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ASSESSMENT OF GROWTH PARAMETERS IN *Pinus sylvestris* L. STANDS: FIVE-YEAR RESULTS OF PRECOMMERCIAL THINNING

İbrahim TURNA[1], Fahrettin ATAR[1]*, Ali Osman GÜZEL[2], Fikret KOÇ[3], Giyasettin AKBİN[4], Halil Barış ÖZEL[5]

SUMMARY

Determining the optimal intensities for precommercial thinning (PCT) in *Pinus sylvestris* stands, which hold significant ecological and economic value in Türkiye, is crucial for enhancing growth performance and ensuring well-formed stems. This study investigates the effects of various PCT intensities on the growth parameters of young, naturally regenerated stands located in the Western Black Sea and Central Anatolia regions of Türkiye. A total of 24 experimental plots (4 PCT intensities × 3 replications × 2 sites) were established in thicket-stage stands, and four PCT treatments were applied: T1 (classic), T2 (0.75–1.0 m spacing), T3 (1.5–2.0 m spacing), and a control (unthinned). Diameter at breast height, height, total basal area, and total volume were measured at the end of each growing season for five consecutive years. The results indicated that PCT intensity had a significant effect ($p < 0.05$) on all measured growth parameters. Both DBH and height increments were positively correlated with increased PCT intensity, with the greatest gains observed in the T1 and T3 PCT treatments. In particular, the relative increment values increased in parallel with the rise in PCT intensity in all measured growth parameters. In conclusion, leaving around 3000–3500 stems per hectare during PCT provides the best outcomes in terms of growth and stand structure. The findings suggest that PCT interventions should be performed on a 3–5 year cycle to maximize growth potential and maintain forest health.

KEY WORDS: Scots pine, stand density, thicket stage, tending operation

INTRODUCTION

The application of appropriate silvicultural interventions at the right time and in the correct intensity is critical for effective wood production and controlling stand development in forest ecosystems (Turna et al. 2017). Due to the wide variations in species diversity and stand compositions in Türkiye's forests, which are influenced by different site conditions, these factors play a direct role both in determining the techniques to be used for regeneration and tending and in the success of such interventions (Özel and Ertekin 2010, Atar 2022). Operations such as precommercial thinning and thinning help trees grow as planned, improve wood quality and yield, shorten rotation periods, enhance stand stability, and support biodiversity (Klädtke 2001, Zeide 2001, Nutto et al. 2005, Fahlvik et al. 2018). The planning and implementation of these interventions are essential steps in forest management to ensure the sustainability of the functions provided by forests (Danusevicius et al. 2016).

A basic silvicultural technique called precommercial thinning (PCT) is used in regenerated and juvenile stands to remove trees with little to no economic value in order to enhance and speed up the growth performance of the remaining trees (Chase et al. 2016, Güney et al. 2021). PCT plays a critical role in forest management

[1] Prof. İbrahim Turna, PhD, Assoc. Prof. Fahrettin Atar, PhD, Department of Forest Engineering, Faculty of Forestry, Karadeniz Technical University, Trabzon, Türkiye
[2] Ali Osman Güzel, General Directorate of Forestry, Ankara, Türkiye
[3] Fikret Koç, Directorate of Central Anatolia Forestry Research Institute, General Directorate of Forestry, Ankara, Türkiye
[4] Giyasettin Akbin, Directorate of Aegean Forestry Research Institute, General Directorate of Forestry, İzmir, Türkiye
[5] Prof. Halil Barış Özel, PhD, Faculty of Forestry, Bartın University, Bartın, Türkiye
* Corresponding author: Fahrettin Atar, email: fatar@ktu.edu.tr

by reducing competition, regulating stand structure, and improving growth conditions (soil, light, water, and nutrients) (Fahlvik et al. 2018). In addition to maintaining the intended species composition and accelerate the growth of the selected individuals, this intervention is used to reduce stress and improve wood quality (Weiskittel et al. 2009, Prévost and Gauthier 2012). PCT is of great importance in achieving desired wood characteristics in the future and reducing the rotation age (Fleming 1994). Additionally, by reducing stand density in the early developmental stages, this intervention promotes the effective use of forest resources, enhancing both vertical and radial growth rates of trees (Smith 1986, Thibodeau et al. 2000).

Like all tending interventions, precommercial thinning must be applied in young stands at the right time and with the appropriate intensity, otherwise, it may lead to irreversible economic losses in forest management (Rice et al. 2001, Eler et al. 2004, Huuskonen and Hynynen 2006). In Scots pine stands, precommercial thinning (PCT) primarily aims to remove undesired individuals—including diseased, suppressed, or poorly formed trees as well as dominant, wide-crowned individuals—that hinder the development of neighboring trees. This intervention regulates stand structure, promotes more uniform growth among selected crop trees, enhances wood production, and improves the timing and economic returns of the first commercial thinning (Frda 1996, Fahlvik et al. 2005). Additionally, PCT plays a significant role in the normal development of tree crowns (Oker-Blom et al. 1988). Careful adjustment of the appropriate PCT intensity and timing is crucial for maximizing the overall growth and yield within the stand (Karlsson et al. 2013, Ulvcrona et al. 2017, Güney et al. 2022).

PCT has proven effective in lowering stand density, enhancing tree growth, fostering future understory development, preserving the desired species composition, and increasing the slenderness ratio, which reflects the mechanical stability of trees againvst damage by wind or snow (Pothier 2002, Pitt and Lanteigne 2008). Along with increasing light availability, which is a key factor for growth (Pothier and Margolis 1991), PCT can also improve nutrient accessibility and water availability (Thibodeau et al. 2000), enhance wind resistance (Achim et al. 2005), and promote uniformity in wood structure (Koga et al. 2002). When applied in young stands composed of different tree species, PCT also promotes the development of individual trees (Simard et al. 2004, Splawinski et al. 2017).

Multiple studies on PCT and various thinning practices have indicated considerable increases in height, diameter, and basal area (Sıvacıoğlu et al. 2006, Skovsgaard 2009, Reventlow et al. 2019, Niemistö and Valkonen 2021, Bayar and Alkan 2023). These interventions are seen as particularly effective methods for enhancing individual tree growth at younger ages (Egnell and Ulvcrona 2015, Reventlow et al. 2019, Wotherspoon et al. 2020).

Scots pine (*Pinus sylvestris* L.), one of the most widely distributed pine species, spans a vast geographic range across Europe and Asia, approximately 3,700 km in width and 14,700 km in length. Its northern boundary reaches the 70th parallel (northern Scandinavia), its southern boundary lies at around the 37th northern parallel (Sierra Nevada, Spain), its western boundary extends to approximately 8°W longitude (Spain), and its eastern boundary reaches as far as 141°E longitude (Russia) (Figure 1) (Pravdin 1969, Boratynski 1991). In Türkiye, Scots pine has a natural distribution between the latitudes 38°34' – 41°48'N and longitudes 28°00' – 43°05'E, starting west of Eskişehir, passing through Sarıkamış, and extending to the Caucasus. It grows at elevations ranging from 1000 to 2500 meters a.s.l., either as pure stands or in mixtures with other species. The vertical distribution of Scots pine varies from the sea level in Sürmene-Trabzon (Çamburnu) to altitudes as high as 2700 meters in Sarıkamış (Kayacık 1963, Saatçioğlu 1976, Turna 2003).

For *P. sylvestris*, a species of high ecological and economic value, determining the optimal PCT conditions is crucial for obtaining well-formed stems and achieving higher economic returns. Several studies have been conducted in various countries where Scots pine is distributed, focusing on the effects of PCT interventions on stand development (Pettersson 1993, Varmola and Salminen 2004, Ulvcrona et al. 2007, Karlsson et al. 2013, Fahlvik et al. 2018). In Türkiye, given the species' broad distribution range, a limited number of studies have been conducted, such as those by Öncül et al. (2016) in the Eastern Anatolia Region and Sıvacıoğlu et al. (2006) in the Central Black Sea Region. However, considering the varying micro and macro ecological factors within the species' extensive range in Türkiye, it is essential to conduct thinning-related studies in different regions of its distribution area. Therefore, this study was carried out in Scots pine stands representing the Western Black Sea (Karabük-Eskipazar province) and Central Anatolia (Çankırı-Çerkeş province) regions of Türkiye. The study aims to investigate the effects of various PCT levels on the growth variables of young *P. sylvestris* stands over a five-year growth period and to find the most suitable PCT intensity. The development of young *P. sylvestris* stands is hypothesized to be significantly impacted by varying PCT intensities. Specifically, by examining the effects of different PCT intensities on growth variables such as diameter, height, basal area, and volume, this study aims to contribute to forest management and the development of silvicultural prescriptions.

MATERIALS AND METHODS

Study area

The study areas are located in natural young *P. sylvestris* stands in Karabük-Eskipazar, situated in the Western Black Sea Region of Türkiye, and in Çankırı-Çerkeş, located in the Central Anatolia Region (Figure 1). The plots were chosen from naturally regenerated Scots pine stands in the early development (thicket) stage. Before our investigation, no precommercial thinning had been done, and these stands had uniform stand characteristics.

The Karabük-Eskipazar plots (41º02'32"N, 32º31'28"E) are located at an average altitude of 1390–1520 meters above sea level, with a slope of 30–50% and a south-southeast aspect. The experimental plots, predominantly composed of non-rocky and stone-free to slightly stony soils in terms of surface rockiness and stoniness, are located on moderate slopes. The litter layer thickness within the plots varies between 2 and 5 cm. In the experimental plots, the amount of litter per unit area was determined to average 41.05 t/ha, with the mean pH of the litter recorded as 5.27. It was determined that the bedrock in the experimental plot consists of sedimentary rocks, specifically sandstone. The soils in the experimental plot are classified as very stony-skeletal in terms of profile stoniness. Generally identified as clay soil, the experimental plot soils fall under the category of "fine-textured (heavy) soils". The average composition of the soil was determined to be 21.97% sand, 45.88% clay, and 32.15% silt. According to long-term averages, the mean, highest, and lowest temperatures are 13.3°C, 32°C, and -7°C during the year, respectively, with a total annual precipitation of 735 mm.

The Çankırı-Çerkeş plots (40º43'05"N, 32º48'39"E) are situated at an average altitude of 1320–1530 meters above sea level, with a slope of 20–40% and a north-northeast aspect. The experimental plots, characterized by non-rocky and stone-free to slightly stony soils in terms of surface rockiness and stoniness, are situated on moderate slopes and ridges. The thickness of the litter layer within the plots ranges between 1.5 and 3 cm. In the experimental area, the average amount of litter per unit area was determined to be 27.97 t/ha, with the mean pH of the litter recorded as 5.92. It was determined that the bedrock in the experimental plot consists of sedimentary rocks, specifically limestone. The soils in the experimental plot are classified as very stony-skeletal in terms of profile stoniness. Identified as clay soil, the experimental plot soils fall under the category of "fine-textured (heavy) soils". The average composition of the soil was determined to be 31.80% sand, 44.51% clay, and 23.69% silt. According to long-term averages, the recorded mean, highest, and lowest temperatures are 11.4°C, 32°C, and -9°C, respectively, with an annual average precipitation amount of 616 mm. Climate data were obtained from the WorldClim database, which provides global climate data as spatial data layers (Fick and Hijmans 2017). All soil property analyses were conducted in the laboratories of the Eskişehir Forest Soil and Ecology Research Institute Directorate. Descriptive information regarding the stand, soil, and climate characteristics of the experimental plots is presented in Table 1. Dominant height values in Table 1 represent the average height of the 100 tallest trees per hectare.

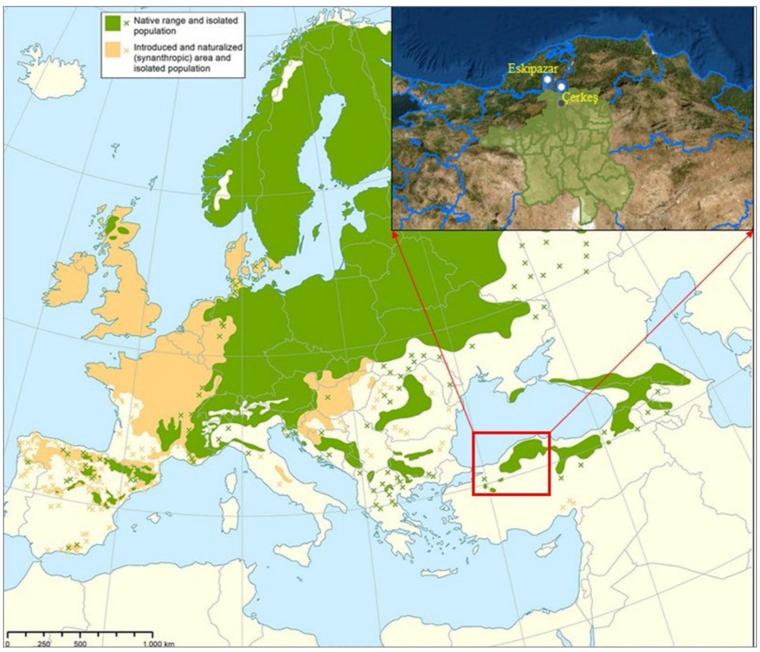

Figure 1 The global distribution of Scots pine and the geographical location of the plots (Caudullo et al. 2017).

Table 1 Descriptive information regarding the stand, soil, and climate characteristics of the experimental plots.

Variables	Karabük-Eskipazar	Çankırı-Çerkeş
Stand properties		
Elevation (m)	1390-1520	1320-1530
Aspect	South-Southeast	North-Northeast
Slope (%)	30-50	20-40
Stand age (years)	32	36
Dominant tree height (m)	9.18	9.35
Mean stem diameter (cm)	5.81	5.24
Site index class	II	II
Soil Properties		
Litter layer thickness (cm)	2-5	1.5-3
Amount of litter (t/ha)	41.05	27.97
Mean pH of litter	5.27	5.92
Sand (%)	21.97	31.80
Silt (%)	32.15	23.69
Clay (%)	45.88	44.51
Climatic attributes		
Mean annual temperature (°C)	13.3	11.4
Mean maximum temperature (°C)	32.0	32.0
Mean minimum temperature (°C)	-7.0	-9.0
Annual precipitation (mm)	735	616

Experimental design and treatments

PCT interventions were applied at four different levels, including a control. In both plots, a randomized block design with three replications was used, resulting in 24 treatment plots (4 PCT treatments × 3 replications × 2 sites). A 5-meter-wide buffer zone was established around each plot. Due to the natural variability in tree density across Scots pine stands at the thicket stage, and in order to ensure comparability across treatments, each plot was arranged to contain exactly 50 trees after thinning. This required adjusting the plot size according to thinning intensity, resulting in plot areas ranging from 50 to 150 m². This approach allowed for balanced sample sizes in statistical analyses and helped prevent disproportionate representation of treatments. Tree spacing was determined based on the targeted thinning intensity to ensure both consistency in tree number and spatial homogeneity across plots (Varmola and Salminen 2004, Zhang et al. 2006, Weiskittel et al. 2009, Wallentin and Nilsson 2011, Güney et al. 2021, Atar 2022).

Control (C): The control (unthinned) plots were not subjected to precommercial thinning and were allowed to grow naturally. In the control (unthinned) sample plots, 50 trees were retained, and each control plot was approximately 50 m² in size. The tree density per hectare was 11350 trees/ha in the Eskipazar plot and 12000 trees/ha in the Çerkeş plot.

Treatment-1 (T1): In the traditional treatment, precommercial thinning was conducted in such a way that there was a canopy gap of one crown between two tree crowns. A total of 50 trees were maintained in each replicate, and the plot size was approximately 150 m². The tree density per hectare was 3390 trees/ha in the Eskipazar plot and 3310 trees/ha in the Çerkeş plot.

Treatment-2 (T2): In the second treatment, the precommercial thinning plots had a spacing of approximately 0.75 to 1.0 meters between the trees. A total of 50 trees were left to grow in each replicate, with a plot size of approximately 70 m². The tree density per hectare was 7320 trees/ha in the Eskipazar plot and 7680 trees/ha in the Çerkeş plot.

Treatment-3 (T3): In the third treatment, the spacing between the trees in the precommercial thinning plots was set at approximately 1.5 to 2.0 meters. A total of 50 trees were left in each replicate, with a plot size of approximately 140 m². The tree density per hectare was 3570 trees/ha in the Eskipazar plot and 3500 trees/ha in the Çerkeş plot.

Measurements

All trees in the plots were marked with a stripe of oil-based paint at breast height (1.30 m) and numbered. Subsequently, the diameters at breast height (DBH) of the trees were measured from this marked point. The heights (H) of the trees were determined using a Vertex-IV hypsometer. Among the selected trees, individuals with healthy, tall, well-formed, strong, straight, and undamaged crowns were preferred. Precommercial thinning interventions commenced after the end of the 2014 growing season. Immediately after the intervention, the diameters and heights of the remaining trees were measured. The measurements were repeated on the same trees at the end of the first (2015), second (2016), third (2017), fourth (2018), and fifth (2019) growing season. However, height measurements for the 2017 growing season could not be conducted. Based on these measurements, total basal area (BA) and volume (V) values were calculated. For volume calculation of the trees in the plots, a two-entry tree volume equation developed by Şenyurt (2011) for Scots pine stands in the Western Black Sea Region was used. The equation, which estimates volume based on the DBH and height of each tree, is presented below.

$$V = 1{,}003506 \exp(-3{,}062228 + 2{,}195122 \times \ln d - 0{,}058577 \times \ln d^2 + 0{,}669187 \times \ln h + 0{,}080075 \times \ln h^2) \quad (1)$$

The equation provided above estimates the single-tree stem volume (dm^3) including bark, based on tree height (m) and diameter at breast height (cm). The statistical values for the equation are as follows: R^2 = 0.996, F = 589,762.29 (P < 0.000), SE = 0.083. (R^2: coefficient of determination, F: F test value, SE: standard error of estimate.)

Statistical analysis

The SPSS (26.0) software was used for all statistical analyses. To assess whether the initial values of the treatments were homogeneous before the effect of the PCT, a one-way ANOVA was performed by measuring the individuals left in the experimental plots immediately after the PCT. The results revealed that there were some variations in the initial DBH, height, basal area, and volume values. Therefore, an analysis of covariance (ANCOVA) model was applied to evaluate the periodic annual increments and adjust for the initial differences among the PCT treatments.

$$Y_{ij} = \mu + \alpha i + \beta\left(X_{ij} - \bar{X}_i\right) + E_{ij} \quad (2)$$

In Equation (2), Y_{ij} represents the dependent variable for the i^{th} individual at the j^{th} factor level, μ is the overall mean, αi denotes the mean response variable that exceeds the overall mean for treatment i, β is the regression coefficient, X_{ij} is the j^{th} observation of the covariate for the i^{th} treatment level, and E_{ij} is the unobserved error term associated with treatment i and replication j.

Because of the initial differences, several researchers have employed the analysis of covariance (ANCOVA) (Lindgren and Sullivan 2013, Atar 2022, Güney et al. 2022). Additionally, the significance levels (p < 0.05) for numerous pairwise comparisons between the PCT intensities were evaluated using Bonferroni's multiple comparison t-test (Özdamar, 2013).

$$t' = \frac{\bar{X}_i - \bar{X}_j}{\sqrt{\frac{S^2}{n} + \frac{S^2}{n}}} = \frac{\bar{X}_i - \bar{X}_j}{\sqrt{\frac{2S^2}{n}}} = \frac{\bar{X}_i - \bar{X}_j}{\sqrt{\frac{2M_{SE}}{n}}} \quad (3)$$

In Equation (3), X_i and X_j = treatments, M_{SE} = the mean squared error, S = the standard deviation.

RESULTS

Based on PCT intensities, DBH and BA were recorded in 2014, 2015, 2016, 2017, 2018, and 2019 (Table 2). Measurements taken immediately after the PCT in the Eskipazar plot showed that the average DBH was 5.12 cm, 6.49 cm, 6.48 cm, and 7.00 cm for the control, T1, T2, and T3 plots, respectively. Five growing seasons after the PCT, the average DBH was 7.13 cm in the control plot, 10.01 cm in T1, 9.43 cm in T2, and 10.32 cm in T3. In the Çerkeş plot, the largest DBH was observed in the T1 treatment, both in 2014 and 2019. As anticipated, the average diameter values rose in proportion to the increasing PCT intensities. At the end of the fifth growing season, the lowest total basal area was recorded in the T1 treatment (29.10 m^2/ha) in the Eskipazar plot and in

Table 2 Mean ± SE diameter at breast height (DBH) and basal area (BA) of trees after PCT at four intensities.

Plot	Variable	PCT intensity	Measurement years					
			2014	2015	2016	2017	2018	2019
Eskipazar	DBH (cm)	C (11350)	5.12±0.18	5.59±0.19	6.06±0.20	6.54±0.21	6.86±0.22	7.13±0.23
		T1 (3390)	6.49±0.24	7.20±0.26	8.01±0.28	8.88±0.30	9.46±0.31	10.01±0.33
		T2 (7320)	6.48±0.21	7.13±0.22	7.80±0.24	8.49±0.25	8.97±0.26	9.43±0.28
		T3 (3570)	7.00±.24	7.66±0.25	8.44±0.27	9.30±0.30	9.85±0.31	10.32±0.33
	BA (m^2/ha)	C (11350)	26.37±1.80	31.09±2.04	36.44±2.35	42.21±2.69	46.58±3.02	50.35±3.30
		T1 (3390)	12.54±0.84	15.32±1.00	18.87±1.22	23.08±1.47	26.04±1.61	29.10±1.79
		T2 (7320)	26.83±1.58	32.26±1.85	38.50±2.19	45.43±2.56	50.57±2.80	55.91±3.08
		T3 (3570)	15.03±0.98	17.88±1.12	21.67±1.36	26.29±1.66	29.39±1.80	32.65±1.96
Çerkeş	DBH (cm)	C (12000)	4.60±0.21	4.97±0.22	5.34±0.23	5.80±0.24	6.08±0.25	6.28±0.26
		T1 (3310)	7.18±0.30	7.93±0.33	8.74±0.37	9.45±0.39	10.01±0.41	10.43±0.42
		T2 (7680)	6.02±0.21	6.50±0.22	6.96±0.23	7.52±0.25	7.91±0.27	8.22±0.28
		T3 (3500)	6.40±0.24	6.94±0.25	7.53±0.27	8.10±0.28	8.53±0.29	8.90±0.30
	BA (m^2/ha)	C (12000)	23.70±2.12	27.41±2.38	31.38±2.68	36.71±3.07	40.29±3.39	42.98±3.58
		T1 (3310)	15.29±1.17	18.60±1.46	22.72±1.85	26.38±2.11	29.52±2.32	32.03±2.49
		T2 (7680)	23.99±1.34	27.88±1.88	31.91±2.14	37.17±2.48	41.32±2.84	44.68±3.10
		T3 (3500)	12.45±0.86	14.53±0.97	17.05±1.16	19.69±1.32	21.79±1.43	23.66±1.54

Notes: C, Control; T1: Classic, T2: 0.75–1.0 m, T3: 1.5–2.0 m the T3 treatment (23.66 m²/ha) in the Çerkeş plot. Conversely, the highest values were found in the T2 treatment in both plots for the more intensive PCT.

At the end of the fifth growing season, the highest height values were recorded in the T1 treatment in both plots. In terms of total volume per hectare, the highest values were observed in the T2 treatment in both plots, with 242.16 m³/ha and 198.22 m³/ha, respectively (Table 3).

Table 3 Mean ± SE height (H) and volume (V) of trees after PCT at four intensities.

Plot	Variable	PCT intensity	Measurement years					
			2014	2015	2016	2017	2018	2019
Eskipazar	H (m)	C (11350)	5.73±1.13	6.05±1.16	6.43±1.22	7.04±1.24	7.35±1.26	7.13±0.23
		T1 (3390)	6.01±1.73	6.42±1.76	6.86±1.83	7.73±1.93	8.28±2.02	10.01±0.33
		T2 (7320)	6.29±1.40	6.67±1.45	7.10±1.50	7.87±1.63	8.27±1.70	9.43±0.28
		T3 (3570)	5.94±1.23	6.36±1.26	6.80±1.26	7.64±1.38	8.15±1.51	10.32±0.33
	V (m³/ha)	C (11350)	81.62±6.28	101.02±7.51	125.36±9.19	173.38±12.59	195.02±15.25	50.35±3.30
		T1 (3390)	42.24±3.51	54.49±4.44	71.01±5.6	107.79±8.20	127.58±9.46	29.10±1.79
		T2 (7320)	91.29±6.32	115.33±7.77	145.56±9.77	209.11±13.63	242.16±15.63	55.91±3.08
		T3 (3570)	47.53±3.71	59.88±4.45	77.01±5.73	115.48±8.35	136.46±9.77	32.65±1.96
Çerkeş	H (m)	C (12000)	4.90±0.10	5.19±0.11	5.49±0.11	6.13±0.12	6.54±0.12	6.28±0.26
		T1 (3310)	7.21±0.22	7.61±0.23	8.04±0.24	8.86±0.25	9.34±0.25	10.43±0.42
		T2 (7680)	6.59±0.15	6.95±0.15	7.34±0.15	7.97±0.15	8.41±0.16	8.22±0.28
		T3 (3500)	5.98±0.12	6.34±0.12	6.74±0.12	7.43±0.13	7.86±0.14	8.90±0.30
	V (m³/ha)	C (12000)	65.16±6.65	79.04±7.83	95.12±9.29	134.57±12.83	152.17±14.26	42.98±3.58
		T1 (3310)	15.29±1.17	18.60±1.46	22.72±1.85	26.38±2.11	29.52±2.32	32.03±2.49
		T2 (7680)	23.99±1.34	27.88±1.88	31.91±2.14	37.17±2.48	41.32±2.84	44.68±3.10
		T3 (3500)	12.45±0.86	14.53±0.97	17.05±1.16	19.69±1.32	21.79±1.43	23.66±1.54

Notes: C, Control; T1: Classic, T2: 0.75–1.0 m, T3: 1.5–2.0 m

In the Eskipazar plot, the 5-year DBH increments for the control, T1, T2, and T3 PCT treatments were 2.34 cm, 3.42 cm, 2.83 cm, and 3.08 cm, respectively. The results indicate that as the PCT intensity increased, the diameter growth also increased (Figure 2). Moreover, the 5-year total basal area increments were 19.41 m²/ha in the control, 23.90 m²/ha in the T1 plot, 24.12 m²/ha in the T2 plot, and 22.82 m²/ha in the T3 plot. Regarding the 5-year total basal area per hectare, the T2 treatment displayed the greatest value. The control, T1, T2, and T3 plots in the Çerkeş plot had 5-year DBH increases of 2.13 cm, 2.90 cm, 2.21 cm, and 2.38 cm, respectively. According to the findings, the control plot's total basal area increased by 15.67 m²/ha between 2014 and 2019, while the T1 PCT's was 19.57 m²/ha, the T2 PCT's was 16.86 m²/ha, and the T3 PCT's was 16.20 m²/ha (Table 4).

Table 4 Increments of DBH and BA regarding PCT intensities and years of measurements.

Plot	Variable	PCT intensity	Increment by years				
			2014-2015	2014-2016	2014-2017	2014-2018	2014-2019
Eskipazar	DBH (cm)	C	0.52±0.01	1.07±0.03	1.63±0.04	2.00±0.07	2.34±0.07
		T1	0.70±0.02	1.48±0.02	2.33±0.05	2.89±0.08	3.42±0.07
		T2	0.64±0.01	1.29±0.04	1.95±0.04	2.40±0.07	2.83±0.06
		T3	0.63±0.02	1.36±0.03	2.17±0.05	2.53±0.08	3.08±0.07
		p	0.000	0.000	0.000	0.000	0.000
	BA (m²/ha)	C	3.92±0.12	8.26±0.26	12.96±0.45	16.51±0.54	19.41±0.61
		T1	4.05±0.14	9.22±0.30	15.16±0.52	19.44±0.62	23.90±0.70
		T2	4.57±0.12	9.71±0.26	15.48±0.45	19.72±0.54	24.12±0.61
		T3	3.75±0.14	8.69±0.31	14.53±0.52	18.58±0.63	22.82±0.71
		p	0.000	0.000	0.000	0.000	0.000
Çerkeş	DBH (cm)	C	0.47±0.02	0.93±0.04	1.49±0.05	1.86±0.06	2.13±0.07
		T1	0.68±0.02	1.43±0.04	2.05±0.06	2.54±0.07	2.90±0.07
		T2	0.49±0.02	0.96±0.03	1.52±0.06	1.91±0.07	2.21±0.07
		T3	0.52±0.02	1.07±0.04	1.62±0.05	2.03±0.06	2.38±0.07
		p	0.000	0.000	0.000	0.000	0.000
	BA (m²/ha)	C	3.04±0.14	6.21±0.31	10.66±0.44	13.49±0.53	15.67±0.62
		T1	3.84±0.15	8.59±0.32	12.93±0.45	16.65±0.56	19.57±0.65
		T2	3.18±0.15	6.36±0.33	10.69±0.46	14.04±0.56	16.86±0.66
		T3	3.01±0.15	6.63±0.33	10.48±0.46	13.62±0.57	16.20±0.67
		p	0.000	0.000	0.000	0.000	0.000

Notes: The values in the table are the transformed values obtained from the analysis of covariance.

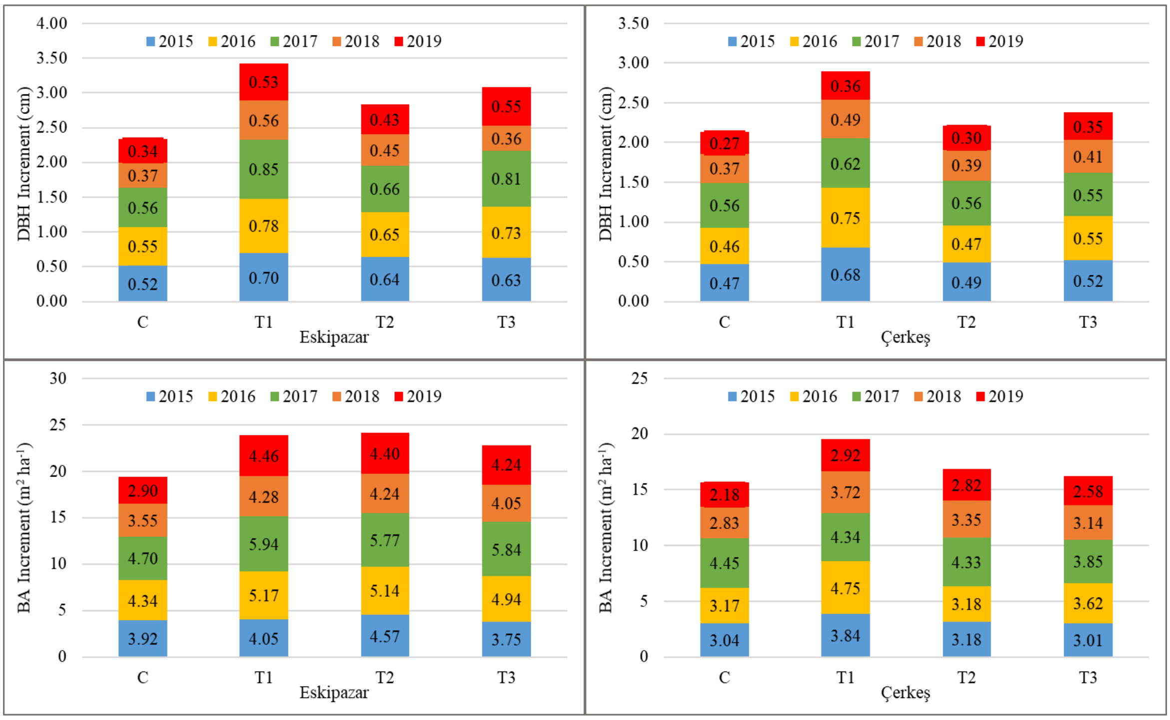

Figure 2 Increments of DBH and BA for each measurement year.

To determine whether there were statistically significant differences in growth parameters based on PCT intensities, an analysis of covariance (ANCOVA) was conducted (Table 4). The analysis revealed that, for both the Eskipazar and Çerkeş plots, statistically significant differences in DBH and BA increments were found between the different PCT intensities each year at a 99% confidence level.

The increment values for height and total volume, which are stand growth variables, based on PCT and measurement years are presented in Table 5. In the Eskipazar plot, the 5-year height increments were found to be 1.68 m in the control plot, 1.97 m in the T2 plot, 2.23 m in the T3 plot, and 2.27 m in the T1 plot. Similarly, in the Çerkeş plot, the highest height increment was recorded in the T1 treatment, with a value of 2.10 m. As the results indicate, height values increased in correlation with the increase in PCT intensity. In terms of total volume increment, the

Table 5 Increments of H and V regarding PCT intensities and years of measurements.

Plot	Variable	PCT intensity	Increment by years			
			2014-2015	2014-2016	2014-2018	2014-2019
Eskipazar	H (m)	C	0.33±0.01	0.72±0.01	1.36±0.03	1.68± 0.04
		T1	0.41±0.01	0.85±0.02	1.72±0.04	2.27± 0.05
		T2	0.37±0.01	0.79±0.02	1.56±0.04	1.97± 0.05
		T3	0.42±0.01	0.87±0.02	1.71±0.05	2.23± 0.05
		p	0.000	0.000	0.000	0.000
	V (m^3/ha)	C	16.60±0.43	37.11±1.06	77.73±2.31	95.54±2.79
		T1	17.87±0.50	42.09±1.22	93.75±2.65	121.23±3.20
		T2	19.18±0.44	42.75±1.07	93.43±2.32	119.83±2.81
		T3	16.84±0.51	40.11±1.24	90.47±2.70	117.60±3.26
		p	0.000	0.000	0.000	0.000
Çerkeş	H (m)	C	0.32±0.01	0.66±0.02	1.32±0.05	1.76±0.06
		T1	0.37±0.01	0.78±0.02	1.56±0.06	2.10±0.06
		T2	0.34±0.01	0.72±0.02	1.33±0.05	1.75±0.06
		T3	0.36±0.01	0.77±0.02	1.46±0.05	1.90±0.05
		p	0.026	0.001	0.002	0.003
	V (m^3/ha)	C	13.40±0.53	28.86±1.27	67.03±2.36	84.09±2.92
		T1	17.47±0.56	40.32±1.33	82.09±2.49	101.56±3.08
		T2	13.65±0.58	28.75±1.38	66.73±2.57	85.50±3.17
		T3	14.01±0.58	32.02±1.37	68.80±2.56	86.46±3.16
		p	0.000	0.000	0.000	0.000

Notes: The values in the table are the transformed values obtained from the analysis of covariance

lowest values were observed in the control plot in both the Eskipazar and Çerkeş plots (95.54 m^3/ha and 84.09 m^3/ha, respectively), while the highest values were found in the T1 treatment (121.23 m^3/ha and 101.56 m^3/ha, respectively).
The analysis of covariance conducted to test the significant differences in growth variables based on PCT intensity (Table 5) revealed that there were statistically significant differences in height and total volume increments across different PCT intensities during all measurement periods. Bonferroni t-test was conducted to determine the statistical significance of the differences between various PCT treatments based on the increments of the measured parameters. (Tables 6 and 7). By the end of the fifth growing season, it was found that in the Eskipazar plot, the differences in DBH values between all PCT treatments were statistically significant, whereas in the Çerkeş plot, the differences between T2 and C, T3 and C, and T2 and T3 treatments were not significant. For BA increments, all differences between the PCT treatments and the control plots in the Eskipazar plot were statistically significant. In the Çerkeş plot, significant differences were found between T1 and C, T1 andT2, and T1 and T3 treatments (Table 6).

Table 6 Bonferroni's t-test results concerning the increments of DBH and BA.

Increment year	PCT levels	Difference of mean increment							
		Eskipazar				Çerkeş			
		DBH	P	BA	P	DBH	P	BA	P
2014–2015	T1 – C	0.168	**	0.129	ns	0.207	**	0.800	**
	T2 – C	0.110	**	0.645	**	0.028	ns	0.140	ns
	T3 – C	0.095	**	-0.172	ns	0.059	ns	-0.035	ns
	T1 – T2	0.058	*	-0.517	*	0.179	**	0.660	*
	T1 – T3	0.072	**	0.301	ns	0.148	**	0.835	**
	T2 – T3	0.014	ns	0.817	**	-0.031	ns	0.175	ns
2014–2016	T1 – C	0.389	**	0.957	ns	0.454	**	2.374	**
	T2 – C	0.203	**	1.447	**	0.008	ns	0.146	ns
	T3 – C	0.254	**	0.432	ns	0.135	ns	0.419	ns
	T1 – T2	0.186	**	-0.490	ns	0.445	**	2.228	**
	T1 – T3	0.135	*	0.525	ns	0.319	**	1.956	**
	T2 – T3	-0.051	ns	1.015	ns	-0.127	ns	-0.273	ns
2014–2017	T1 – C	0.684	**	2.190	*	0.538	**	2.268	**
	T2 – C	0.318	**	2.514	**	0.015	ns	0.031	ns
	T3 – C	0.507	**	1.569	ns	0.136	*	-0.184	ns
	T1 – T2	0.367	**	-0.324	ns	0.523	**	2.237	**
	T1 – T3	0.177	ns	0.622	ns	0.402	**	2.452	**
	T2 – T3	-0.189	*	0.946	ns	-0.121	ns	-0.215	ns
2014–2018	T1 – C	0.878	**	2.937	**	0.679	**	3.166	**
	T2 – C	0.414	**	3.209	**	0.054	ns	0.555	ns
	T3 – C	0.650	**	2.071	ns	0.193	ns	0.131	ns
	T1 – T2	0.464	**	-0.272	ns	0.625	**	2.611	**
	T1 – T3	0.228	*	0.866	ns	0.485	**	3.035	**
	T2 – T3	-0.236	**	1.138	ns	-0.139	ns	0.424	ns
2014–2019	T1 – C	1.087	**	4.486	**	0.781	**	3.902	**
	T2 – C	-0.535	**	4.712	**	0.099	ns	1.190	ns
	T3 – C	-0.823	**	3.415	**	0.275	*	0.528	ns
	T1 – T2	0.551	**	-0.226	ns	0.682	**	2.712	*
	T1 – T3	0.264	*	1.071	ns	0.506	**	3.374	**
	T2 – T3	-0.287	**	1.297	ns	-0.176	ns	0.662	ns

*$p < 0.05$; **$p < 0.01$; ns: not significant

The Bonferroni t-test results for height and total volume values in Table 7 indicate that, by the end of the five-year growth period, the only statistically significant differences in height for the Çerkeş plot were between T1 and C and T1 and T2 treatments, while in the Eskipazar plot, only the differences between T1 and T3 treatments were not statistically significant. In terms of total volume, the results showed that in the Eskipazar plot, the differences between the control and all intervention treatments were statistically significant at a 99% confidence level by the fifth growing season. In the Çerkeş plot, significant differences were found between T1 and C, T1 and T2, and T1 and T3 treatments.

Table 7 Bonferroni's t-test results concerning the increments of H and V.

Increment year	PCT levels	Difference of mean increment							
		Eskipazar				Çerkeş			
		H	*P*	V	*P*	H	*P*	V	*P*
2014–2015	T1 – C	0.078	**	1.268	ns	0.044	ns	4.074	**
	T2 – C	0.041	*	2.578	**	0.018	ns	0.259	ns
	T3 – C	0.090	**	0.231	ns	0.041	*	0.610	ns
	T1 – T2	0.037	ns	-1.310	ns	0.026	ns	3.815	**
	T1 – T3	-0.012	ns	1.037	ns	0.003	ns	3.464	**
	T2 – T3	-0.049	**	2.347	**	-0.023	ns	-0.351	ns
2014–2016	T1 – C	0.129	**	4.980	*	0.104	**	11.469	**
	T2 – C	0.080	*	5.645	**	0.051	ns	-0.101	ns
	T3 – C	0.153	**	3.007	ns	0.102	**	3.166	ns
	T1 – T2	0.049	ns	-0.665	ns	0.053	ns	11.570	**
	T1 – T3	-0.024	ns	1.973	ns	0.002	ns	8.303	**
	T2 – T3	-0.073	*	2.638	ns	-0.051	ns	-3.267	ns
2014–2018	T1 – C	0.381	**	16.020	**	0.266	**	15.058	**
	T2 – C	0.217	**	15.702	**	0.038	ns	-0.300	ns
	T3 – C	0.368	**	12.739	**	0.143	ns	1.763	ns
	T1 – T2	0.163	*	0.319	ns	0.227	**	15.357	**
	T1 – T3	0.013	ns	3.282	ns	0.123	ns	13.294	**
	T2 – T3	-0.151	ns	2.963	ns	-0.105	ns	-2.063	ns
2014–2019	T1 – C	0.616	**	25.696	**	0.294	**	17.469	**
	T2 – C	0.302	**	24.293	**	0.034	ns	1.406	ns
	T3 – C	0.566	**	22.064	**	0.143	ns	2.367	ns
	T1 – T2	0.314	**	1.404	ns	0.260	**	16.063	**
	T1 – T3	0.050	ns	3.632	ns	0.151	ns	15.102	**
	T2 – T3	-0.264	**	2.228	ns	-0.109	ns	-0.961	ns

*$p < 0.05$; **$p < 0.01$; ns: not significant

DISCUSSION

PCT is a crucial silvicultural intervention applied to manage stand structure and promote individual tree growth at an early stage (Smith 1986, Özdemir et al. 1987, Fahlvik et al. 2018). This practice is used to alter stand structure by allocating growth resources to the selected stems. The growth response of the stand after PCT varies depending on several factors, such as the timing of the intervention, stand age, density levels, biological characteristics of the species, and local climate conditions (Pitt and Lanteigne 2008, Holmström et al. 2016, Bjelanovic et al. 2021). Studies have shown that PCT intensity levels have statistically significant effects on increases in height, diameter, total volume and total basal area (Ginn et al. 1991, Simard et al. 2004, Yılmaz et al. 2010).

In this study, which investigated the effect of PCT treatments on the development of natural Scots pine stands at the thicket stage, it was found that the thinning treatments applied at varying intensities in both plots had a statistically significant effect on the average diameter increment. Following the thinning interventions applied after the 2014 growing season, significant differences were observed in the average diameter increment across all treatments at the end of the fifth growing season (2019). The lowest diameter increment was observed in the control treatment (2.34 cm in the Eskipazar plot and 2.13 cm in the Çerkeş plot), while the highest diameter increment was recorded in the traditional treatment (3.42 cm in the Eskipazar plot and 2.90 cm in the Çerkeş plot). It was also observed that the average diameter increments increased as the thinning intensity increased in the plots. Similarly, Öncül et al. (2016) found that thinning in natural Scots pine stands resulted in the lowest diameter increment in the control treatment (5.34 cm) and the highest in the heavy intervention treatment (6.64 cm) after three years, also noting that diameter increments increased with greater thinning intensity. Ulvcrona et al. (2007) highlighted that DBH values increased in Scots pine stands in relation to the intensity and timing of PCT. Similarly, diameter growth increased with the intensity of PCT in *P. sylvestris* (Mäkinen and Isomäki 2004). In a similar study by Bataineh et al. (2013) on *Abies balsamea* (L.) Mill. and *Picea rubens* Sarg. stands, diameter growth 13 to 24 years after PCT was higher in the thinned plots (3.9 cm) compared to the control plots (3.1 cm). Pitt and Lanteigne (2008) investigated how growth parameters in *P. rubens* and *A. balsamea* stands 42–44 years after PCT were affected by varying PCT intensities (spacing of 1.2 m, 1.8 m, and 2.4 m). They found that average diameters rose in response to greater PCT intensities. Numerous studies have reported increased diameter growth due to decreased stem density following thinning (Miller 2000, Varmola and Salminen 2004, Linkevičius et al. 2014, Bayar and Deligöz 2019, Deligöz et al. 2022).

The primary reason for the increase in diameter growth after thinning interventions is that the remaining trees utilize available resources more efficiently due to the reduction in tree density. This allows the remaining individuals to access more light, water, and nutrients, which consequently enhances photosynthesis (Goudiaby et al. 2011). Makineci (2005) also highlighted in his study that diameter growth increases in thinned areas as a result of higher soil moisture and reduced root competition, since fewer individuals can benefit from a larger soil volume. Wider spacing is associated with greater diameter growth (Ferguson et al. 2011).

The impact of PCT on tree height can differ based on factors such as PCT intensity levels, timing of the intervention, tree species, and regional biological characteristics. This study found that over the five-year growth period, there were notable differences in height increments due to varying PCT intensities. It was determined that as the intensity of the PCT intervention increased, tree height also increased. Similarly, average tree heights in PCT plots were found to be greater than those in the control plots in *P. sylvestris* stands (Sıvacıoğlu et al. 2006). Weiskittel et al. (2009) reported that in *A. balsamea* and *P. rubens* stands, height growth, crown ratio, and crown width increased significantly within 25 years following PCT compared to control plots. In Scots pine stands, average tree heights after various levels of PCT ranged between 1.2 and 8.3 meters (Fahlvik et al. 2005). According to Zhang et al. (2006), *Pinus banksiana* Lamb. height increments were lowest in the control plots and largest with heavy PCT treatments. Brissette et al. (1999) determined that, 18 years after thinning, trees in the treated plots were 32% taller than those in the control plots. Other studies have shown that the effects of PCT can vary between species. For instance, according to research by Zhang et al. (2009) on *A. balsamea* stands, PCT plots showed less height increases than the control plots. Additionally, no significant effect of PCT on height growth was found in *Pinus contorta* var. *latifolia* Engelm. stands (Lindgren and Sullivan 2013). Kaymakçı et al. (2000) noted that delayed PCT had no effect on increasing height growth in *Pinus nigra* J.F.Arnold stands but limited diameter expansion. Research on other tree species indicated that different PCT intensities have no discernible effect on height growth (Pinkard and Neilsen 2003, Simard et al. 2004, Rytter and Stener 2005, Rytter 2013).

Among the most important markers of stand growth are total basal area and volume. In both study plots, the effect of thinning treatments on total basal area and volume per hectare was found to be statistically significant during each growth period, with the highest basal area increments in the Eskipazar plot recorded in the T2 treatment and in the Çerkeş plot in the T1 treatment. The highest total volume increments were also observed in the T1 treatment in both plots. One of the key findings of this study was the declining trend in growth increments after the third growing season, particularly evident in DBH and volume metrics. This trend suggests that the benefits of a single PCT intervention may diminish over time, necessitating a follow-up intervention within 3–5 years to sustain growth momentum. These observations support a rotation-based thinning regime rather than a one-time intervention, a recommendation echoed by Varmola and Salminen (2004) in similar studies on Scots pine in Nordic regions. Similar to the findings of this study, Ruha and Varmola (1997) noted that PCT significantly increased diameter and volume increments during the second decade in young Scots pine stands. Another study on *P. banksiana* stands showed that intensive thinning (2.13 m spacing or 2,212 stems/ha) increased tree diameter by more than 20% and stem volume per tree by more than 75% as compared to the control (Zhang et al. 2006). Conversely, other studies have reported decreases in total volume and basal area with increasing PCT intensity (Simard et al. 2004, Bayar and Deligöz 2020). For instance, in a study on *Picea abies* (L.) H.Karst. and *P. sylvestris* stands, while diameter growth increased with a reduction in tree density, total volume decreased after PCT interventions (Pettersson 1993). According to Pothier (2002) study on *A. balsamea* stands, the PCT intensity of 2,000 trees/ha produced the highest total volume with DBH greater than 15 cm, while the PCT intensity of 15,000 trees/ha produced the highest total volume with DBH greater than 1.1 cm. Another study reported that heavy PCT resulted in a volume loss of over 20% after 20 years in young *P. abies* stands (Sterba 2003). Furthermore, another study that looked at how different PCT levels affected *A. balsamea* and *P. rubens* stands found that the 1.8 m spacing treatment had the largest total basal area and stand volume (Pitt and Lanteigne 2008). Despite a significant diameter increase after PCT, the overall basal area of *Picea mariana* Britton, Sterns et Poggenb. declined 20 years after the intervention, according to research by Wotherspoon et al. (2020). However, despite an initial reduction in the basal area after thinning, in later years, total basal area in thinned plots surpassed that in control plots due to greater diameter growth. It was noted that the greater diameter development at the time of intervention made up for the decrease in basal area (Sıvacıoğlu et al. 2006).

Although both experimental sites shared similar stand ages and soil texture classifications, site-specific differences such as total precipitation, litter biomass, and soil pH may have contributed to the variations in growth responses across treatments. The Eskipazar and Çerkeş plots differed in several key ecological parameters, including litter biomass, soil pH, and annual precipitation. For instance, the higher litter accumulation in Eskipazar

(41.05 t/ha vs. 27.97 t/ha) may have enhanced nutrient cycling and microbial activity, potentially leading to more favorable growth conditions in denser treatments such as T2. Moreover, the more acidic soil pH in Eskipazar (5.27 vs. 5.92) could have influenced nutrient availability, particularly for elements like nitrogen and phosphorus, which play a critical role in early-stage growth. The 119 mm difference in annual precipitation between the two sites also may have affected water availability and root competition dynamics, especially in more intensively thinned plots. These findings underscore the need to consider site-specific edaphoclimatic factors when formulating thinning prescriptions and extrapolating growth models across regions.

CONCLUSIONS

This study demonstrated that site-specific edaphoclimatic factors, particularly litter biomass, soil pH, and annual precipitation significantly influenced the growth responses of Scots pine to precommercial thinning (PCT). Improved growth performance in denser treatments in Eskipazar, characterized by higher litter accumulation and more acidic soils, emphasizes the need to tailor thinning strategies to local site conditions when applying growth models across different regions.

The findings also provide important guidance on optimal thinning intensity. In natural Scots pine stands in Türkiye, maintaining approximately 3000–3500 stems per hectare appears to achieve the most favorable outcomes in terms of diameter, height, basal area, and total volume. Notably, while Scandinavian thinning recommendations generally suggest retaining 2000–2500 stems per hectare depending on site productivity (Parvianen 1978, Ruha and Varmola 1997, Varmola and Salminen 2004), results from this study suggest that slightly higher densities may be preferable in natural stands in Türkiye to optimize growth.

Furthermore, the observed trend of increasing growth increments during the initial three years, followed by a decline in the subsequent years, suggests that a thinning interval of approximately 3–5 years may be beneficial for maintaining stand vigor and productivity, especially in fast-growing stands. However, this interval may vary depending on site quality and growth rates. In addition, careful consideration should be given to the protection of residual trees, particularly in heavily thinned plots, to mitigate risks from wind and snow damage. Conversely, neglecting timely PCT interventions may increase the likelihood of damage caused by snow pressure and competition stress, especially in high-elevation sites. Finally, the selection of future crop trees should prioritize individuals with superior form and vitality, characterized by symmetrical crowns, slender branches, straight stems, and the absence of permanent defects.

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