkan et al. (2020), Aleppo pine by Bueis et al. (2018), and Scots pine by Çömez et al. (2019). In two separate studies on Aleppo pine, the carbon concentration in needles was reported as 48.6% and 53.7% (Lado-Monserrat et al., 2016; Segura et al., 2017); in our study, the carbon concentration of black pine needles fell within this range. Furthermore, the carbon concentrations of miscellaneous materials for black pine were found to be lower compared to Aleppo pine (50.5–52.5%) and Calabrian pine (52.5%) (Erkan et al., 2020; Lado-Monserrat et al., 2016). It is emphasized that the composition of chemicals such as lignin can vary among tree species, leading

Table 5 Changes in litterfall by components according to the years [Mean ± SE (%)]

Years	Litterfall components (kg ha^{-1})					
	Needles	Branches	Bark	Cones	Miscellaneous	Total
2019	2507 **a** ± 182 (58.1)	43 **a** ± 13 (1.0)	109 **a** ± 19 (2.5)	1070 **b** ± 194 (24.8)	585 **b** ± 40 (13.6)	4315 **a** ± 304
2020	3181 **b** ± 250 (77.0)	152 **ab** ± 60 (3.7)	198 **b** ± 34 (4.8)	125 **a** ± 30 (3.0)	472 **a** ± 27 (11.5)	4130 **a** ± 352
2021	4030 **c** ± 246 (52.3)	199 **b** ± 41 (2.6)	270 **b** ± 34 (3.5)	2545 **c** ± 247 (33.0)	666 **b** ± 43 (8.6)	7712 **b** ± 510
F values	11.143	3.525	7.229	44.599	6.761	25.542
P	< 0.001	< 0.05	< 0.01	< 0.001	< 0.01	< 0.001

Data are presented as the mean value ± standard error and (%) values show litterfall components in total litterfall. The same letters in the columns indicate similar groups with no significant difference ($P>0.05$)

Table 6 Changes in carbon and nutrient concentrations according to litterfall components (% and ppm ± SE)

Elements	Litterfall components					F values	P	Weighted
	Needles	Branches	Bark	Cones	Miscellaneous			
C (%)	51.2 **d** ± 0.2	50.3 **bc** ± 0.3	49.8 **ab** ± 0.2	50.5 **c** ± 0.4	49.5 **a** ± 0.1	10.866	< 0.001	50.75
N (%)	0.53 **b** ± 0.01	0.55 **b** ± 0.02	0.38 **a** ± 0.02	0.57 **b** ± 0.04	1.16 **c** ± 0.05	116.804	< 0.001	0.60
P (ppm)	579 **bc** ± 13	447 **b** ± 18	254 **a** ± 5	728 **c** ± 68	1437 **d** ± 89	78.614	< 0.001	690
K (ppm)	2675 **c** ± 87	1118 **b** ± 81	747 **a** ± 27	4080 **e** ± 255	3099 **d** ± 128	112.978	< 0.001	2937
Ca (ppm)	8583 **d** ± 197	11,268**e** ± 477	7682 **c** ± 72	1475 **a** ± 144	6129 **b** ± 190	183.819	< 0.001	6704
Mg (ppm)	1263 **c** ± 23	971 **b** ± 31	764 **a** ± 26	755 **a** ± 30	1354 **d** ± 31	96.935	< 0.001	1129
S (ppm)	502 **c** ± 10	520 **c** ± 18	313 **a** ± 8	447 **b** ± 26	756 **d** ± 25	81.644	< 0.001	510
Na (ppm)	35 **b** ± 2.2	51 **d** ± 3.6	44 **c** ± 2.4	26 **a** ± 1.8	51 **d** ± 1.8	18.652	< 0.001	35
Fe (ppm)	276 **b** ± 5	608 **c** ± 30	639 **c** ± 13	166 **a** ± 12	997 **d** ± 32	241.670	< 0.001	348
Cu (ppm)	6.9 **a** ± 0.3	14.3 **b** ± 0.9	14.8 **bc** ± 0.7	16.3 **c** ± 1.0	19.5 **d** ± 0.6	57.580	< 0.001	11
Zn (ppm)	41 **b** ± 0.6	42 **b** ± 1.5	32 **a** ± 0.8	34 **a** ± 1.8	64 **c** ± 1.4	130.598	< 0.001	42
Mn (ppm)	470 **e** ± 8.7	186 **c** ± 5.7	129 **b** ± 6.0	46 **a** ± 2.8	261 **d** ± 8.5	473.313	< 0.001	330

Data are presented as the mean (%) and ppm value ± standard error. The same letters in the rows indicate similar groups with no significant difference (*P* > 0.05)

to differences in the carbon content of their litterfall components (Çömez et al., 2019).

Within the scope of this study, carbon ratios based on litterfall components were determined to calculate the amount of carbon in the total litterfall. Taking into account the proportions of litterfall components in the total litterfall, the weighted carbon ratio for black pine afforestation sites was determined as 50.75%. Weighted ratios were also calculated separately for other macro–micro nutrient elements (Table 6). Erkan et al. (2020) and Kiracıoğlu et al. (2023) reported weighted carbon ratios of 51.6% for Calabrian pine and 50.3% for Oriental beech (*Fagus orientalis* Lipsky). The difference in carbon ratios in these studies is thought to stem from variations in growth environment characteristics.

In our study, the concentration values of macronutrients in needles were ordered Ca > N > K > Mg > P, which is consistent with a similar study on Aleppo pine (Lado-Monserrat et al., 2016). In the study conducted by Blanco et al. (2008) on Scots pine, the highest concentrations of the macronutrients N, P, K, Ca, and Mg were found in miscellaneous parts, followed by the needles. When comparing these results to ours, we found that N, P, and Mg were highest in the miscellaneous parts of black pine litterfall but, unlike Blanco et al. (2008), the highest concentrations of K and Ca were found in the cones and branches, respectively. Klemmedson et al. (1990) conducted a study on the ponderosa pine (*Pinus ponderosa* Laws.) and discovered lower concentrations of C, Ca, and K and higher concentrations of N, P, S, Mg, and Na in the branches compared to our results. In our study, the concentrations of N, P, Mg, and K in the miscellaneous litterfall were found higher compared to those reported in the study by Klemmedson et al. (1990). In their study on *Nothofagus antarctica* (G. Forst.) Oerst., Bahamonde et al. (2015) found that the branches and needles in the litterfall material had higher N content (0.79% and 0.76%, respectively) than that in our study and similar N content in the miscellaneous fraction (1.15%). In addition, the values of P (1,450 ppm), Ca (10,291 ppm), S (820 ppm), and Mg (2,220 ppm) in the needles were higher than in our study, while the K content (2,675 ppm) in the needles was similar. The analysis of the nutrient content of the branches (P = 646 ppm, K = 2,802 ppm, Ca = 12,210 ppm, S = 517 ppm, Mg = 1,115 ppm) and of the miscellaneous parts (P = 957 ppm, K = 3,300 ppm, Ca = 10,421 ppm, S = 710 ppm, Mg = 1,070 ppm) showed a similar nutrient composition to our study.

In black pine, the N concentrations measured in the needles were 0.53%, which was consistent with the result (0.52%) from Erkan et al.'s (2020) study on Calabrian pine; however, these values were lower in comparison to those of other tree species (Blanco et al., 2008; Irmak & Çepel, 1968; Segura et al., 2017). Our study demonstrated that N concentration in the miscellaneous material analyzed was lower (1.16%) than the recorded values for various pine species in the Mediterranean region. For instance, Blanco et al. (2008) reported that the concentration of N in miscellaneous materials for Scots pine was 1.25%, while Lado-Monserrat et al. (2016) found that the concentration of N for Aleppo pine ranged from 0.71% to 0.89% depending on the thinning intensity.

Our black pine litterfall samples had a weighted P concentration of 690 ppm. Erkan et al. (2020) conducted a study on Calabrian pine and found a P concentration of 727 ppm, which is similar to our findings. Lado-Monserrat et al. (2016) and Bueis et al. (2018) reported lower P concentrations for Aleppo pine, at 170 and 360 ppm, respectively, compared to our study. This variation in P concentration may be explained by the fact that the study areas are under different environmental conditions, with different chemical properties of soils and bedrock (Erkan et al., 2020). Our findings indicate that the concentration of P in needles was lower than that reported in a previous study on black pine by Irmak and Çepel (1968).

In our study, the weighted K concentrations were determined to be 2,937 ppm, whereas the K concentrations in related studies on pine species were lower, at 2,120 and 2,444 ppm (Çepel et al., 1988; Erkan et al., 2020). The K concentrations in needles in our study are consistent with the black pine study conducted by Irmak and Çepel (1968).

Erkan et al. (2020) conducted a study on Calabrian pine that revealed higher weighted concentrations of Ca, Mg, and Na (12,563, 2,255, and 164 ppm, respectively) compared to our findings. We detected the highest Ca concentration in the branch component, which is consistent with the results of Erkan et al.'s study. The concentrations of Ca, Mg, and Na in black pine needles were higher for Ca and lower for Mg and Na as compared to Irmak and Çepel's (1968) study. In both our study and theirs, the Ca and N concentrations were found to be higher than those of the other elements. The higher concentrations of Ca and N in needles compared to other elements can be attributed to the fact that N is more readily incorporated into organic materials like stems, bark, and leaves-needles. Conversely, Ca is more prevalent in soil (Irmak & Çepel, 1968).

The weighted Mn concentration in black pine was 330 ppm in our study. Bueis et al. (2018) found Mn concentrations of 14–86 ppm for Aleppo pine, Erkan et al. (2020) 18–73 ppm for Calabrian pine, both lower than in our findings, while Finér (1996) found a higher Mn concentration (672 ppm). Our weighted Fe concentrations were 348 ppm, which is close to those of Erkan et al. (2020) and Segura et al. (2017) (316–350 ppm) and higher than that of Finér (1996) (118 ppm). Furthermore, the weighted Cu and Zn concentrations in our study were higher than in the studies performed by Erkan et al. (2020) and Bueis et al. (2018).

Differences in the chemical composition of litterfall components between tree species may be due to growth conditions or tree species characteristics (Augusto et al., 2002). However, certain environmental factors may also influence the nutrient content of litterfall components. It has been reported that stands that receive increased light after forest treatments can experience variations in litterfall component concentrations.

Carbon and nutrient input via litterfall

Significant differences ($P < 0.05$) in the amounts of Ca, Fe and Zn entering the forest floor via litterfall were found between the treatments in our study. The highest amount of Ca was found in the control treatment plot, at 41.2 kg ha^{-1} $year^{-1}$ and the lowest in the moderate treatment plot, at 29.6 kg ha^{-1} $year^{-1}$. Fe and Zn contents were highest in the control treatment plot, at 2.2 and 0.27 kg ha^{-1} $year^{-1}$, respectively, and lowest in the heavy treatment plot, at 1.5 and 0.16 kg ha^{-1} $year^{-1}$, respectively. Although litterfall in the control plot resulted in 1.5 times higher C input (3,347 kg ha^{-1} $year^{-1}$) compared to the heavy treatment plot (2,233 kg ha^{-1} $year^{-1}$), this difference was not statistically significant. As shown in Table 7, there were no significant differences between the treatments in terms of N, P, K, Mg, S, Na, Cu, and Mn levels.

Studies have shown that the amount of C entering the forest floor via litterfall decreases significantly as the intensity of thinning treatments increases; i.e., the higher the basal area, the higher the amount of C and there is a positive relationship between them (Kim, 2016; Lado-Monserrat et al., 2016; Segura et al., 2017; Pérez-Alavez et al., 2021). However, Blanco et al. (2008) reached a similar result to our findings, determining that thinning treatments had

Table 7 Amounts of carbon and nutrients entering the forest floor via litterfall in areas with different thinning intensity (Mean ± SE)

Elements (kg ha^{-1})	Thinning				F values	P
	Control	Light	Moderate	Heavy		
C	3347**a** ± 372	2967**a** ± 431	2494**a** ± 338	2233**a** ± 299	1.856	> 0.05
N	34.6**a** ± 4.1	30.6**a** ± 4.3	25.4**a** ± 4.0	23.4**a** ± 3.2	1.685	> 0.05
P	4.0**a** ± 0.6	3.4**a** ± 0.6	3.0**a** ± 0.5	2.6**a** ± 0.4	1.201	> 0.05
K	17.8**a** ± 1.9	14.9**a** ± 2.2	13.8**a** ± 1.9	11.8**a** ± 1.8	1.629	> 0.05
Ca	41.2**b** ± 1.9	34.3**a** ± 1.8	29.6**a** ± 1.9	30.8**a** ± 1.7	7.857	< 0.001
Mg	**7.8a** ± 0.9	6.5**a** ± 0.9	5.6**a** ± 0.7	5.4**a** ± 0.6	1.815	> 0.05
S	3.2**a** ± 0.5	2.7**a** ± 0.4	2.3**a** ± 0.4	2.1**a** ± 0.3	1.402	> 0.05
Na	0.22**a** ± 0.03	0.18**a** ± 0.03	0.15**a** ± 0.03	0.15**a** ± 0.02	1.227	> 0.05
Fe	2.2**b** ± 0.2	1.9**ab** ± 0.3	1.5**a** ± 0.2	1.5**a** ± 0.2	3.618	< 0.05
Cu	0.07**a** ± 0.01	0.06**a** ± 0.01	0.05**a** ± 0.01	0.05**a** ± 0.01	0.538	> 0.05
Zn	0.27**b** ± 0.03	0.22**ab** ± 0.03	0.21**ab** ± 0.02	0.16**a** ± 0.02	3.117	< 0.05
Mn	2.3**a** ± 0.3	1.9**a** ± 0.3	1.8**a** ± 0.2	1.4**a** ± 0.2	2.266	> 0.05

Data are presented as the mean ± standard error. The same letters in the rows indicate similar groups with no significant difference (P>0.05)

no significant effect on some macro–micro nutrients and C content for Scots pine. According to Kim (2016), a negative relationship was detected between basal area and C and K amounts in Japanese red pine, while a positive relationship was observed for other nutrients. In our study, both C and all other nutrients increased with the increase in basal area. In our study, the amount of C entering the ecosystem via needle drop was recorded to be 1,295 kg ha^{-1} $year^{-1}$ in heavy treatment stands which was consistent with the study conducted in black pine forest by Çakır et al. (2023). The amount of C in the total litterfall was 1,516 kg ha^{-1} $year^{-1}$ in Calabrian pine (Erkan et al., 2020), 600–2,400 kg ha^{-1} $year^{-1}$ in Scots pine (Çömez et al., 2019), 1,009 kg ha^{-1} $year^{-1}$ in Aleppo pine (Lado-Monserrat et al., 2016), and 125 kg ha^{-1} $year^{-1}$ in smooth-bark Mexican pine (Pérez-Alavez et al., 2021)—all less than the average value (2,760 kg ha^{-1}) we found for C in our study. Therefore, it can be inferred that black pine forests have a higher annual C input to the soil compared to Scots pine, Calabrian pine, Aleppo pine, and smooth-bark Mexican pine forests, as reported.

Blanco et al. (2008) conducted a study on 20% and 30% thinning in Scots pine and found that the amounts of N, P, K, Ca, and Mg decreased significantly in the 30% thinned area compared to the control treatment. In the study by Novák et al. (2020) on Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), nutrient levels in the thinning treatment and control plots were as follows: N: 33.9–40, P: 2.1–2.6, K: 3.6–4.7, Ca: 15.3–20.6, and Mg: 1.6–2 kg ha−1 year−1. Similarly, nutrient levels were higher in the control plot than in the thinning treatment areas in our study. Çakır et al. (2023) determined that the amount of N in needle drop (47.3 kg ha−1 year−1) was higher in black pine stands corresponding to our study. Koray and Tolunay (2020) determined that 1,744 kg C, 10.1 kg N, 1.7 kg P, 11.4 kg K, 25.7 kg Ca, 2.4 kg Mg, 5.9 kg S, 307 g Na, 1.3 kg Fe, 309 g Mn, 140 g Zn, and 63.1 g Cu entered the ecosystem via litterfall in black pine. In our study, considering all treatments, the amounts of C, N, P, K, Ca, Mg, Fe, Mn, and Zn were found to be higher, the amounts of S and Na were lower, and the amounts of Cu were similar compared to those of Koray and Tolunay (2020). The input of carbon and nutrients into the forest floor through litterfall fluctuates depending on the species and geographical location, even within the same species.

Conclusions

Our study aimed to evaluate the impact of various thinning levels on litterfall (including needles, branches, bark, cones, and miscellaneous material) and carbon and nutrient input into the ecosystem in black pine afforestation sites in Türkiye. Results revealed that the total litterfall ranged from 4,378 kg ha^{-1} $year^{-1}$ to 6,543 kg ha^{-1} $year^{-1}$ depending on the intensity of treatments. Moreover, the amount of litterfall decreased as the thinning intensity increased. In the black pine afforestation area, 60% of the annual litterfall was composed of needle drop. There was a statistically significant difference between the amount of needle drop in the control plots and in the light, moderate, and heavy thinning treatment plots. In our study, the amount of C entering the ecosystem via litterfall increased with increasing basal area as reported in previous studies, but this did not statistically differ between the thinning interventions applied. It was revealed that the highest C input to the forest ecosystem by litterfall was in the control treatment plot, with 3,347 kg ha^{-1} year^{-1} and the lowest was in the heavy treatment plot, with 2,233 kg ha^{-1} year^{-1}. The weighted carbon content of the litterfall (50.8%) was also determined and this value can be used to calculate the amount of carbon supplied by the litterfall to the forest floor in black pine plantations. Both needle drop (1,716 kg ha^{-1}) and total litterfall (1,942 kg ha^{-1}) were highest in the fall season.

Significant relationships were found between litterfall and stand and climatic characteristics. Increasing the intensity leads to reduced carbon input to the stand. However, as this study shows 3-year results, it is unclear whether stands exposed to thinning intervention can recover to non-intervention levels of litterfall over time. Long-term monitoring of litterfall sampling in the study area is therefore recommended. In addition, considering carbon-focused planning, it is recommended that thinning interventions on forests to be performed at a moderate level and with short rotations in the stand. This will help to maintain the health and sustainability of the forest while taking management objectives into account.

Acknowledgements This study was conducted as part of the project titled "The effects of thinning on the amount of carbon and nutrient that enter into forest floor via litterfall in black pine afforestation (ESK-40(6325)/2019-2022)" that was funded by Turkish General Directorate of Forestry.

Author contribution Furkan Atalar: Data collection, Writing—original draft, Writing—review & editing. Şükrü Teoman Güner: Conceptualization, Methodology, Data collection, Formal analysis, Data curation, Writing—original draft, Writing—review & editing, Visualization. Rıza Karataş: Conceptualization, Methodology, Data collection, Writing—review & editing. Dilek Güner: Data collection, Writing—review & editing. Abdullah Sarımehmetoğlu: Writing—review & editing.

Funding This work was supported by the Turkish General Directorate of Forestry ESK-40(6325).

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

Declarations

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.

References

Agreement, P. (2015). *Report of The Conference of The Parties on Its Twenty-First Session, Held in Paris from 30 November to 13 December 2015*. FCCC/CP/2015/10/Add. 1, United Nations, European Commision Secretariate.

Augusto, L., Ranger, J., Binkley, D., & Rothe, A. (2002). Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science,59*, 233–253. https://doi.org/10.1051/forest:2002020

Baek, G., Baek, G., Kim, H., Lee, J., Kim, H., & Kim, C. (2022). Thinning effects on litterfall inputs and litter decomposition in Pinus densiflora S. et Z. and Quercus variabilis Blume stands. *Journal of Forest and Environmental Science,38*(1), 48–54. https://doi.org/10.7747/JFES.2022.38.1.48

Bahamonde, H. A., Peri, P. L., Martínez Pastur, G., & Monelos, L. (2015). Litterfall and nutrients return in *Nothofagus antarctica* forests growing in a site quality gradient with different management uses in Southern Patagonia. *European Journal of Forest Research,134*, 113–124. https://doi.org/10.1007/s10342-014-0837-z

Beedlow, P. A., Tingey, D. T., Phillips, D. L., Hogsett, W. E., & Olszyk, D. M. (2004). Rising atmospheric CO_2 and carbon sequestration in forests. *Frontiers in Ecology and the Environment,2*(6), 315–322. https://doi.org/10.1890/1540-9295(2004)002[0315:RACACS]2.0.CO;2

Blanco, J. A., Bosco, J., & Castillo, F. J. (2006a). Effects of thinning on nutrient content pools in two *Pinus sylvestris* forests in the western Pyrenees. *Canadian Journal of Forest Research,21*(2), 143–150. https://doi.org/10.1080/02827580600559726

Blanco, J. A., Imbert, J. B., & Castillo, F. J. (2006b). Influence of site characteristics and thinning intensity on litterfall production in two *Pinus sylvestris* L. forests in the western Pyrenees. *Forest Ecology and Management*, *237*(1–3), 342–352. https://doi.org/10.1016/j.foreco.2006.09.057

Blanco, J. A., Imbert, J. B., & Castillo, F. J. (2008). Nutrient return via litterfall in two contrasting Pinus sylvestris forests in the Pyrenees under different thinning intensities.

Forest Ecology and Management,256(11), 1840–1852. https://doi-org.srv-proxy2.library.tamu.edu/10.1016/j.foreco.2008.07.011.

Blanco, J. A., Zavala, M. A., Imbert, J. B., & Castillo, F. J. (2005). Sustainability of forest management practices: Evaluation through a simulation model of nutrient cycling. *Forest Ecology and Management*, *213*, 209–228. https://doi-org.srv-proxy2.library.tamu.edu/10.1016/j.foreco.2005.03.042

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science,320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Bueis, T., Bravo, F., Pando, V., & Turrión, M.B. (2017). Influencia de la densidad del arbolado sobre el desfronde y su reciclado en pinares de repoblación del norte de España. *Bosque (Valdivia), 38*(2), 401-407. https://doi.org/10.4067/S0717-92002017000200017

Bueis, T., Bravo, F., Pando, V., & Turrión, M. B. (2018). Local basal area affects needle litterfall, nutrient concentration, and nutrient release during decomposition in Pinus halepensis Mill. plantations in Spain. *Annals of Forest Science, 75*, 1–12. https://doi.org/10.1007/s13595-018-0699-5

Çakır, M., & Akburak, S. (2017). Litterfall and nutrients return to soil in pure and mixed stands of oak and beech. *Journal of the Faculty of Forestry Istanbul University, 67*(2), 178–193. https://doi.org/10.17099/jffiu.301602

Çakır, M., Sargıncı, M., & Akburak, S. (2023). Determining the amount of needle-fall, and carbon and nitrogen return to the soil ecosystem in black pine (*Pinus nigra* Arnold.) stands. *Düzce University Faculty of Forestry Journal of Forestry, 19*(2), 269–282. https://doi.org/10.58816/duzceod.1371917

Caldentey, J., Ibarra, M., & Hernández, J. (2001). Litter fluxes and decomposition in Nothofagus pumilio stands in the region of Magallanes, Chile. *Forest Ecology and Management, 148*(1–3), 145–157. https://doi-org.srv-proxy2.library.tamu.edu/. https://doi.org/10.1016/S0378-1127(00)00532-6

Çepel, N., Dündar, M., Özdemir, T., & Neyişçi, T. (1988). *Needlefall in Brutia pine (Pinus brutia Ten.) ecosystems and the amount of nutrients returned to the soil*. Central Anatolia Forestry Research Institute Directorate Press.

Clark, D. A., Brown, S., Kicklighter, D. W., Chambers, J. Q., Thomlinson, J. R., Ni, J., & Holland, E. A. (2001). Net primary production in tropical forests: An evaluation and synthesis of existing field data. *Ecological Applications,11*(2), 371–384. https://doi.org/10.1890/1051-0761(2001)011[0371:NPPITF]2.0.CO;2

Çömez, A., Güner, ŞT., & Tolunay, D. (2021). The effect of stand structure on litter decomposition in *Pinus sylvestris* L. stands in Turkey. *Annals of Forest Science,78*, 1–13. https://doi.org/10.1007/s13595-020-01023-2

Çömez, A., Tolunay, D., & Güner, Ş. T. (2019). Litterfall and the effects of thinning and seed cutting on carbon input into the soil in Scots pine stands in Turkey. *European Journal of Forest Research,138*(1), 1–14. https://doi.org/10.1007/s10342-018-1148-6

Erkan, N., Çömez, A., & Aydin, A. C. (2020). Litterfall production, carbon and nutrient return to the forest floor in *Pinus brutia* forests in Turkey. *Scandinavian Journal of Forest Research,35*(7), 341–350. https://doi.org/10.1080/02827581.2020.1815830

Erkan, N., Çömez, A., Aydin, A. C., Denli, O., & Erkan, S. (2018). Litterfall in relation to stand parameters and climatic factors in *Pinus brutia* forests in Turkey. *Scandinavian Journal of Forest Research,33*(4), 338–346. https://doi.org/10.1080/02827581.2017.1406135

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. https://doi.org/10.26650/forestist.2018.330657

Finér, L. (1996). Variation in the amount and quality of litterfall in a Pinus sylvestris L. stand growing on a bog. *Forest Ecology and Management,80*(1–3), 1–11. https://doi.org/10.1016/0378-1127(95)03652-0

Foss Tecator. (2014). Sample preparation/burning process. Application Note.

García-Plé, C., Vanrell, P., & Morey, M. (1995). Litter fall and decomposition in a *Pinus halepensis* forest on Mallorca. *Journal of Vegetation Science, 6*(1), 17–22. https://doi.org/10.2307/3236251

GDF. (2022). Forestry Statistics 2020. Turkish General Directorate of Forestry. https://www.ogm.gov.tr/tr/e-kutuphane/resmi-istatistikler. Accessed 10 Feb 2024.

GDM. (2022). *Meteorological service in Turkey*. Department of Meteorological Data Processing.

Giweta, M. (2020). Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: A review. *Journal of Ecology and Environment,44*(1), 11. https://doi.org/10.1186/s41610-020-0151-2

González-Rodríguez, H., López-Hernández, J.M., Ramírez-Lozano, R.G., Gómez-Meza, M.V., Cantú-Silva, I., Sarquís-Ramírez, J.I., & Mora Olivo, A. (2019). Litterfall deposition and nutrient return in pine-oak forests and scrublands in northeastern Mexico. *Madera y Bosques 25*(3), e2531514. https://doi.org/10.21829/myb.2019.2531514

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, ŞT., Çömez, A., Özkan, K., Karataş, R., & Çelik, N. (2016). Modelling the productivity of Anatolian black pine plantations in Turkey. *Journal of the Faculty of Forestry Istanbul University,66*(1), 159–172. https://doi.org/10.17099/jffiu.18731

Güner, ŞT., & Güner, D. (2021). Changes in carbon stocks of soil and forest floor in black pine plantations in Turkey. *Journal of Forestry Research,32*(1), 339–347. https://doi.org/10.1007/s11676-019-01073-x

Irmak, A., & Çepel, N. (1968). Determining litterfall amount and nutrient return to the soil through litterfall in a beach, oak, and pine stands in Belgrad Forest. *Journal of the Faculty of Forestry Istanbul University,17*(2A), 53–76.

IUSS Working Group WRB. (2006). World reference base for soil resources 2006. International soil classification system for naming soils and creating legends for soil maps. World soil resources reports no. 103. FAO, Rome.

Jiménez, M. N., & Navarro, F. B. (2016). Thinning effects on litterfall remaining after 8 years and improved stand resilience in Aleppo pine afforestation (SE Spain). *Journal of Environmental Management,169*, 174–183. https://doi.org/10.1016/j.jenvman.2015.12.028

Kacar, B., & İnal, A. (2008). *Plant analysis*. Nobel Press.

Kara, O., Bolat, I., Cakıroğlu, K., & Şentürk, M. (2014). Litter decomposition and microbial biomass in temperate forests in Northwestern Turkey. *Journal of Soil Science and Plant Nutrition,14*(1), 31–41. https://doi.org/10.4067/S0718-95162014005000003

Kim, C. (2016). Basal area effects on a short-term nutrient status of litter fall and needle litter decomposition in a *Pinus densiflora* stand. *Journal of Ecology and Environment,39*(1), 51–60. https://doi.org/10.5141/ecoenv.2016.006

Kimmins, J. P. (2004). *Forest ecology, a foundation for sustainable management and environmental ethics in forestry*. Prentice-Hall.

Kiracıoğlu, Ö., Güner, Ş.T., & Karataş, R. (2023). Determination of the amount of litterfall according to the development stages and of the carbon stock input into the litter in the oriental beech forests in the Marmara Region. *Turkish Journal of Forestry, 24*(3), 213–222. https://doi.org/10.18182/tjf.1318425

Klemmedson, J. O., Meier, C. E., & Campbell, R. E. (1990). Litterfall transfers of dry matter and nutrients in ponderosa pine stands. *Canadian Journal of Forest Research,20*(7), 1105–1115. https://doi.org/10.1139/x90-146

Koray, E. Ş, & Tolunay, D. (2020). Nutrient inputs by litterfall into ecosystems in Anatolian black pine stands at Türkmendağı. *Turkish Journal of Forestry,21*(3), 201–214.

Kutbay, H. G., & Horuz, A. (2001). Litter all and nutrient return in *Quercus cerris* L. var. c*erris* forests inthe central black sea region of Turkey. *Pakistan Journal of Botany, 33*(3), 293–303.

Lado-Monserrat, L., Lidón, A., & Bautista, I. (2016). Erratum to: Litterfall, litter decomposition and associated nutrient fluxes in Pinus halepensis: Influence of tree removal intensity in a Mediterranean forest. *European Journal of Forest Research,135*(1), 203–214. https://doi.org/10.1007/s10342-015-0923-x

Leco. (2000). *TruSpec CN analyzer*. Leco Cooperation, St. Joseph.

Meentemeyer, V., Box, E. O., & Thompson, R. (1982). World patterns and amounts of terrestrial plant litter production. *BioScience,32*(2), 125–128. https://doi.org/10.2307/1308565

Navarro, F. B., Romero-Freire, A., Del Castillo, T., Foronda, A., Jiménez, M. N., Ripoll, M. A., Sánchez-Miranda, A., Huntsinger, L., & Fernández-Ondono, E. (2013). Effects of thinning on litterfall were found after years in a *Pinus halepensis* afforestation area at tree and stand levels. *Forest Ecology and Management,289*(1), 354–362. https://doi.org/10.1016/j.foreco.2012.09.026

Neumann, M., Ukonmaanaho, L., Johnson, J., Benham, S., Vesterdal, L., Novotný, R., Verstraeten, A., Lundin, L., Thimonier, A., Michopoulos, P., & Hasenauer, H. (2018). Quantifying carbon and nutrient input from litterfall in european forests using field observations and modeling. *Global Biogeochemical Cycles,32*, 784–798. https://doi.org/10.1029/2017GB005825

Novák, J., Kacálek, D., & Dušek, D. (2020). Litterfall nutrient return in thinned young stands with Douglas fir. *Central European Forestry Journal,66*(2), 78–84. https://doi.org/10.2478/forj-2020-0006

Novák, J., & Slodičák, M. (2006). Litter-fall as a source of nutrients in mountain Norway spruce stands in connection with thinning. In Jurásek et al. (Ed.), *Stabilization of forest functions in biotopes disturbed by anthropogenic activity* (pp. 297–310). Opočno

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

Pausas, J. G. (1997). Litter fall and litter decomposition in *Pinus sylvestris* forests of the eastern Pyrenees. *Journal of Vegetation Science, 8*(5), 643–650. https://doi.org/10.2307/3237368

Pérez-Alavez, Y., Rodríguez-Ortiz, G., Santiago-García, W., Campos-Angeles, G. V., Enríquez-del Valle, J. R., & Martin, M. P. (2021). Effect of thinning intensity on litterfall biomass and nutrient deposition in a naturally regenerated Pinus pseudostrobus lind. Forest in Oaxaca, Mexico. *Journal of Sustainable Forestry,42*(1), 1–18. https://doi.org/10.1080/10549811.2021.1946410

Pérez-Suárez, M., Arredondo-Moreno, J. T., Huber-Sannwald, E., & Vargas-Hernández, J. J. (2009). Production and quality of senesced and green litterfall in a pine–oak forest in central-northwest Mexico. *Forest Ecology and Management,258*(7), 1307–1315. https://doi.org/10.1016/j.foreco.2009.06.031

Pitman, R. M. (2013). Litterfall—biomass, chemistry, leaf area, and links with wider ecosystem functioning. *Developments in Environmental Science,12*, 251–264. https://doi.org/10.1016/B978-0-08-098222-9.00014-5

Qin, Q., Wang, H., Li, X., Xie, Y., Lei, X., Zheng, Y., Yang, D., & Wang, F. (2019). Spatial heterogeneity and affecting factors of litter organic carbon and total nitrogen over natural spruce-fir mixed forests in northeastern China. *CATENA,174*, 293–300. https://doi.org/10.1016/j.catena.2018.11.020

Rodríguez-Ortiz, G., De Los Santos-Posadas, H. M., González-Hernández, V. A., Aldrete, A., Gómez- Guerrero, A., & Fierros-González, A. M. (2012). Modelos de biomasa aérea y foliar en una plantación de pino de rápido crecimiento en Oaxaca. *Madera y Bosques,18*(1), 25–41. https://doi.org/10.21829/myb.2012.1811116

Roig, S., del Río, M., Cañellas, I., & Montero, G. (2005). Litter fall in Mediterranean Pinus pinaster Ait. stands under different thinning regimes. *Forest Ecology and Management,206*(1–3), 179–190. https://doi.org/10.1016/j.foreco.2004.10.068

Santa Regina, I., & Gallardo, J. F. (1989). Biogeochemical cycles in forests of the Sierra de Bejar (Salamanca, Spain): Return of bioelements in rainfall. *Acta Oecologica,10*(4), 433–438.

Sarıyıldız, T., Parlak, S., Gönültaş, O., & Savacı, G. (2023). Effects of thinning on litterfall production and leaf litter decomposition rates of Karacabey forested wetlands, Bursa. Türkiye. *European Journal of Forest Engineering, 9*(1), 26–33. https://doi.org/10.33904/ejfe.1317805

Segura, C., Fernández-Ondoño, E., Jiménez, M. N., & Navarro, F. B. (2017). Thinning affects the needlefall nutrient return to soil in a semiarid Aleppo pine afforestation while the nutrient dynamics remain unchanged. *Forest Ecology and Management,405*, 257–270. https://doi.org/10.1016/j.foreco.2017.09.049

Shen, G., Chen, D., Wu, Y., Liu, L., & Liu, C. (2019). Spatial patterns and estimates of global forest litterfall. *Ecosphere,10*(2), e02587. https://doi.org/10.1002/ecs2.2587

SPSS. (2015). *SPSS 22.0 Guide to Data Analysis.* Prentice Hall, Upper Saddle River.

Starr, M., Saarsalmi, A., Hokkanen, T., Merilä, P., & Helmisaari, H. S. (2005). Models of litterfall production for Scots pine (*Pinus sylvestris* L.) in Finland using stand, site and climate factors. *Forest Ecology and Management,205*, 215–225. https://doi.org/10.1016/j.foreco.2004.10.047

Tobin, B., Black, K., Osborne, B., Reidy, B., Bolger, T., & Nieuwenhuis, M. (2006). Assessment of allometric algorithms for estimating leaf biomass, leaf area index and litterfall in different-aged Sitka spruce forests. *Forestry,79*(4), 453–465. https://doi.org/10.1093/forestry/cpl030

Tüfekçioğlu, A., Güner, S., & Tilki, F. (2005). Thinning effects on production, root biomass and some soil properties in a young oriental beech stand in Artvin, Turkey. *Journal of Environmental Biology,26*(1), 91–95.

Ukonmaanaho, L., Pitman, R., Bastrup-Birk, A., Bréda, N., & Rautio, P. (2020). *Sampling and analysis of litterfall*. Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Chapter: Part XIII: Sampling and analysis of litterfall. UNECE ICP Forests Press.

Wei, X., Li, Q., Waterhouse, M. J., & Armleder, H. M. (2012). Organic matter loading affects lodgepole pine seedling growth. *Environmental Management,49*, 1143–1149. https://doi.org/10.1007/s00267-012-9846-1

Zhang, H., Yuan, W., Dong, W., & Liu, S. (2014). Seasonal patterns of litterfall in forest ecosystem worldwide. *Ecological Complexity,20*, 240–247. https://doi.org/10.1016/j.ecocom.2014.01.003