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Effects of elevation and aspect on the morphological traits of 10- and 15-year-old Scots pine individuals

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Abstract: Scots pine (*Pinus sylvestris* L.) is a widely distributed forest tree species of major importance in global forestry and afforestation, whose growth performance varies in response to site and stand conditions. This study evaluates the effects of elevation and aspect on the morphological development of Scots pine individuals grown under afforestation conditions in the Aslandag Provincial Forest, Bayburt, Türkiye.
The research material consisted of 10- and 15-year-old individuals established at two elevations (1600, 1750 m) and two aspects (sunny and shady). A total of 720 individuals were evaluated from 24 plots established in a full factorial design. Morphological traits measured included height, root collar diameter, branch length, crown area, crown asymmetry index, terminal shoot length (for 10-year-olds), and diameter at breast height (for 15-year-olds).
The study results showed that lower elevation (1600 m) and shady aspect conditions generally supported better growth. For 10-year-old individuals, the highest mean values for height, root collar diameter, and crown area were 213.1 cm, 6.1 cm, and 2.21 m^2, respectively. In 15-year-old individuals, these values increased to 581.3 cm in height, 14.2 cm in root collar diameter, and 4.36 m^2 in crown area, which showed strong positive correlations with height and root collar diameter, emphasizing its value as a growth indicator. In contrast, the crown asymmetry index reached its highest value at 1600 m (0.116 in 10-year-olds), and tended to decrease with age, indicating a transition toward more balanced crown forms over time.
The findings demonstrate that both environmental factors and age jointly shape the morphological traits of Scots pine, offering valuable guidance for afforestation practices and silvicultural planning in similar temperate conditions.

Keywords: afforestation, crown morphology, crown asymmetry index, topographic factors, site-related variation

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Introduction

As in the rest of the world, the forests in Türkiye are among the most important natural resources. Their sustainable management, considering biological, ecological, economic, and socio-cultural functions, is gaining increasing significance (Saraçoğlu, 1988; Koparan et al., 2024). Among the key tree species of these forests, Scots pine (*Pinus sylvestris* L.) is recognized as one of the most ecologically and economically valuable conifers in Europe (Krakau et al., 2013; O'Reilly-Wapstra et al., 2014; Sevik & Topacoglu, 2015; Wójkiewicz et al., 2016). Its broad natural distribution across Eurasia, spanning diverse climatic, edaphic and environmental conditions, has resulted in remarkable morphological variation and the formation of numerous ecotypes (Shutyaev & Giertych, 1997; Rehfeldt et al., 2002; Turna, 2003; Krakau et al., 2013). In Türkiye, Scots pine occurs in the Black Sea, Central Anatolia, and Eastern Anatolia regions, and represents the southernmost limit of the species' natural range worldwide. With its growth and yield characteristics as well as its considerable economic value, Scots pine constitutes a principal native forest tree species in the country (Çepel, 1976; Atalay, 2014; Sağlam & Sakıcı, 2022) and exhibits high adaptability to diverse ecological conditions (Turna & Güney, 2009).

Since tree growth can be influenced by a wide range of abiotic and biotic factors, it is well known that climate and soil conditions determine species composition and the growth of forest ecosystems. Additionally, geomorphic factors such as slope aspect and slope gradient can substantially modify the local environment of plants by altering microclimatic conditions and small-scale soil development (Ellenberg, 1988; Oberhuber & Kofler, 2000). The wide altitudinal range of Scots pine in Türkiye, from sea level up to 2700 m, provides a unique opportunity to assess how elevation shapes its morphological responses (Turna & Güney, 2009; Sevik et al., 2010; Bilgen et al., 2011; Güney et al., 2023). Importantly, morphological development serves as a fundamental indicator of species' potential to adapt to varying ecological conditions in afforestation practices (Lawson & Michler, 2014; Jahdi et al., 2020; Kennedy et al., 2020; Bhusal et al., 2021; Silvestro et al., 2023).

In this regard, long-standing silvicultural experience has also emphasized that sustainable forest management relies on fundamental relationships such as the link between crown size and diameter increment, underlining the critical role of canopy structure for tree and stand productivity (Dieler & Pretzsch, 2013). Building on this, tree crowns represent the three-dimensional architecture of trees, reflecting not only their structural form but also their functional role in forest ecosystems (Godin et al., 1999). As the interface between the canopy and the atmosphere, crowns regulate essential processes such as light interception, carbon assimilation, and water exchange, which directly influence tree productivity and ecosystem functioning (Santiago et al., 2004; Strigul et al., 2008). Crown asymmetry is widely recognized as an adaptive mechanism that enables trees to optimize light capture and growth under heterogeneous conditions imposed by neighbouring competition, topography, or solar radiation (Getzin & Wiegand, 2007). Moreover, empirical studies have demonstrated that crown size and crown area are strong predictors of tree growth and competitive performance, emphasizing the central role of crown traits in explaining growth variation across different environments (Seidel et al., 2015; Htoo et al., 2024).

Evaluating the effects of site-specific factors such as elevation and aspect on the growth and morphological development of Scots pine is highly relevant for both silvicultural planning and afforestation practices. Therefore, this study aims to examine how these factors jointly influence classical growth traits (height, diameter, length) and advanced crown metrics (area, asymmetry index) in 10- and 15-year-old Scots pine individuals under afforestation conditions in Aslandag Provincial Forest, Bayburt, Türkiye.

Materials and Methods

The research material consisted of Scots pine (*Pinus sylvestris* L.) individuals of different ages established since 1991 within the framework of the Green Belt Afforestation Project located within the management area of the Bayburt Forest Sub-District Directorate, Bayburt Forest Enterprise Directorate, Trabzon Regional Directorate of Forestry (TRDF), Türkiye. According to the Erinç Climate Classification, which was calculated using the long-term climate data (1991–2020) provided by the Turkish State Meteorological Service, the precipitation effectiveness index for Bayburt province is 33.03, indicating a semi-humid climate type. Consistently, the Thornthwaite Climate Classification for the same period also defines Bayburt as semi-humid with a pronounced summer water deficit, corresponding to the s_2 category (MGM, 2025).

The afforestation site in the Aslandag Provincial Forest, Bayburt, is characterized by sandy soils developed over granites and crystalline schists, and mechanical site preparation was conducted prior to planting. The plantation was established using 1 + 1-year-old containerized Scots pine seedlings produced from seeds collected from a certified seed stand located within the Karanlıkdere Forest Sub-District Directorate of the Gümüşhane Forest Enterprise Directorate, also under TRDF, geographically close to

Bayburt and characterized by similar climatic conditions. Following planting, necessary maintenance operations were carried out regularly on the site. Due to the pronounced summer drought conditions in the region, supplemental irrigation was essential during the early establishment phase.

Within the study area, sample plots were established in 2019 to identify differences in the developmental levels of 10- and 15-year-old Scots pine individuals, based on two elevation levels (1600 and 1750 m) and two aspect types (shady and sunny). A Global Positioning System (GPS) was used to

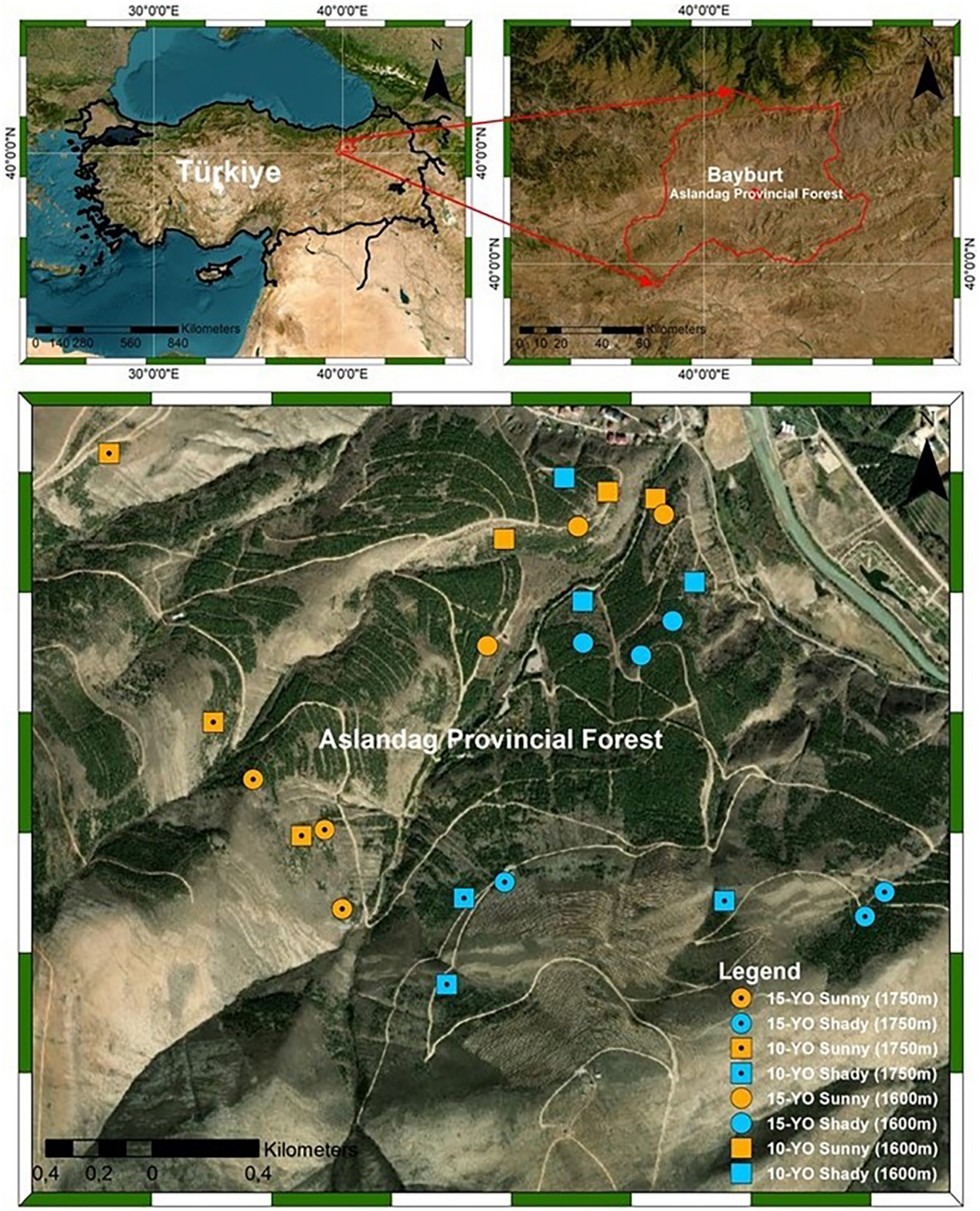

Fig. 1. Spatial distribution of sample plots in Aslandag Provincial Forest

determine the elevations and aspects of the sample plots. In this study, plots located on the northern, northeastern, northwestern, and eastern aspects were classified as shady, while those located on the southern, southeastern, southwestern, and western aspects were classified as sunny. The map showing the locations of the sample plots in the Aslandag Provincial Forest is presented in Fig. 1.

A total of 24 sample plots were selected, comprising two age groups, each arranged in a 2 (elevation) × 2 (aspect) factorial structure with three replicate plots per combination. Measurements were conducted on 30 Scots pine individuals within each plot (135 m^2, with an initial planting spacing of 1.5 × 3 m), resulting in a total of 720 individuals. As no thinning operations had been conducted prior to measurement, stand density remained structurally comparable across all elevations and aspects. The morphological measurements performed on Scots pine individuals are presented below.

Height (H): The heights of 10- and 15-year-old individuals were measured from the root collar level to the tip of the terminal shoot using a measuring tape and recorded in centimeters with a precision of 1 cm.

Root Collar Diameter (RCD): The root collar diameters of 10- and 15-year-old individuals were measured at ground level using a caliper and recorded to the nearest 0.1 cm.

Branch Length (BL): The longest branches in the north, south, east, and west directions of 10- and 15-year-old individuals were measured in centimeters using a measuring tape and recorded with a precision of 1 cm. For each individual, the mean branch length was calculated from these measurements, and the average values were used in the statistical analyses.

Crown Area (CA): The crown areas of 10- and 15-year-old individuals were estimated as the projected area of four ellipse quarters, using branch lengths measured in the north, south, east, and west directions. In the formula below, CR_{NS} denotes the mean branch length in the north–south directions, and CR_{EW} denotes the mean branch length in the east–west directions (Loubota Panzou & Feldpausch, 2020).

$$CA = \pi \times CR_{NS} \times CR_{EW}$$

Crown Asymmetry Index (CAI): The crown asymmetry index of 10- and 15-year-old individuals was calculated using branch lengths measured in the north, south, east, and west directions, based on the following formula. In the formula, R_{min} represents the shortest branch length, while $\overline{R}$ denotes the mean branch length. The crown asymmetry index is scaled between 0 and 1, with values closer to 1 indicating the presence of an asymmetrical crown structure (Curtin, 1970; Kong et al., 2021).

$$CAI = 1 - \frac{R_{min}}{\overline{R}}$$

Terminal Shoot Length (TSL): In 10-year-old individuals, the lengths of terminal shoots were measured using a measuring tape and recorded to the nearest 1 cm.

Diameter at Breast Height (DBH): In 15-year-old individuals, diameters at breast height ($d_{1.30}$) were determined using a caliper and recorded in centimeters with a precision of 0.1 cm.

For the evaluation of the data obtained from measurements in the study area, statistical analyses were conducted using SPSS 27.0 and RStudio. Assumptions of normality and homogeneity of variances were examined prior to analysis. Normality was evaluated based on skewness–kurtosis values and inspection of residual distributions, and homogeneity of variances was assessed using Levene's test. The data were considered suitable for parametric analysis. The effects of elevation, aspect, and their interaction on morphological traits were analysed separately for 10- and 15-year-old individuals using two-way factorial ANOVA within the GLM (univariate) framework. Pearson correlation analysis was additionally performed to determine the direction and strength of relationships among morphological traits (Ercan, 1997; Özdamar, 1999; Zar, 1999; Quinn & Keough, 2002; Özkan, 2003; Crawley, 2013).

Results

The results of the univariate analysis regarding the effects of elevation, aspect, and their interactions on the morphological traits of 10-year-old Scots pine individuals are presented in Table 1.

According to the univariate analysis results presented in Table 1, statistically significant differences

Table 1. Univariate analysis results for 10-year-old Scots pine individuals

		Elevation	Aspect	Elevation × Aspect
H	F	289.196	7.142	102.673
	p	0.000**	0.008**	0.000**
RCD	F	34.422	15.850	82.446
	p	0.000**	0.000**	0.000**
BL	F	143.958	105.684	19.414
	p	0.000**	0.000**	0.000**
TSL	F	406.299	7.863	0.180
	p	0.000**	0.005**	0.672
CA	F	120.365	82.788	8.459
	p	0.000**	0.000**	0.004**
CAI	F	3.433	22.008	1.428
	p	0.065	0.000**	0.233

** $p < 0.01$: statistically significant difference at the 99% confidence level.

at the 99% confidence level were found in height, root collar diameter, and branch length of 10-year-old individuals with respect to elevation, aspect, and elevation × aspect interaction. For terminal shoot length, statistically significant differences ($p < 0.01$) were also observed in relation to elevation and aspect factors, while no significant difference was detected for the elevation × aspect interaction. In addition, the results of the univariate analysis revealed that the elevation factor had a strong effect on height (F = 298.196) and terminal shoot length (F = 406.299). For crown area, statistically significant

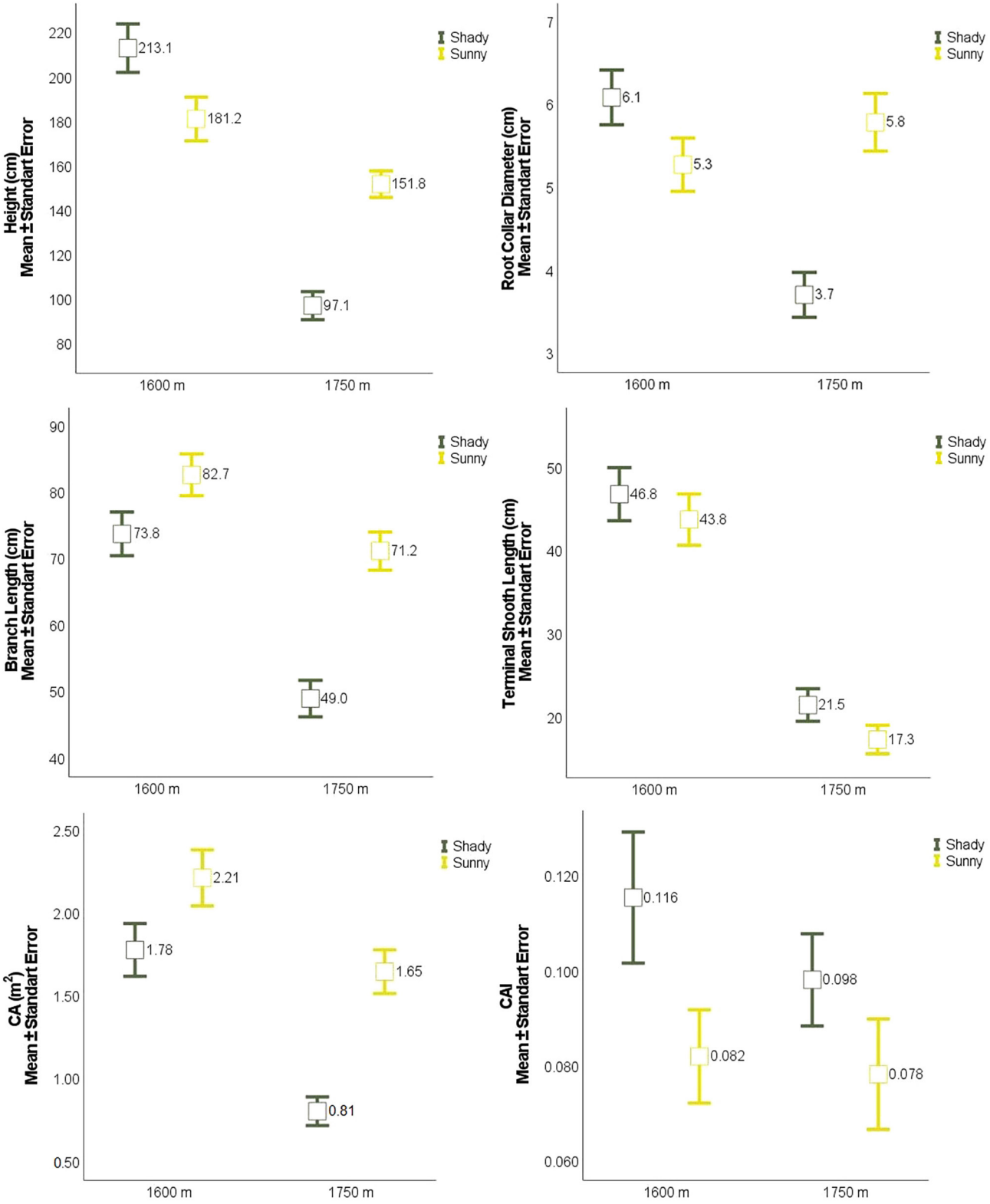

Fig. 2. Mean values (± SE) of morphological traits in 10-year-old Scots pine individuals

differences at the 99% confidence level were detected for elevation, aspect, and elevation × aspect interaction, whereas for crown asymmetry index, significant differences ($p < 0.01$) occurred only with respect to the aspect factor. The mean values (± SE) of height, root collar diameter, branch length, terminal shoot length, crown area and crown asymmetry index in 10-year-old Scots pine individuals are illustrated in the graphs presented in Fig. 2.

In 10-year-old individuals, the highest height value was measured as 213.1 cm at 1600 m elevation on the shady aspect, while the lowest value was recorded as 97.1 cm at 1750 m elevation on the shady aspect. The mean height values were 197.2 cm at 1600 m (shady and sunny aspects combined) and 124.5 cm at 1750 m. For root collar diameter and terminal shoot length, the highest values were obtained at 1600 m elevation on the shady aspect, with 6.1 cm and 46.8 cm, respectively. The lowest root collar diameter was 3.7 cm on the shady aspect at 1750 m, whereas the lowest terminal shoot length was 17.3 cm on the sunny aspect at 1750 m. The mean root collar diameter and terminal shoot length values were 5.7 cm and 45.3 cm, respectively, at 1600 m, compared to 4.8 cm and 19.4 cm at 1750 m. In terms of branch length, the maximum value of 82.7 cm was observed on the sunny aspect at 1600 m, whereas the minimum value of 49.0 cm was recorded on the shady aspect at 1750 m. The mean branch length at 1600 m (78.2 cm) was likewise higher than the mean value at 1750 m (60.1 cm), similar to the other morphological traits.

For crown area, the highest mean value was recorded as 2.21 m² at 1600 m elevation on the sunny aspect, followed by 1.78 m² on the shady aspect at the same elevation. The lowest value for this trait was measured as 0.81 m² on the shady aspect at 1750 m. At an elevation of 1600 m, the mean crown area was 2.00 m², while at 1750 m this value decreased to 1.23 m². Regarding the crown asymmetry

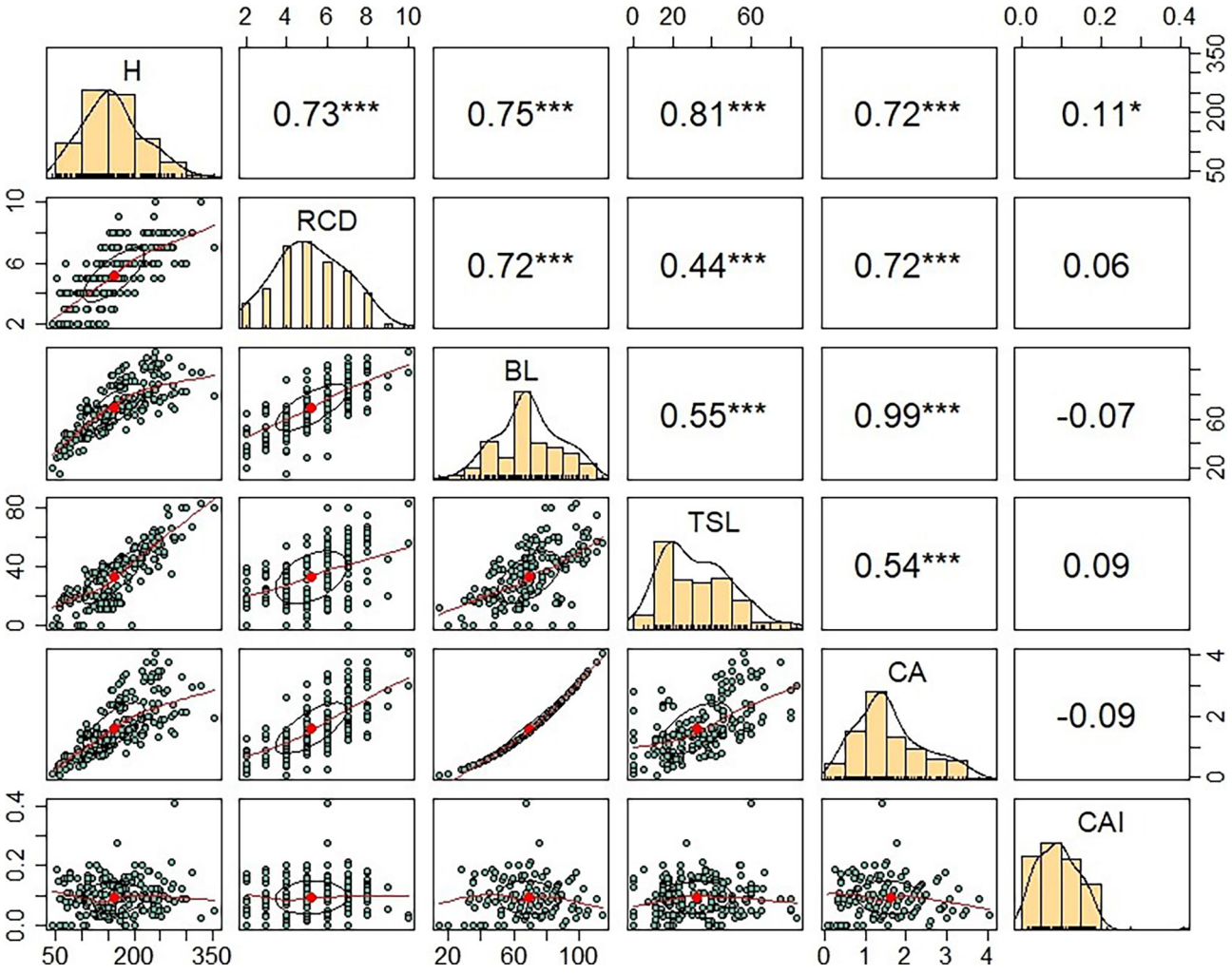

Fig. 3. Pearson correlation analysis results for morphological traits of 10-year-old Scots pine individuals (Diagonal panels show histograms of trait distributions, the lower triangle presents scatter plots with regression curves, and the upper triangle displays Pearson correlation coefficients (r). Asterisks indicate statistical significance: ***$p < 0.001$, *$p < 0.05$; values without asterisks represent non-significant correlations, $p \geq 0.05$)

index, the highest value was 0.116 on the shady aspect at 1600 m, while the lowest value was 0.078 on the sunny aspect at 1750 m, followed by 0.082 on the sunny aspect at 1600 m. The mean crown asymmetry index was 0.099 at an elevation of 1600 m, whereas it was 0.088 at 1750 m. Overall, crown area values were higher under sunny aspect conditions, whereas crown asymmetry index values were higher on shady aspects. The results of the Pearson correlation analysis, which reveal the direction and strength of relationships among morphological traits of 10-year-old Scots pine individuals, are presented in Fig. 3.

In the Pearson correlation analysis plot presented in Fig. 3, the correlation coefficients and significance levels in the upper triangle, together with the scatter plots and regression curves in the lower triangle, provide supporting evidence for the coefficients by visually demonstrating linear trends among the variables. Particularly for variable pairs with statistically significant and high correlation coefficients, the data points formed clear linear patterns.

The correlation analysis results revealed statistically significant ($p < 0.001$) positive relationships among the morphological traits of 10-year-old Scots pine individuals, with the exception of the crown asymmetry index. In particular, a strong correlation was observed between height and terminal shoot length (r = 0.81). Similarly, height showed strong correlations with root collar diameter (r = 0.73) and branch length (r = 0.75). The correlation between root collar diameter and branch length was strong (r = 0.72), whereas the relationships of root collar diameter with terminal shoot length (r = 0.44) and of branch length with terminal shoot length (r = 0.55) were moderate. In addition to the very strong correlation between crown area and branch length (r = 0.99), crown area also showed strong correlations with height (r = 0.72) and root collar diameter (r = 0.72). By contrast, no significant correlations were observed between the crown asymmetry index and other morphological traits ($p \geq 0.05$), except for weak but statistically significant ($p < 0.05$) positive correlation with height (r = 0.11). The univariate analysis results concerning the effects of elevation, aspect, and elevation × aspect interaction on the morphological traits of 15-year-old Scots pine individuals are presented in Table 2.

Table 2. Univariate analysis results for 15-year-old Scots pine individuals

		Elevation	Aspect	Elevation × Aspect
H	F	773.793	205.270	36.047
	p	0.000**	0.000**	0.000**
RCD	F	17.719	81.594	18.723
	p	0.000**	0.000**	0.000**
BL	F	9.102	9.110	6.510
	p	0.003**	0.003**	0.011*
BHD	F	4.910	71.378	4.097
	p	0.027*	0.000**	0.044*
CA	F	4.119	12.537	9.538
	p	0.043*	0.000**	0.002**
CAI	F	5.221	3.452	6.655
	p	0.023*	0.064	0.010*

* $p < 0.05$: Statistically significant difference at the 95% confidence level.

** $p < 0.01$: Statistically significant difference at the 99% confidence level.

When Table 2 is examined, statistically significant differences at the 99% confidence level were detected in height and root collar diameter of 15-year-old Scots pine individuals with respect to elevation, aspect, and elevation × aspect interaction. For branch length, the factors of elevation and aspect, and for diameter at breast height, the aspect factor, also revealed statistically significant differences at the 99% confidence level. In addition, the interaction of elevation × aspect for branch length, as well as elevation and elevation × aspect interaction for diameter at breast height, yielded significant differences at the 95% confidence level. For crown area, the elevation factor showed significance at the 95% confidence level, while aspect and elevation × aspect interaction exhibited significance at the 99% confidence level. Regarding crown asymmetry index, only elevation and elevation × aspect interaction were found to be significant ($p < 0.05$), whereas the aspect factor, despite approaching the threshold ($p = 0.064$), was not considered statistically significant. Among the results of the univariate analysis, the most striking finding was the dominant effect of elevation on height, reflected in the extremely high F-value (F = 773.793). The mean values of height, root collar diameter, branch length, and diameter at breast height for 15-year-old Scots pine individuals are shown in Fig. 4.

In 15-year-old Scots pine individuals, the highest height value was measured as 581.3 cm at 1600 m elevation on the shady aspect, while the lowest value was recorded as 326.1 cm at 1750 m on the sunny aspect. The mean height value was 520.4 cm at 1600 m, which was markedly higher than the mean value of 351.3 cm at 1750 m. Regarding root collar diameter, the maximum value was 14.2 cm at 1600 m on the shady aspect. The lowest root collar diameter (10.4 cm) occurred on the sunny aspect at both elevation levels. In terms of mean values, root collar diameter averaged 12.3 cm at 1600 m and 11.1 cm at 1750 m. For branch length, the highest value was observed on the shady aspect at 1750 m with 114.6 cm, followed by 113.6 cm on the shady aspect at 1600 m and on the sunny aspect at 1750 m. The lowest value was measured as 102.0 cm on the sunny aspect at 1600 m. The mean branch length was 107.9 cm at 1600 m and 114.1 cm at 1750 m. A similar pattern was observed for diameter at breast height, with the highest value recorded as 9.8 cm at 1600 m on the

shady aspect. The lowest value was 7.3 cm on the sunny aspect at 1750 m. The mean values for the diameter at breast height were 8.6 cm at 1600 m and 8.1 cm at 1750 m.

Crown area reached its maximum mean value of 4.36 m^2 at 1600 m elevation on the shady aspect, whereas the minimum mean value (3.30 m^2) was observed on the sunny aspect at the same elevation. At 1750 m elevation, crown area values were 4.19 m^2 on the shady aspect and 4.12 m^2 on the sunny aspect, showing similar magnitudes. Regarding the crown asymmetry index, the highest value was 0.076 on

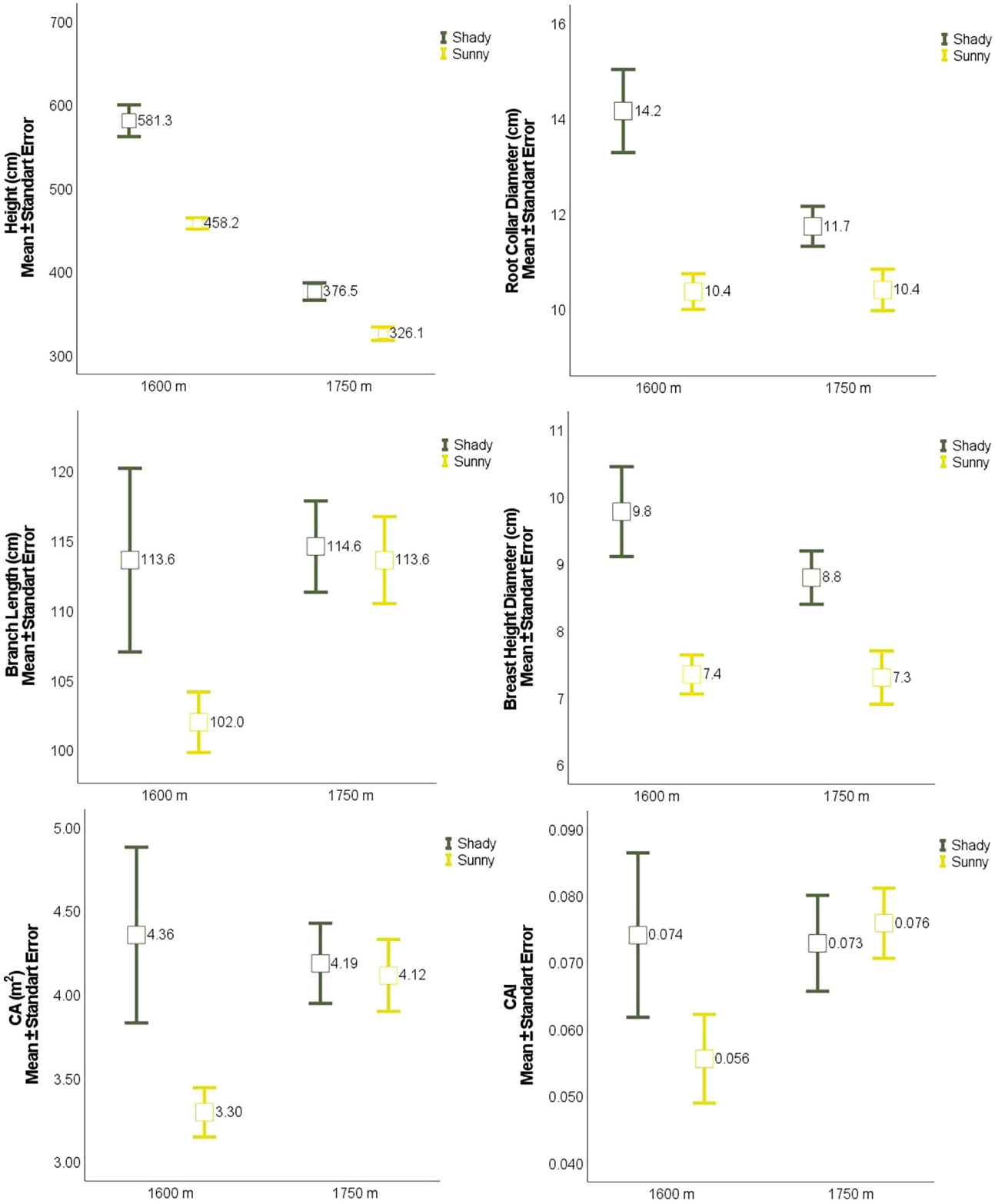

Fig. 4. Mean values of morphological traits in 15-year-old Scots pine individuals

the sunny aspect at 1750 m, while the lowest value was 0.056 on the sunny aspect at 1600 m. In general, crown asymmetry index values were lower in 15-year-old individuals compared to those observed in 10-year-old individuals. The results of the Pearson correlation analysis for morphological traits of 15-year-old Scots pine individuals are presented in Fig. 5.

When the Pearson correlation analysis results presented in Fig. 5 are examined, the crown asymmetry index showed negative and statistically significant correlations with height ($p < 0.01$) and with root collar diameter, branch length, diameter at breast height, and crown area ($p < 0.001$). Apart from these relationships, all other morphological traits exhibited positive and highly significant correlations ($p < 0.001$). The correlation coefficients and significance levels presented in the upper triangle of the graph support the scatter plots and regression trends in the lower triangle. Particularly for variable pairs with strong positive correlations, clear linear distributions were observed.

As in the correlation findings for 10-year-old Scots pine individuals, the highest correlation coefficient (r = 0.99) in 15-year-old individuals was observed between branch length and crown area calculated from these lengths. A very strong positive correlation was also found between root collar diameter and diameter at breast height (r = 0.93). Root collar diameter showed moderate positive correlations with height (r = 0.59) and branch length (r = 0.56). Similarly, diameter at breast height was moderately correlated with height (r = 0.53) and branch length (r = 0.62). By contrast, the correlation between height and branch length was weak (r = 0.28). Crown area exhibited weak positive correlations with height (r = 0.33) and moderate positive correlations with root collar diameter (r = 0.59) and diameter at breast height (r = 0.64). The crown asymmetry index showed weak negative correlations

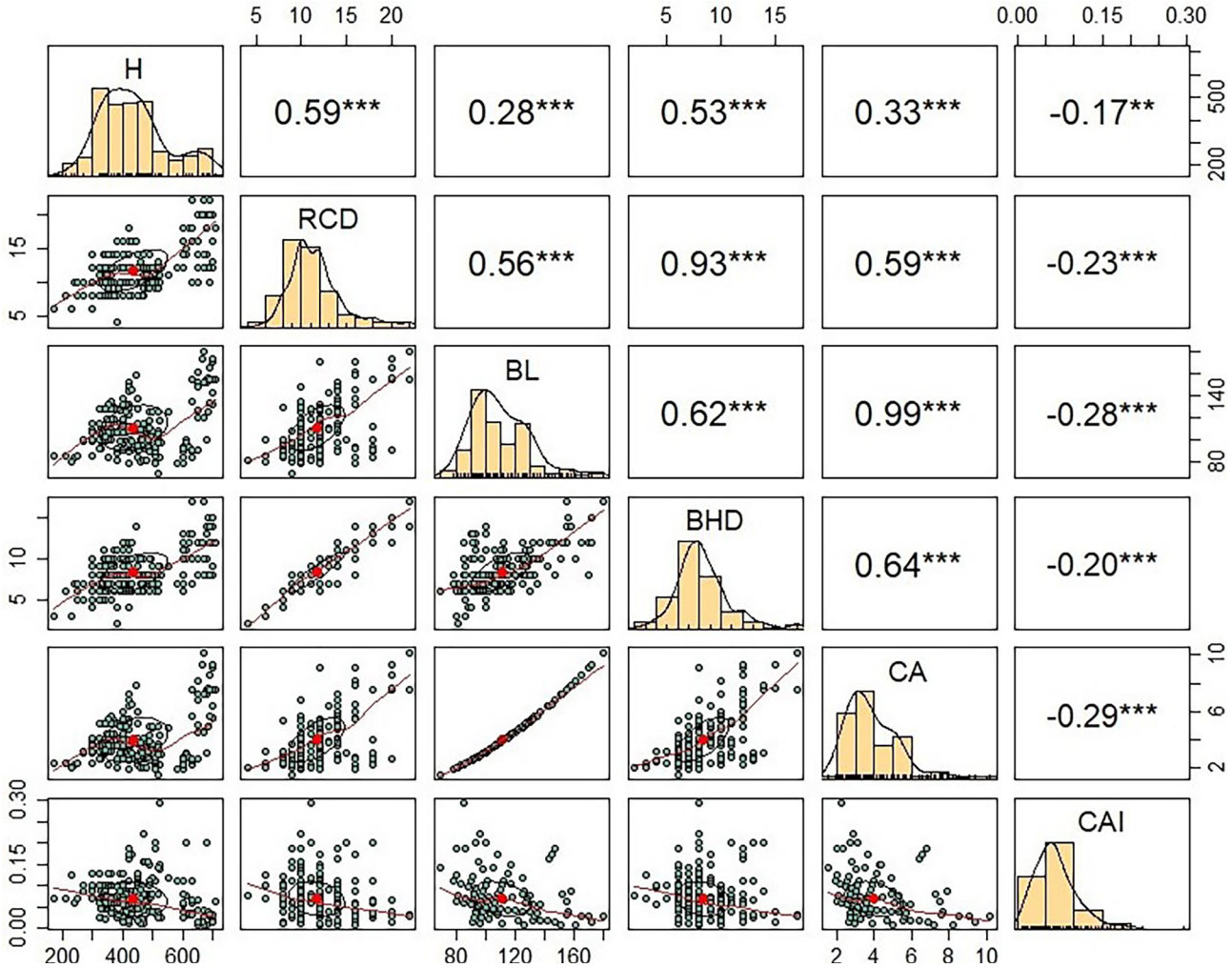

Fig. 5. Pearson correlation analysis results for morphological traits of 15-year-old Scots pine individuals (Diagonal panels show histograms of trait distributions, the lower triangle presents scatter plots with regression curves, and the upper triangle displays Pearson correlation coefficients (r). Asterisks indicate statistical significance: ***$p < 0.001$, **$p < 0.01$)

with all traits. The correlation coefficients were $r = -0.17$ with height, $r = -0.23$ with root collar diameter, $r = -0.28$ with branch length, $r = -0.20$ with diameter at breast height, and $r = -0.29$ with crown area.

Discussion

In this study, the effects of different elevation (1600 and 1750 m) and aspect (sunny and shady) conditions on the morphological traits of 10- and 15-year-old Scots pine (*Pinus sylvestris* L.) individuals were evaluated in the Green Belt Afforestation sites of the Aslandag Provincial Forest, located within the boundaries of Bayburt province. The results demonstrated that, in both age groups, elevation and aspect factors exerted statistically significant effects on the morphological traits.

Comparisons with similar studies in the literature reveal that the environmental factors influencing the morphological development of Scots pine individuals can exert effects in different directions depending on age. Turna and Güney (2009) found that among 23 morphological characters of Scots pine populations in northern Türkiye, altitude was a major factor differentiating groups, which supports the present finding that elevation significantly influenced the morphological traits of Scots pine individuals in the Bayburt region, Türkiye. In studies aimed at tree growth patterns along altitudinal gradients, Fernández-Pérez et al. (2019) reported that Scots pine growth increased at low altitudes over the last several decades, whereas growth slowed at higher elevations, a trend consistent with our finding that the lowest elevation (1600 m) yielded the highest mean height values. Similarly, Sewerniak (2016) observed that in naturally regenerated stands on inland dunes in Poland, Scots pines growing on north-facing slopes were significantly taller and thicker than those on south-facing slopes, which aligns with our finding that shady aspects provided more favorable conditions for height and diameter growth. In addition, Zhirnova et al. (2020) concluded that slope orientation played the main role in defining the climatic response of Scots pine growth, indicating that its influence could be stronger than that of elevation. Moreover, Seyis and Özalp (2022) reported that in an afforestation site established with 1 + 2 year-old Scots pine seedlings in 2012 and assessed in 2018 (corresponding to nine-year-old individuals), survival was higher on north-facing slopes, whereas seedlings on south-facing slopes attained greater height. As in our study, these results suggest that there may not be a universally valid condition for all morphological traits, since their responses are likely to vary depending on age, elevation, and aspect.

In a study conducted in the Şavşat-Tepeköy region, measurements of seedling height, root collar diameter, and current annual shoot length were carried out in 2005 on 2 + 0 Scots pine seedlings planted in 2003. According to the findings, the highest mean seedling height was 39.86 cm, recorded at 1749 m elevation in a southeast-facing plot, while the highest mean current annual shoot length was 15.66 cm, measured at 1755 m elevation in a northwest-facing plot. For root collar diameter, the highest mean value of 10.63 mm was determined in plots at 1772 m elevation with a southwest aspect and at 1743 m elevation with a south aspect (Durmuş, 2006). In a similar study conducted in the Kars-Sarıkamış region, measurements performed in 2008 on seedlings planted in 1991 at age 2 + 0 revealed that the highest mean height value was 398.00 cm at 2267 m elevation in a north-facing plot, while the highest mean diameter at breast height was 88.97 mm at 2169 m elevation in a northwest-facing plot. Furthermore, the highest mean current annual shoot length was recorded as 40.74 cm at 2291 m elevation in a southwest-facing plot (Ayar, 2008).

Based on the findings of these studies, a comparative analysis with the present research demonstrates that variations in morphological traits become more pronounced with age and environmental conditions. In the study conducted by Durmuş (2006), the fact that the highest morphological values were predominantly measured under sunny aspect conditions suggests that individuals in the early age stages may exhibit a faster initial growth in environments with higher light intensity and relatively warmer microclimatic conditions. This may be related to the greater sensitivity of young seedlings to fluctuations in moisture and temperature due to their still underdeveloped root systems. Therefore, in this age group, well-lit areas with higher photosynthetic capacity may have provided a short-term stimulatory effect on growth. By contrast, when compared with the young seedlings examined by Durmuş (2006), both the present study and the research of Ayar (2008) – which can be considered as addressing later age stages of Scots pine – reported that the highest morphological values were obtained under shady aspect conditions. Taken together, both studies indicate that individuals between approximately 10 and 20 years of age tend to achieve greater height and diameter growth in aspects where light intensity is lower and moisture conditions may be relatively more stable. This can be explained by the increasing leaf area and the need to maintain water/carbon balance with age, which turns the more moderate microclimatic conditions of shady aspects into an environmental advantage supporting growth. Furthermore, in line with the results of the present study where the highest mean height values were observed at 1600 m elevation, it has also

been reported that height growth generally decreases with increasing elevation (Çepel, 1976).

Tree crown structure is influenced by a wide range of factors, including environmental conditions (Loubota Panzou & Feldpausch, 2020), structural properties of trees (Feldpausch et al., 2011; Banin et al., 2012; Loubota Panzou & Feldpausch, 2020), and forest dynamics and carbon sequestration (Brienen et al., 2015; Hubau et al., 2020). Various crown asymmetry indices, developed for purposes such as assessing tree growth and competition, stand dynamics, stem form, crown architecture, and treefall risk, have been reported to serve as important indicators for understanding tree responses to environmental conditions (Curtin, 1970; Kio, 1970; Franco, 1986; Young & Hubbell, 1991; Young & Perkocha, 1994; Umeki, 1995; Lei et al., 2012).

In this study, the highest mean crown area in the 10-year-old group was 2.21 m^2 at 1600 m elevation on the sunny aspect, followed by 1.78 m^2 on the shady aspect at the same elevation. In contrast, in the 15-year-old group, the largest crown area was recorded as 4.36 m^2 on the shady aspect at 1600 m. These findings indicate that younger individuals tend to exhibit greater crown expansion on sunny aspects, whereas older individuals develop more pronounced crown forms under shady conditions. This suggests that, with increasing age, variations in crown architecture may occur due to changes in light requirements and competition with neighboring trees. Another noteworthy point regarding crown area is the near doubling of its mean values with increasing age. In fact, Htoo et al. (2024) stated that crown area is approximately proportional to light interception capacity and plays a decisive role in individual growth rates. Similarly, Seidel et al. (2015) reported that horizontal crown expansion, i.e., the increase in crown area, is one of the most important indicators of individual tree growth. In the present study, the very strong correlation between crown area and branch length, together with the moderate to strong correlations with height and diameter, demonstrates the coordinated integration of lateral growth–related crown expansion and overall tree growth.

In terms of crown asymmetry index, the highest value in the 10-year-old group within the scope of this study was 0.116 on the shady aspect at 1600 m, while in the 15-year-old group it was 0.076 on the sunny aspect at 1750 m. The crown asymmetry index may be influenced by various environmental factors, and our findings suggest that as trees age, this index tends to decrease, with crowns exhibiting a more balanced growth pattern. This tendency implies that crown architecture may gradually stabilize with increasing age, resulting in a more symmetrical canopy structure under relatively consistent environmental conditions. Similar results were reported by Rouvinen and Kuuluvainen (1997), who found in Scots pine that local competition had only a minor effect on crown base height and crown width, whereas crown asymmetry was largely shaped by plastic responses to the directionality of solar radiation. They emphasized that developmental plasticity in crown architecture was influenced both by the spatial distribution of neighboring trees and by environmental factors, particularly light geometry. Furthermore, Saarinen et al. (2022) showed that in Scots pine individuals, increasing stem density reduced crown size, whereas thinning enhanced crown dimensions. Indeed, Getzin and Wiegand (2007) emphasized that the spatial relationship between crowns and stem positions is complex (crown asymmetry) and can be shaped by large- and small-scale light heterogeneity as well as mechanical constraints. Similarly, Kong et al. (2021) attributed asymmetric crown development to the adaptive morphological responses (plasticity) of individual trees to continuously changing light conditions, driven by competition for the unidirectional resource of light within stands.

The absolute growth rate of individual trees varies depending on their size (morphological traits) (Stephenson et al., 2014; Sheil et al., 2017). In general, larger trees tend to exhibit higher growth rates than smaller individuals, as they are able to capture essential resources such as light and nutrients more efficiently (Binkley et al., 2013). In this context, not only morphological traits such as height, diameter, and branch length, but also crown-related characteristics such as crown area and crown asymmetry index can be considered important determinants of growth performance, as they reflect the capacity of individuals to utilize environmental resources more effectively.

Conclusion

The findings of this study clearly demonstrate that environmental factors such as elevation and aspect play a decisive role in the morphological development of Scots pine individuals. In particular, shady aspect conditions at 1600 m elevation were found to provide the most favorable environment, as they generally yielded the highest mean values for key growth parameters such as height, diameter, and crown area in both the 10- and 15-year-old groups. This highlights the positive influence of low elevation and moist, semi-shaded microclimatic conditions on individual development. Crown area was found to be strongly associated with morphological development in both age groups. In addition, the marked increase in crown area with age and the strengthening of correlations among traits suggest that the growth process progresses in a coordinated and integrated manner.

On the other hand, the crown asymmetry index varied depending on the interaction among age, elevation, and aspect, showing an overall decreasing trend with increasing age. Also, this index showed either no significant relationships or weak correlations with other morphological traits. This indicates that crown morphology becomes more balanced over time, the morphological response to environmental factors may vary throughout the developmental process, being shaped primarily by environmental constraints rather than by individual development per se.

For Scots pine, age-dependent light requirements and growth strategies should be considered in silvicultural planning, and differentiated practices should be developed based on elevation and aspect for different age stages. Consequently, particularly in young stands, monitoring crown morphology along with key morphological traits such as height, root collar diameter, diameter at breast height, and branch length, as well as evaluating the interactions of these traits with environmental conditions, may provide important insights into understanding growth potential and planning silvicultural interventions more effectively. In the future, research should integrate morphological data with physiological measurements (e.g., chlorophyll content, water potential) to enable a more comprehensive and holistic understanding of individual responses to environmental stress.

Authors' contribution

İT planned the study, contributed to fieldwork, and assisted in manuscript revision. TG carried out the field measurements, organized the dataset, and prepared the initial draft of the manuscript. AB contributed to the planning of the study, performed the statistical analyses, participated in fieldwork, and finalized the manuscript. FA contributed to the planning of the study, participated in fieldwork, and supported the statistical analyses. DG contributed to the study design and provided support in manuscript preparation and overall conceptualization of the study.

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