

Early Tending Alters Growth and Height-Diameter Relationship in Turkish Red Pine (*Pinus brutia* Ten.) Seedlings

Ayşe Kaya ^a and Figen Çakır ^{b,*}

Early tending, involving the selective removal of competing seedlings to regulate density in young stands, is an important silvicultural practice for reducing competition, yet its short-term effects on growth dynamics of *Pinus brutia* seedlings are not well understood. Here, the impact of early tending was evaluated by comparing five treated and five control plots over 2.5 years, measuring seedling height and root-collar diameter. Tending reduced seedling density by approximately 89.7%, resulting in significantly accelerated growth; mean height and diameter in tended plots were 215 and 5.19 cm, respectively, compared to 111 and 2.51 cm in controls. Growth increments were about 3.7 and 3.6 times greater in tended plots. Additionally, tending altered the height–diameter relationship, indicating altered coordination between height and radial development. These findings demonstrate that early tending not only enhances growth magnitude but also reshapes growth trajectories in *Pinus brutia* seedlings, supporting its role as an effective silvicultural intervention to improve stand development under high competition.

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Contact information: a: Çankırı Karatekin University, Institute of Science, 18200, Çankırı, Türkiye;

b: Çankırı Karatekin University, Faculty of Forestry, Department of Silviculture, 18200, Çankırı, Türkiye;

* Corresponding author: figencakir@karatekin.edu.tr

INTRODUCTION

Turkish red pine (*Pinus brutia* Ten.) is one of the principal coniferous species in the Eastern Mediterranean basin. It is valued in Türkiye for its wide natural distribution and extensive use in afforestation. In its juvenile stage, the species often forms dense stands, leading to intense competition among individuals for light, water, and nutrients. This heightened competition can suppress growth in young stands and hinder the development of desirable future stand structures. Consequently, early density regulation is recognized as a fundamental silvicultural practice to support individual growth and guide stand development (Boydak 2004; Erkan *et al.* 2017).

In this study, early tending refers to a set of silvicultural treatments applied during the juvenile regeneration stage, primarily involving selective density reduction to alleviate competition, together with the removal of poorly formed, damaged, diseased, or suppressive seedlings and competing vegetation. Although selective thinning was a major component of the treatment, early tending is used here as the broader term because the intervention included additional juvenile stand-care operations. Previous studies on various conifer species have shown that diameter growth is generally more responsive to tending

treatment, while height growth exhibits a more variable response depending on species, age, habitat, and intervention intensity (Petersson 1993; Pothier 2002; Pitt and Lanteigne 2008). Similarly, research in Türkiye on young stands of *Pinus nigra* Arnold. and *Picea orientalis* L. has demonstrated significant effects of early tending on growth parameters (Bayar and Deligöz 2020; Atar 2022). However, evaluating the effect of tending solely through average height and diameter values may be insufficient. Assessing growth trajectories provides deeper insight, as silvicultural interventions can alter not only the total amount of growth but also its temporal pattern.

In young Turkish red pine stands under Mediterranean conditions, tending treatments are important not only for increasing average growth but also for reshaping growth dynamics by reducing competitive pressure. Lower stand density increases the growing area, light, and soil resources available to each seedling, which can influence both height and diameter development. Previous studies have shown that the intensity of silvicultural interventions is decisive for growth and increment relationships in Turkish red pine (Erkan *et al.* 2017), and that reducing competition can also affect biomass allocation and developmental patterns in various species (Alfaro-Sánchez *et al.* 2015; Güney *et al.* 2022).

One important but less studied aspect of tending is its ability to influence the morphological development of individuals, particularly the height-diameter relationship. The allometric relationship between height and diameter provides important information about resource allocation, structural balance, and competition strategies of individuals. Recent studies have shown that thinning and similar density management practices can alter the height-diameter relationship of trees, indicating changes in allometry that are often closely linked to the level of competition (Deng *et al.* 2019; Qiu *et al.* 2021). Therefore, the effects of tending should be evaluated not only in terms of increased growth, but also in terms of the type of growth response generated.

However, there are few studies that comprehensively examine the effects of early tending on short-term growth trajectories, reduction of competition, and height-diameter relationships in young *Pinus brutia* seedlings. Most existing research focuses on stands at later developmental stages or on stand-level increment relationships, while the effects of sharply reducing density at the seedling stage on individual growth patterns remain less well understood (Boydak 2004; Erkan *et al.* 2017). This knowledge gap is particularly important for young stand management in Mediterranean ecosystems.

This study aimed to evaluate the short-term effects of early tending in high-density young *Pinus brutia* stands. Specifically, temporal changes in seedling height and root-collar diameter were compared between treated and untreated areas, the effect of reduced competition following treatment on growth was examined, and the potential alteration of the height-diameter relationship due to treatment was assessed. The main hypothesis is that early tending will significantly reduce competitive pressure, accelerate the growth trajectory of *Pinus brutia* seedlings, and lead to differentiation in height-diameter relationships over time.

EXPERIMENTAL

Study Area and Experimental Design

The study area is located within the Çakıllı Forest Subdistrict of Çamlıyayla, Mersin, southern Türkiye, on the Mediterranean-facing slopes of the Taurus Mountains

(Fig. 1). The experimental plots are situated at approximately 830 to 900 m a.s.l. and have a predominantly south–southeastern aspect. The region is characterized by a Mediterranean climate with hot, dry summers and cool, wetter winters. Based on long-term records from the Tarsus meteorological station, mean annual temperature is 17.9 °C and annual precipitation is approximately 503.3 mm. The highest monthly mean maximum temperature occurs in August (32.3 °C), whereas the lowest monthly mean minimum temperature occurs in January (4.0 °C). Precipitation is strongly seasonal, ranging from 2.4 mm in August to 127.3 mm in December. Because the experimental site is at a substantially higher elevation than the meteorological station, local conditions are expected to be cooler and are additionally influenced by the complex topography of the Taurus Mountains. The site is developed on sedimentary geological formations dominated by limestone, sandstone, and marl. Soils are typical red Mediterranean soils with a sandy-clay texture, slightly alkaline reaction, high carbonate content, and relatively high organic matter content.

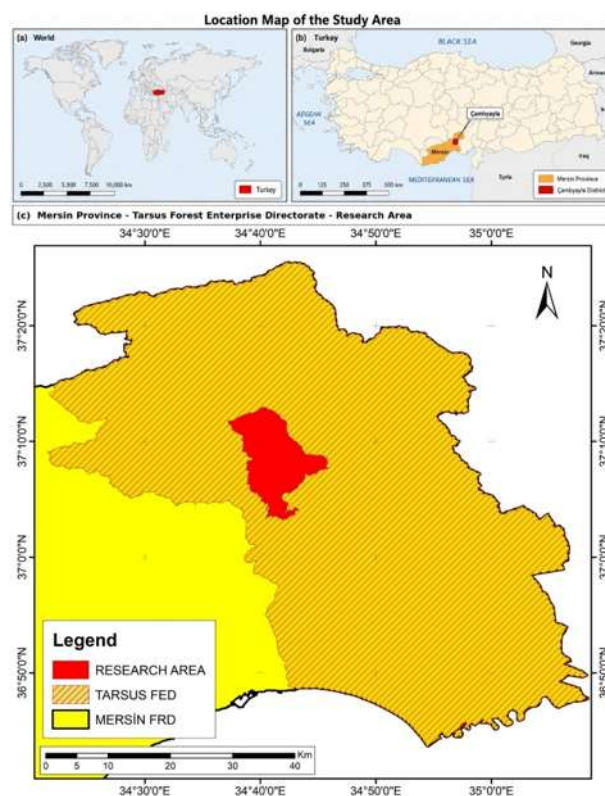


Fig. 1. The study was carried out in the natural regeneration area of *Pinus brutia* located in Çamlıyayla District of Mersin Province, Türkiye

This study was conducted in 10 experimental plots that were established to determine the effects of tending treatment on seedling growth in young *Pinus brutia* regeneration stands. Five experimental plots received the early tending treatment, whereas five were left untreated as controls. Each experimental plot was 100 m² (10 m × 10 m) in size. Tending treatment was carried out in March 2023, when the seedlings were 3 years old, and measurements were started immediately after the tending treatment.

In the tended areas, the mean seedling density before treatment was 520 individuals per 100 m², which decreased to 51 individuals per 100 m² after treatment. In the control

areas, the density remained at a mean of 435 individuals per 100 m². Accordingly, the treatment intervention reduced the seedling density by a mean of 89.7% in the treated areas.

Measurements

Measurements were taken on four different dates: March 2023, November 2023, October 2024, and October 2025. In tended plots, the number of seedlings remaining in the area after the intervention was measured. In control areas, 40 seedlings were sampled from each area. Seedling height (cm) and root-collar diameter (cm) were recorded for each individual. Thus, a temporal dataset covering four consecutive measurement periods was created for both variables.

The tending treatment was selective rather than random. Selective thinning constituted the principal density-regulation component of the early tending treatment. Seedlings showing poor development, severe forking, excessive leaning, weak vigor, disease or visible damage, as well as individuals contributing to excessive crowding or suppression, were removed. Spacing and the target number of retained seedlings per unit area were also considered, and seedlings with better form and greater potential for future development were retained whenever possible. Removed seedlings were cut at the root-collar level. In control plots, no tending treatment was applied apart from the removal of individuals visibly affected by insects, fungi, or other damage; 40 seedlings per plot were then selected randomly for measurement. These individuals were not permanently marked or tagged (*e.g.*, with ribbons), and individual identity was not tracked across measurement dates.

Descriptive statistics in tended and control areas were calculated as mean $\pm$ standard deviation for each measurement period. Cumulative increases in height and diameter from March 2023 to October 2025 were also determined. After tending, seedling density per hectare served as an indicator of competitive pressure.

Statistical Analysis

In the analysis of the height and root-collar diameter data obtained within the scope of the research, a two-way mixed-design repeated measures analysis of variance (ANOVA) was used to evaluate the effects of tending and time together on growth. In the analysis model, tending status (early tending applied/control) was defined as a constant between-group factor (between-subject factor), and measurement time (March 2023, November 2023, October 2024, and October 2025) was defined as a repeated within-group factor (within-subject factor). Analyses were conducted separately for the dependent variables, height and root-collar diameter.

The statistical model can be expressed as follows,

$$Y_{ijk} = \mu + T_i + Z_j + (T \times Z)_{ij} + \varepsilon_{ijk} \quad (1)$$

where Y_{ijk} represents the dependent variable (height or root-collar diameter) measured in the i -th treatment group, at the j -th measurement time, and at the k -th observation unit, μ represents the overall mean, T_i represents the effect of tending, Z_j represents the effect of time, $(T \times Z)_{ij}$ is the tending $\times$ time interaction, and ε_{ijk} is the error term.

The following effects were tested as part of this analysis:

- Time as the main effect: overall variation depending on measurement periods.
 - Main effect of tending: overall difference between tended and control groups.
 - Time $\times$ tending interaction: whether the tending effect changes over time.
- eta-squared (η_p^2) values were reported to evaluate the effect size.

Independent-samples t-tests were used to evaluate differences between the tended and control groups separately at each measurement period. In these analyses, the mean difference between the two groups in terms of height and root-collar diameter was tested for each date.

To evaluate the effect of competition release following tending on growth, the relationships between post-tending seedling density and cumulative height and diameter increments during the period March 2023 to October 2025 were examined using linear regression analysis. The basic model used was as follows:

$$G_i = \alpha + \beta D_i + \varepsilon_i \quad (2)$$

Here, G_i represents the cumulative growth increment (height or diameter increment) in the relevant plot, D_i the seedling density after tending (seedling ha^{-1}), α the constant term, β the regression coefficient, and the error term is ε_i .

An allometric model was used to examine whether tending application affects the height-diameter relationship of the seedlings using the October 2025 data,

$$\ln(H_{\text{seedling}}) = a + b \ln(D_{\text{root}}) \quad (3)$$

where H_{seedling} represents seedling height (cm), D_{root} represents root-collar diameter (cm), a is the intercept, and b is the allometric slope coefficient. Separate allometric models were fitted for tended and control seedlings. For each model, the intercept and slope coefficients, their standard errors, 95% confidence intervals, coefficient of determination (R^2), F-statistic, and associated p-values were calculated.

To formally test whether the height-diameter relationship differed between tended and control seedlings, a combined model including treatment and the interaction between treatment and $\ln(D)$ was additionally fitted,

$$\ln(H) = \beta_0 + \beta_1 \ln(D) + \beta_2 T + \beta_3 [\ln(D) \times T] + \varepsilon \quad (4)$$

where T is a categorical treatment variable coded as 0 for control seedlings and 1 for tended seedlings. In this model, β_0 represents the intercept for the control group, β_1 represents the height-diameter slope for the control group, β_2 represents the difference in intercept between tended and control seedlings, and β_3 represents the difference in allometric slope between the two treatments. A significant $\ln(D_{\text{root}}) \times T$ interaction was interpreted as evidence that tending significantly altered the height-diameter relationship.

For biological interpretation, the fitted log-linear allometric model was also expressed on the original measurement scale as:

$$H = \exp(a) \times (D_{\text{root}})^b \quad (5)$$

where $\exp(a)$ is the antilogarithm of the intercept and $(D_{\text{root}})^b$ denotes root-collar diameter raised to the power of the allometric coefficient b .

Prior to analysis, data were examined for normality and homogeneity of variance. Significance $p < 0.05$ was accepted as the level of significance in all statistical evaluations. Statistical analyses were performed using the IBM SPSS Statistics software package.

A mixed-methods repeated measures analysis of variance was chosen to evaluate the temporal variation pattern obtained from repeated measurements, aiming to test both within-group and between-group effects. Independent samples t-tests were applied to separately evaluate the differences between tending and control groups in each measurement period, thus revealing not only the overall pattern over time but also group differences based on dates.

Linear relationships between post-tending density and cumulative growth increments were evaluated as additional analyses to assess the direction of competition release on growth, while the height-diameter relationship was evaluated to examine possible differentiation in the morphological development pattern.

RESULTS

Tending Intensity and Seedling Density

The tending treatment significantly reduced seedling density. In the treated plots, the average density before intervention was 52,020 seedlings ha⁻¹, while after treatment it decreased to 5,080 seedlings ha⁻¹. In the control plots, the average density remained at 43,900 seedlings ha⁻¹ (Table 1). Accordingly, the tending treatment reduced seedling density by an average of 89.7%. This result shows that competitive pressure was significantly reduced in the study.

Table 1. Stand Density Before and After Tending and in Untreated Control Plots

Group	Initial Density (seedlings ha ⁻¹)	Final Density (seedlings ha ⁻¹)	Average Reduction (%)
Tending	52.020	5.080	89.70
Control	43.900	43.900	0.00

Height Growth

At the initial measurement, no significant difference was found in average height between the tending and control plots. In the March 2023 measurement, the mean height was determined to be 76.38 ± 19.25 cm in the tended areas and 73.77 ± 17.94 cm in the control areas, and the difference between the groups was found to be statistically insignificant ($t = 1.483$, $p = 0.139$; Table 2). In contrast, in the November 2023 measurement, this difference became significant; the mean height increased to 95.38 ± 19.82 cm in the tended areas, while it was measured as 82.72 ± 18.07 cm in the control areas, and the difference between the groups became significant ($t = 7.126$, $p < 0.001$). The same trend continued in the October 2024 and October 2025 measurements; In the treated areas, the average height reached 120.60 ± 21.19 cm and 215.24 ± 41.04 cm, respectively, while in the control areas these values were determined as 108.92 ± 24.11 cm and 111.36 ± 20.56 cm. The difference between the groups was found to be highly statistically significant on both dates ($t = 13.881$, $p < 0.001$; $t = 34.127$, $p < 0.001$; Table 2, Fig. 2).

Table 2. Comparison of Height Values (cm) in Tended Plots and Untreated Control Plots During Measurement Periods (Independent Samples t-Test Results)

Treatment	Seedling Height (cm)			
	March 23	Nov. 23	Oct. 24	Oct. 25
Tending	76.38±19.25	95.38±19.82	120.60±21.19	215.24±41.04
Control	73.77±17.94	82.72±18.07	108.92±24.11	111.36±20.56
t	1.483	7.126	13.881	34.127
Sig (2-tailed)	0.139	0.000	0.000	0.000

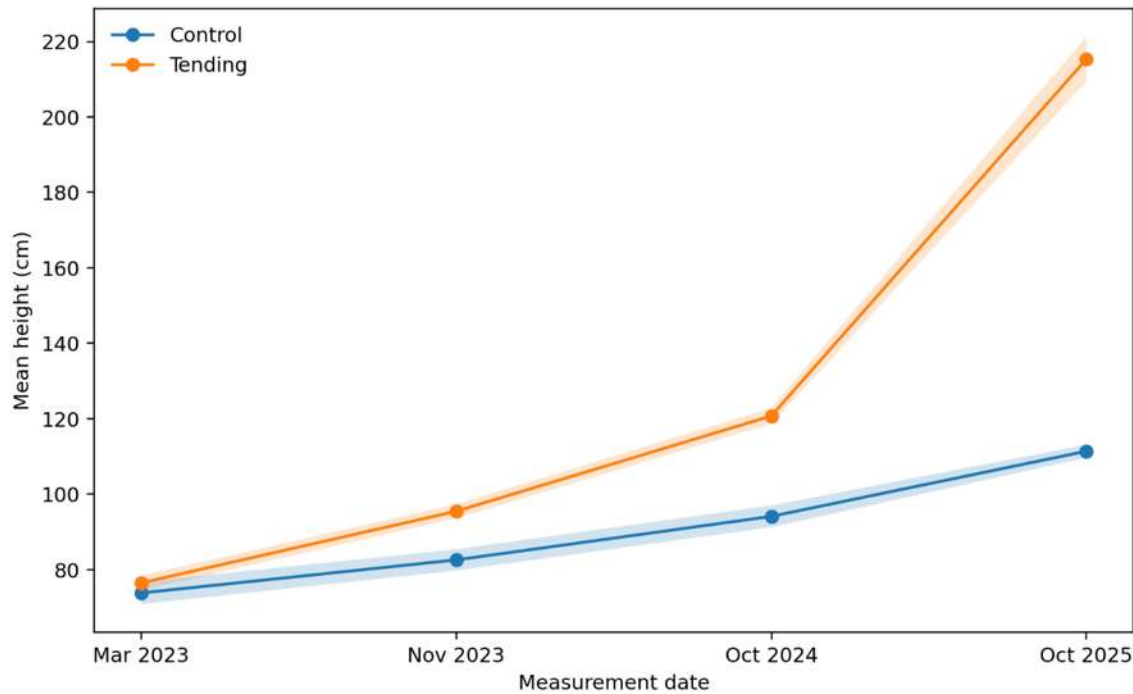


Fig. 2. Height growth trajectories of seedlings in tending and control plots

The repeated-measures ANOVA results for height growth showed that the time factor alone had a very strong effect ($F = 2016.14$, $p < 0.001$, $\eta_p^2 = 0.817$; Table 3). The highly significant time $\times$ intervention interaction ($F = 611.68$, $p < 0.001$, $\eta_p^2 = 0.575$) revealed that height increase occurred much faster over time in the areas where tending was applied compared to the control areas. The intervention factor alone was also significant ($F = 546.39$, $p < 0.001$, $\eta_p^2 = 0.547$). These findings indicate that early tending strongly affects height growth and that this effect becomes more pronounced over time.

Table 3. Repeated Measures ANOVA on the Effects of Time and Treatment on Height Growth in Tending Plots and Untreated Control Plots

Effect (Source)	Degrees of Freedom (df1, df2)	F- value	p - value	Partial Eta Square (η_p^2)
Time	3, 1356	2016.14	0.000	0.817
Time $\times$ Tending	3, 1356	611.68	0.000	0.575
Tending	1, 452	546.39	0.000	0.547

Root-Collar Diameter Development

In terms of root-collar diameter, no significant difference was found between the tending and control plots at the initial measurement. In the March 2023 measurement, the average diameter was determined to be 1.52 ± 0.41 cm in the tending areas and 1.47 ± 0.37 cm in the control areas, and the difference was found to be insignificant ($t = 1.179$, $p = 0.239$; Table 4). However, in the November 2023 measurement, the difference between the groups became significant; the average diameter was measured as 2.06 ± 0.41 cm in the tending areas and 1.87 ± 0.40 cm in the control areas ($t = 4.896$, $p < 0.001$).

In the October 2024 and October 2025 measurements, this difference became even more pronounced; the average diameter in the tending areas was determined to be 2.60 ± 0.42 cm and 5.19 ± 1.39 cm, respectively, and in the control areas 2.22 ± 0.42 cm and 2.51 ± 0.75 cm, respectively. The difference was found to be highly statistically significant on both dates ($t = 9.407$, $p < 0.001$; $t = 24.55$, $p < 0.001$; Table 4, Fig. 3).

Table 4. Comparison of Diameter Values in Tending Treatment Sites and Untreated Control Sites During Measurement Periods (Independent Samples t-Test Results)

Intervention	Seedling Diameter (cm)			
	March 23	Nov. 23	Oct. 24	Oct. 25
Tending	1.52 ± 0.41	2.06 ± 0.41	2.60 ± 0.42	5.19 ± 1.39
Control	1.47 ± 0.37	1.87 ± 0.40	2.22 ± 0.42	2.51 ± 0.75
t	1.179	4.896	9.407	24.55
Sig (2-tailed)	0.239	0.000	0.000	0.000

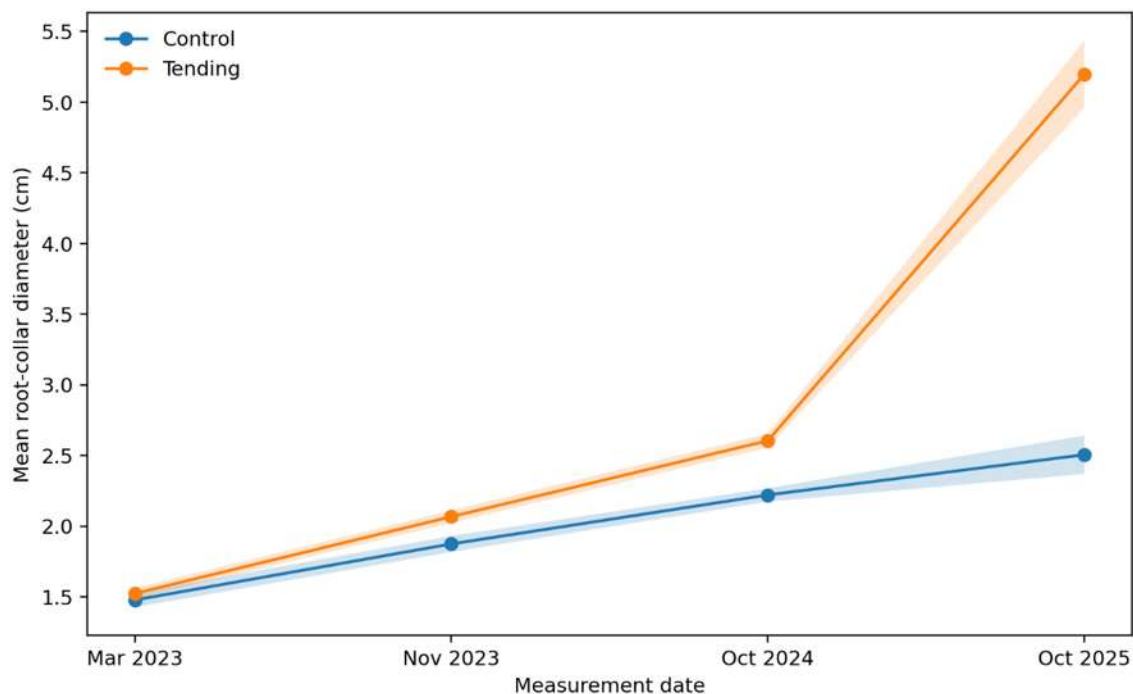


Fig. 3. Diameter growth trajectories of seedlings in tending and control plots

The repeated measures ANOVA results for diameter growth revealed a very strong effect of the time factor ($F = 1473.09$, $p < 0.001$, $\eta_p^2 = 0.765$; Table 5). The highly significant time $\times$ tending interaction ($F = 473.76$, $p < 0.001$, $\eta_p^2 = 0.512$) indicates that diameter development is strongly dependent not only on the natural growth process but also on tending treatment. The intervention factor alone was also found to be significant ($F = 407.82$, $p < 0.001$, $\eta_p^2 = 0.474$). These results show that early tending positively affects root-collar diameter development and that this effect strengthens over time.

Table 5. Repeated Measures ANOVA on the Effects of Time and Treatment on Diameter Growth in Tended and Untended Young Stands

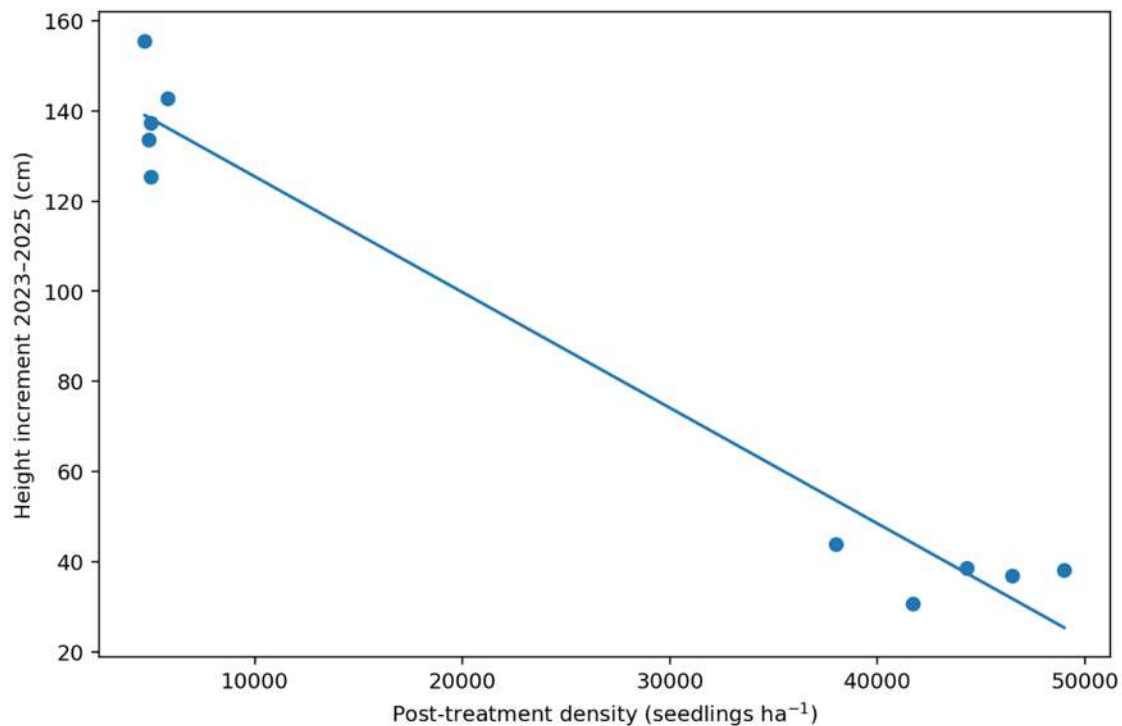
Effect (Source)	Degrees of Freedom (df1, df2)	F- value	p - value	Partial Eta Square (η_p^2)
Time	3,1356	1473.09	0.000	0.765
Time $\times$ Tending	3,1356	473.76	0.000	0.512
Tending	1,452	407.82	0.000	0.474

Cumulative Growth Response

The average height increase in the tended plots between March 2023 and October 2025 was calculated as 138.9 cm, while in the control plots it was 37.6 cm. During the same period, root-collar diameter increased by 3.67 cm in the tended plots and by 1.03 cm in the control plots. Accordingly, the tending treatment increased cumulative height growth by approximately 3.7 times and root-collar diameter growth by approximately 3.6 times. This difference became particularly pronounced during the October 2024 to October 2025 period.

Relationship between Competition Release and Growth

Strong negative correlations were found between post-tending seedling density, and cumulative height and diameter increments during the period March 2023 to October 2025. The linear regression model for cumulative height increment was found to be significant, with each 10,000-seedling/ha increase in post-tending density being associated with a decrease of approximately 25.66 cm in height increment ($\beta = -25.66$, $R^2 = 0.963$, $p < 0.001$; Fig. 4).

**Fig. 4.** Relationship between post- treatment seedling density and cumulative height increment (2023–2025)

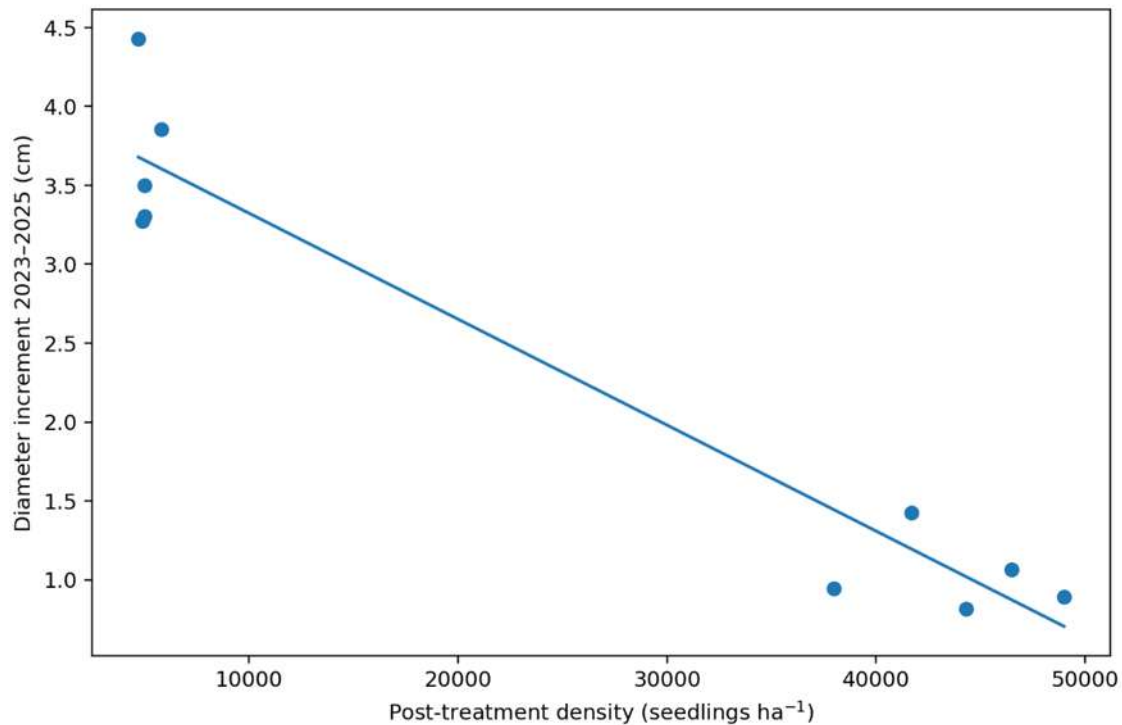


Fig. 5. Relationship between post- treatment seedling density and cumulative diameter increment (2023–2025)

Similarly, a strong negative correlation was obtained for cumulative diameter increment; each 10,000 seedling/ha increase in post-tending density was associated with a decrease of approximately 0.67 cm in diameter increment ($\beta = -0.67$, $R^2 = 0.928$, $p < 0.001$; Fig. 5). These results indicate that reduced competitive pressure is closely related to accelerated growth. However, since post-treatment seedling density is a direct result of the applied intervention, this relationship should be considered not as an independent dose-response pattern, but as a complementary finding supporting the mechanistic effect of treatment on growth.

Height-Diameter Relationship

The height–diameter relationship in October 2025 was evaluated using the allometric model $\ln(H) = a + b \ln(D)$, where H represents seedling height and D represents root-collar diameter. Separate models were fitted for tended and control seedlings (Table 6). In tended seedlings, the fitted relationship was $\ln(H) = 4.5658 + 0.4889 \ln(D)$. The allometric slope was positive and highly significant ($b = 0.4889$, $SE = 0.0324$, $t = 15.108$, $p < 0.001$), and the model explained 47.5% of the variation in log-transformed height ($R^2 = 0.475$). On the original measurement scale, the corresponding equation was $H = 96.1 \times D^{0.4889}$.

In contrast, the fitted relationship for control seedlings was $\ln(H) = 4.7245 - 0.0326 \ln(D)$. The slope did not differ significantly from zero ($b = -0.0326$, $SE = 0.0402$, $t = -0.810$, $p = 0.419$), and the model explained virtually none of the variation in log-transformed height ($R^2 = 0.003$). On the original measurement scale, the corresponding equation was $H = 112.7 \times D^{(-0.0326)}$.

A combined model including treatment and the $\ln(D) \times$ treatment interaction was then used to formally test whether the allometric slopes differed between groups. The

interaction term was highly significant ($\beta = 0.5215$, $SE = 0.0513$, $t = 10.174$, $p < 0.001$), confirming that tending significantly altered the height–diameter relationship. The combined model was highly significant ($R^2 = 0.822$, adjusted $R^2 = 0.821$, $F = 694.03$, $p < 0.001$; $n = 454$). Thus, height and root-collar diameter development were strongly coordinated in tended seedlings, whereas no significant allometric relationship was detected under the high-density control conditions.

Figure 6 illustrates the observed October 2025 height and root-collar diameter measurements together with the fitted allometric curves for tended and control seedlings. The figure visually supports the statistical results by showing a clear positive height–diameter relationship in tended seedlings, whereas the control group exhibits a much weaker and essentially flat relationship.

Table 6. Parameter Estimates and Goodness-of-Fit Statistics for the Height–Diameter Allometric Models of Tended and Control *Pinus brutia* Seedlings in October 2025

Treatment	n	Intercept (a)	SE(a)	Slope (b)	SE(b)	95% CI for b	R ²	F	p
Tending	254	4.5658	0.0529	0.4889	0.0324	0.4252–0.5527	0.475	228.26	< 0.001
Control	200	4.7245	0.0375	−0.0326	0.0402	−0.1118–0.0467	0.003	0.66	0.419

Note. The difference between allometric slopes was tested using a combined model containing the $\ln(D) \times$ treatment interaction. The interaction was highly significant ($\beta = 0.5215$, $SE = 0.0513$, $t = 10.174$, $p < 0.001$).

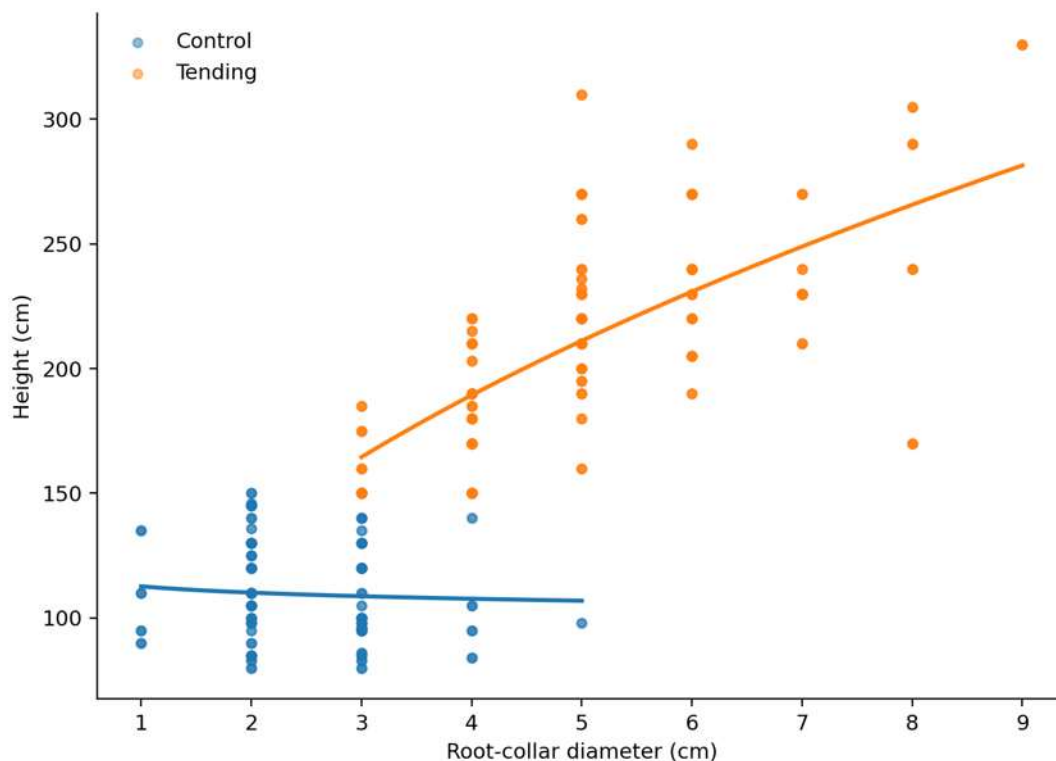


Fig. 6. Height-diameter relationship of *Pinus brutia* seedlings in tended and control plots in October 2025. Fitted curves represent the allometric models. The slight negative slope observed in the control group was not statistically significant ($b = -0.0326$, $p = 0.419$), indicating the absence of a meaningful height–diameter relationship rather than a decline in seedling growth.

DISCUSSION

This study demonstrated that early tending applied to three-year-old *Pinus brutia* seedlings significantly accelerated both height and root-collar diameter development in a short period of time. The lack of a significant difference between the tended and control plots at the initial measurement suggests that the divergence observed in subsequent measurement periods is due to the direct intervention effect, not the initial conditions. This finding is consistent with the silvicultural literature showing that reducing competitive pressure early in young stands can alter growth patterns. Indeed, regeneration management and pre-commercial thinning practices have long been known to accelerate the growth of young individuals; more recent studies, however, show that this effect is not limited to short-term individual growth but can also be decisive in long-term timber production potential and management outcomes (Haikarainen *et al.* 2021; Uotila and Saksa 2021).

The naturally high regeneration density observed in *Pinus brutia* may also provide an ecological advantage during the early establishment phase. Rapid occupation of available growing space by numerous seedlings may contribute to early site dominance and may restrict the establishment or growth of competing vegetation. However, this potential early advantage may gradually decline as the young stand develops and competition among seedlings increases. Thus, high initial density may be beneficial for successful site occupation, whereas subsequent density regulation becomes important for maintaining individual growth. In this context, early tending can be interpreted as a management intervention that follows successful regeneration and reduces the competitive costs associated with excessive seedling density.

The earlier divergence of height growth compared to diameter growth suggests that the reduction in competitive pressure primarily affects light capture and shoot elongation. Superstructure growth in young seedlings, especially in densely populated stands, is highly sensitive to light competition; therefore, an accelerated increase in height after tending is an expected pattern. In contrast, the stronger and later apparent response in diameter growth suggests that the remaining individuals gain an advantage in growth area, root volume, and carbon allocation over time. It has been reported that density reduction interventions in Mediterranean pine stands can alter the growth response not only through total growth but also through the distribution of growth over time and resource use efficiency (Aldea *et al.* 2023; Ordóñez *et al.* 2024). In this respect, the divergence between height and diameter observed in this study indicates that early tending may influence resource competition in young *Pinus brutia* individuals.

The most striking result of the tending treatment is the very strong reduction in competitive pressure. A density reduction of approximately 89.7% translates to a sharp increase in light, water, and nutrient availability per individual. Indeed, the strong negative correlations identified between post-tending density and cumulative height and diameter increases demonstrate that the growth response is closely related to the competition release. However, it should be noted that the post-tending density change is a direct result of the intervention; therefore, the regression relationships identified here should not be considered as independent dose-response evidence, but rather as supporting findings that strengthen the mechanistic interpretation of the treatment effect. This interpretation is also consistent with recent studies examining the effects of different thinning intensities on growth and carbon accumulation in *Pinus brutia* plantations. Erkan *et al.* (2023) showed that while thinning in *Pinus brutia* plantations does not always increase total volume, it can shift growth towards larger individuals and that reduced competition particularly

supports diameter increase. Similarly, recent studies examining the relationship between stand structure and growth efficiency in Mediterranean pine forests reveal that intervention intensity is often more decisive than the intervention method (Ordóñez *et al.* 2024).

Although the 89.7% density reduction applied in this study represents an intensive tending treatment, its interpretation should consider the exceptionally high initial regeneration density. The post-tending density remained approximately 5,080 seedlings ha^{-1} , which is within or above the range of residual densities commonly retained in several pre-commercial thinning studies of young conifer stands (Pettersson 1993; Bayar and Deligöz 2020; Güney *et al.* 2022). Therefore, the high percentage reduction does not necessarily indicate an excessively sparse residual stand. Nevertheless, because only one tending intensity was evaluated, the present study cannot identify an optimal residual density for young *Pinus brutia* stands.

Although tending markedly increased individual seedling growth, the present results should not be interpreted as evidence of increased stand-level wood production. The 89.7% reduction in seedling density represents a substantial shift in stand structure and implies a trade-off between stem number and growth of the remaining individuals. Because the present study did not directly measure stem volume or biomass and no juvenile-specific biomass equation was applied, it is not possible to determine whether the enhanced individual growth fully compensates for the reduction in stem number at the stand level. Therefore, the effects of early tending on total wood production should be evaluated through longer-term measurements of stand-level volume and biomass. From a silvicultural perspective, the enhanced growth of retained seedlings may contribute to the development of larger future crop trees; however, the present study does not provide direct evidence on merchantable timber volume, wood quality, or lumber production.

One of the most notable findings of this study was the marked divergence in the height–diameter relationship between tended and control seedlings by 2025. In tended seedlings, height increased significantly with root-collar diameter, with an allometric slope of 0.489, whereas no significant height–diameter relationship was detected in the control seedlings. More importantly, the significant $\ln(D_{\text{root}}) \times \text{treatment}$ interaction confirmed that the difference between the two allometric slopes was statistically supported rather than reflecting only numerical variation between fitted coefficients. This result suggests that early competition release altered the coordination between height and radial development. Under reduced competition, seedlings were able to maintain a stronger coupling between height and diameter growth, whereas this relationship was substantially weakened under the high-density control conditions. Similar responses have been reported following thinning or reductions in competitive pressure, where changes in stand density can modify height–diameter allometry by altering access to growing space and above- and below-ground resources (Deng *et al.* 2019; Qiu *et al.* 2021). However, because biomass allocation, crown development, and physiological responses were not directly measured in the present study, the observed allometric divergence should be interpreted as evidence of altered morphological growth coordination rather than as direct evidence of changes in biomass allocation. Furthermore, because the allometric comparison was based on the October 2025 measurement, longer-term observations are required to determine whether this divergence persists as stand development proceeds.

The significance of these results within the context of Mediterranean forestry should be emphasized. *Pinus brutia* is a fast-growing species adapted to arid summer conditions and is very important for Turkish forestry; however, it can also be sensitive to environmental limitations such as climate, microtopography, and surface temperature

during regeneration and juvenile stages. A recent study has shown that *Pinus brutia* regeneration success in some low-altitude Mediterranean sites is weakened due to environmental constraints, necessitating a reassessment of traditional silvicultural practices (Kaplan and Özbey 2025). In this context, reducing competitive pressure early in the juvenile stage can be considered not only a growth-accelerating practice but also an adaptive silvicultural tool that can mitigate the impact of climate pressures. Particularly in Mediterranean ecosystems where the risk of drought is increasing, regulating density early can improve access to resources for young individuals, laying the foundation for a more resilient stand structure in later age classes (Aldea *et al.* 2023; Kaplan and Özbey 2025).

From an applied forestry perspective, the findings indicate that early tending should not be delayed in high-density juvenile pine areas. Larger-scale studies on juvenile stand management show that timely tending can positively affect not only short-term growth but also medium- and long-term production potential (Haikarainen *et al.* 2021). It has been shown that the operational timing of thinning applications can also affect management costs (Uotila and Saksa 2021). Although this study does not include an economic analysis, the fact that tending creates a strong growth advantage in a very short time demonstrates that early intervention is clearly justified biologically. Especially at the high initial densities seen in this study, delaying tending can increase inter-individual suppression, leading to irreversible losses in both height and diameter growth.

However, this study had some limitations. First, the monitoring period was limited to approximately 2.5 years; therefore, it is not yet known whether the growth advantage identified here will persist into later years, how it will be reflected in total stand-level production, and how it will affect structural stability. Second, only height and root-collar diameter variables were evaluated; mechanistic variables such as light transmittance, soil moisture, nutrient status, root development, and biomass allocation were not directly measured. Third, the allometric interpretation was based on a single late-stage measurement. Therefore, future studies need to include longer-term monitoring, multiple tending intensities, and eco-physiological variables. In particular, a combined analysis of the relationships between competition reduction, drought tolerance, and morphological response will provide a more robust explanation of the effects of early tending on young *Pinus brutia* development.

Overall, this study demonstrated that early tending not only accelerates the growth rate in young *Pinus brutia* seedlings but also influences the timing, distribution, and morphological organization of this growth. The findings revealed that intensive early tending reduces competitive pressure, creating a rapid growth advantage. This effect was evident not only in height and diameter growth trajectories but also in the significant divergence of the height–diameter relationship between tended and control seedlings. Therefore, early tending in young *Pinus brutia* regeneration areas should be considered not only a density reduction process but also a fundamental silvicultural tool that can influence early stand development trajectory.

Because the present study evaluated only short-term responses, longer-term monitoring is required to determine whether the observed growth advantage persists during subsequent stages of stand development and influences stand structure, stability, productivity, and drought tolerance. Future studies should incorporate mechanistic variables, including light availability, soil moisture, nutrient status, and biomass allocation, to clarify the processes linking competition release to changes in seedling growth trajectories.

CONCLUSIONS

1. Early tending substantially altered the growth dynamics of young *Pinus brutia* seedlings. Following an approximately 89.7% reduction in stand density, both height and root-collar diameter increments increased markedly in the tended plots.
2. Growth trajectories in the tended plots progressively diverged from those in the untreated control plots, demonstrating a rapid release from intense intraspecific competition.
3. The height–diameter relationship differed significantly between tended and control seedlings by 2025, indicating that early tending affected not only the magnitude of seedling growth but also the coordination between height and radial development.
4. Early tending should therefore be considered not merely as a density-reduction treatment, but as an effective silvicultural intervention capable of reshaping both the quantity and pattern of growth in young *P. brutia* stands under high competitive pressure.

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Conflict of Interest

The authors declare that they have no known financial or personal relationships that could have influenced the work reported in this manuscript.

Use of Generative AI

The authors used ChatGPT (OpenAI) to review and improve the English translation of text originally written in Turkish. The tool was used solely for language editing, including improvements in grammar, clarity, and readability. It was not used for data analysis, interpretation of the results, collation of references, or preparation of images, figures, graphs, or diagrams. All AI-assisted text was critically reviewed and revised by the authors, who take full responsibility for the accuracy and content of the manuscript.

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