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Evaluation of Scots Pine (*Pinus sylvestris* L.) High Mountain Afforestation: The Case of the Galyan

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Research Article

Abstract − This study aims to evaluate the afforestation success based on the 10-year development of Scots pine (*Pinus sylvestris* L.) seedlings planted at higher elevations within the current forest boundary as part of the "Galyan Afforestation Project." Sample plots were selected from the Scots pine reforestation area, established in 2007, based on three different aspects (north, northeast, northwest) and two elevation ranges (1790–1890 m, 1891–1990 m). In 2011, data were collected from each sample plot, including seedling length, root collar diameter, the number of branches on the latest shoot, the lengths of the longest branches in the north, south, east, and west directions, and the number of terminal buds. Additionally, the growth trends of the same areas were monitored based on on-site inspections conducted in 2016 (when the seedlings were 10 years old), and evaluations were made accordingly. Statistical tools such as ANOVA, Duncan test, t-test, and correlation analysis were employed to evaluate growth performance. The results showed that the average seedling height was 59.64 cm in 2010 and 93.85 cm in 2016, with height growth being more pronounced at lower elevations and on north-facing slopes. While initial growth was adequate, extreme climatic conditions such as frost, snow pressure, and waterlogging led to deformities, including branch and terminal shoot damage. Despite these challenges, the findings highlight that careful site selection—favoring northern aspects and lower elevations—can enhance growth outcomes. Furthermore, integrating ecological and forestry research with practical forestry strategies is essential for sustainable reforestation in mountainous regions.

Anahtar Kelimeler − *High mountain forestation, Scots pine, seedling morphology, elevation, Galyan*

Sarıçam (*Pinus sylvestris* L.) Yüksek Dağ Ağaçlandırmasının Değerlendirilmesi: Galyan Örneği

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Araştırma Makalesi

Öz − Bu çalışmada, “Galyan Ağaçlandırma Projesi” kapsamında aktüel orman sınırının yüksek kesimlerinde dikimi gerçekleştirilen sarıçam (*Pinus sylvestris* L.) fidanlarının 10 yıllık gelişimlerine göre ağaçlandırma başarısının ortaya konması amaçlanmıştır. 2007 yılında dikimi gerçekleştirilen sarıçam ağaçlandırma alanından üç farklı bakı (kuzey, kuzeydoğu, kuzeybatı) ve iki yükselti (1790-1890 m, 1891-1990 m) olacak şekilde örnek alanlar belirlenmiştir. 2011 yılında her bir örnek alanda fidan boyu, kök boğaz çapı, son sürgündeki dal sayısı, kuzey-güney-doğu-batı yönlerindeki en uzun dalların uzunlukları ve tepe tomurcuk sayıları belirlenmiştir. Ayrıca aynı sahaların 2016 yılında (10 yaşındaki) yerinde yapılan incelemelere dayanılarak büyüme seyri takip edilmiş ve buna göre değerlendirmelerde bulunulmuştur. Çalışmada büyüme performansını değerlendirmek için ANOVA, Duncan testi, t-testi ve korelasyon analizi gibi istatistiksel araçlar kullanılmıştır. Sonuçlar, fidan boylarının 2010 yılında ortalama 59,64 cm ve 2016 yılında 93,85 cm değere sahip olduğunu, düşük rakımlarda ve kuzey bakılarda boy büyümesinin daha yüksek olduğu göstermiştir. Başlangıçtaki büyüme yeterli düzeyde olsa da, don, kar basıncı ve su basması gibi aşırı olumsuz iklim koşulları fidanlarda dallanma ve son sürgün hasarı gibi deformasyonlara yol açmıştır. Bunlara rağmen, çalışma sonuçları, kuzeye bakan bakılar ve daha düşük rakımları tercih etmek gibi dikkatli yer seçiminin büyüme sonuçlarını iyileştirebileceğini göstermiştir. Ayrıca, ekolojik ve ormancılık araştırmalarının pratik ormancılık stratejileriyle bütünleştirilmesinin dağlık bölgelerde sürdürülebilir ağaçlandırma için elzem olduğu sonucuna varılmıştır.

Keywords − *Yüksek dağ ağaçlandırması, Sarıçam, fidan morfolojisi, yükselti, Galyan*

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1. Introduction

High mountain forests are ecosystems located near the upper altitudinal limits of tree growth, characterized by challenging environmental conditions such as low temperatures, high wind speeds, and short growing seasons. These forests play a vital role in preserving biodiversity, regulating water cycles, and preventing soil erosion. According to the Food and Agriculture Organization (FAO), mountain forests cover approximately 9 million square kilometers, representing about 23% of the world's forest cover. These ecosystems are critical for the livelihoods of both mountainous and lowland communities (FAO 2011).

In the context of "High Mountain Silviculture," all silvicultural measures aimed at creating stable and highly vital stands within the high mountain forest zone are understood as efforts to optimize forest functions, particularly protective functions, under extreme living and survival conditions. High mountain forests exhibit a mosaic structure, consisting of sites both suitable and unsuitable for forest growth (Pitterle 1993). In these forests, silvicultural practices must be adapted to the unique challenges imposed by the environment. Santopuoli et al. (2021) emphasize the importance of climate-smart silvicultural practices that enhance forest resilience and resistance, particularly in the face of climate change adaptation in such areas.

Mountainous regions are unique habitats where significant climatic changes occur over short distances, resulting in the formation of diverse ecosystems. Environmental factors such as temperature decrease, variations in precipitation, wind speed, increased solar radiation, shorter vegetation periods, and prolonged snow cover lead to a distinct vertical stratification of vegetation. This highlights the unique importance of mountainous areas in terms of biodiversity and ecosystem services (Barry, 2008; Körner, 2007). Körner (2007) emphasizes the impact of temperature decline with altitude on plant distribution, noting its decisive role in the adaptation of plant communities, particularly within mountain ecosystems. Similarly, studies by Körner (1998) reveal that high-altitude tree lines are shaped by environmental variables such as temperature, radiation, and growing season length. Above these tree lines, plant communities typically exhibit dwarf forms, which are understood as an adaptive response to harsh environmental conditions.

The climatic characteristics of mountainous regions play a crucial role in shaping plant gradients and maintaining ecological balance. Whittaker (1967) elaborates on how environmental gradients influence plant communities and how these communities respond to environmental changes, explaining the role of factors such as temperature and humidity in the vertical stratification of vegetation in mountainous areas. Similarly, Holdridge (1967) highlights the ecological richness of mountainous regions, emphasizing the significance of climatic factors in the formation of plant communities. The creation of unique ecological zones at each elevation level significantly enhances the biodiversity of these regions. Consequently, the ecological structure of mountainous areas is closely tied to environmental variables. Factors such as temperature, solar radiation, vegetation periods, and snow cover determine the distribution of plant communities, underscoring the critical importance of these regions for ecosystem services and biodiversity (Barry, 2008; Körner, 2007; Whittaker, 1967; Holdridge, 1967).

One of the most striking characteristics of the subalpine zone is the slowed length growth during the early years. For instance, in high-altitude areas, it may take 50 years or more for *Picea abies* (L.) Karst. to reach breast length. However, after attaining a length of 1–3 meters, its growth rate may accelerate, resembling that of lower elevation zones (Indermühle 1978). Planning and implementation in high mountainous regions must be tailored to the specific conditions of each watershed. Despite these differences, the common denominator remains the fragile, marginal, and extreme nature of high mountain ecosystems. In watersheds where multidimensional planning and utilization of natural resources are to be conducted, objectives must be clearly defined. When the goals and purposes of a watershed are well established, achieving sustainable watershed management becomes more feasible. The objectives of high-altitude afforestation efforts often vary according to local needs (Leibundgut 1982). High mountain afforestation typically involves the establishment of forests in previously non-forested areas. These practices are critical for increasing carbon sequestration, enhancing biodiversity, and providing ecosystem services. Duan and Abduwali (2021) emphasize that afforestation should be approached from an ecosystem perspective, taking into account factors such as light, water, carbon dioxide, and various nutrients, which are essential for sustainability.

Restoring degraded areas in high-altitude zones to forested conditions is feasible but requires meticulous and patient afforestation efforts. Such projects are more costly, time-consuming, and challenging at these elevations. Success becomes increasingly difficult with altitude and is particularly challenging near the natural forest boundary. Similar afforestation challenges are observed in the belt immediately below the anthropogenic alpine forest boundary (Boydak and Çalışkan 2014). In high mountain afforestation, determining the upper limit where afforestation can be conducted (the alpine forest boundary) and identifying small priority sites for afforestation is of critical importance. To this end, site condition studies are conducted, and decisions are often based on the evaluation of remnant forests and indicator plants (Boydak and Çalışkan 2014). The use of native trees, shrubs, and woody species is fundamental in high-altitude afforestation projects. Additionally, the appropriate provenance of native species must be utilized. High-altitude provenances are genetically distinct from those of lower elevations, as plants adapted to these sites can survive extreme ecological and physiological conditions. Choosing unsuitable provenances, particularly within the forest's "battle zone," can have negative consequences (Tieffenbacher 1992).

In different geographical regions of Türkiye, various species form the forest boundaries; however, particularly in higher altitudes, deforestation and the loss of shrub cover due to degradation are significant concerns (Boydak and Çalışkan, 2014). The Eastern Black Sea Region is one of Türkiye's most sensitive areas due to its high population density per unit area, dispersed settlement patterns, rugged terrain, and variable ecological features. In this region, especially in high mountainous areas (upper belts), human activities such as transhumance and eco-tourism have caused a significant disruption of the ecological balance, leading to forests diverging from their natural structure (Turna, 2005). Scots pine (*Pinus sylvestris* L.), one of the principal species that can be utilized in the high-altitude areas of the Northeastern Black Sea, stands out with its extensive geographical range and adaptability (Boydak and Çalışkan, 2014). Scots pine has a broad natural distribution, extending approximately 3,700 km in width and 14,700 km in length across Europe and Asia, within the latitudes of 37°–70° N and longitudes of 7°–137° E. Its northern range reaches 70° latitude in Scotland, Norway, Sweden, and Finland, forming the forest boundary along with Siberian larch in the Siberian steppes. Its southern range is scattered in high-altitude areas of the Pyrenees in Spain, the Alps, Carpathians, Yugoslavia, Bulgaria, Anatolia, Crimea, and the Caucasus (Critchfield et al., 1966; Alemdağ, 1967; Pamay, 1962; Kayacık, 1977; Boratynski, 1991; Atalay, 2002; Turna, 2003). In Turkey, Scots pine is mainly distributed in the northern, northeastern, northwestern, and central Anatolian regions, with its densest occurrence in the inner regions of Northern Anatolia, extending into Central Anatolia (Alemdağ, 1967). In particular, to ensure the sustainability of ecological balance, it is imperative to determine appropriate land use practices, implement necessary conservation measures, and conduct rehabilitation efforts (Turna, 2005).

This study aims to evaluate the 10-year growth performance of Scots pine (*Pinus sylvestris* L.) seedlings planted at higher altitudes near the forest boundary as part of the "Galyan Afforestation Project." Additionally, it seeks to assess the success of the afforestation effort based on variations in aspect and elevation.

2. Materials and Methods

2.1. Materials

The study area is located within the Şahinkaya series under the jurisdiction of the Trabzon Forest Regional Directorate, Maçka Forest Management Directorate, Esiroğlu Forest Management Chiefdom. It is geographically situated between 39°40'07" and 39°45'28" E longitudes and 40°39'55" and 40°43'39" N latitudes (Figure 1). Sample plots were identified in areas afforested under the scope of the 2007 afforestation project in the

Galyan watershed. The selection of sample plots prioritized sites at the upper altitudes of the project area with Scots pine plantings, ensuring variation in elevation and aspect.

The sample plots are located at elevations between 1790 and 1990 meters, with an average slope of 60% (Table 1). The soil type in the study area was identified as clay loam. According to the records from the Meryemana meteorological station (10 years of climate data), the region has a climate classified as "very humid, micro-thermal, with little to no water deficit, and close to an oceanic climate," with a total annual precipitation of 1250 mm (Thornthwaite and Hare, 1955).

The afforestation in the study area used *Pinus sylvestris* (Scots pine) seedlings of the Sarıkamış origin, one-year-old, with enso-type containerized roots. All seedlings planted in the project area were sourced from the Trabzon/Of nursery. The study material consists of one-year-old Scots pine seedlings planted in 2007 as part of the Galyan afforestation project.

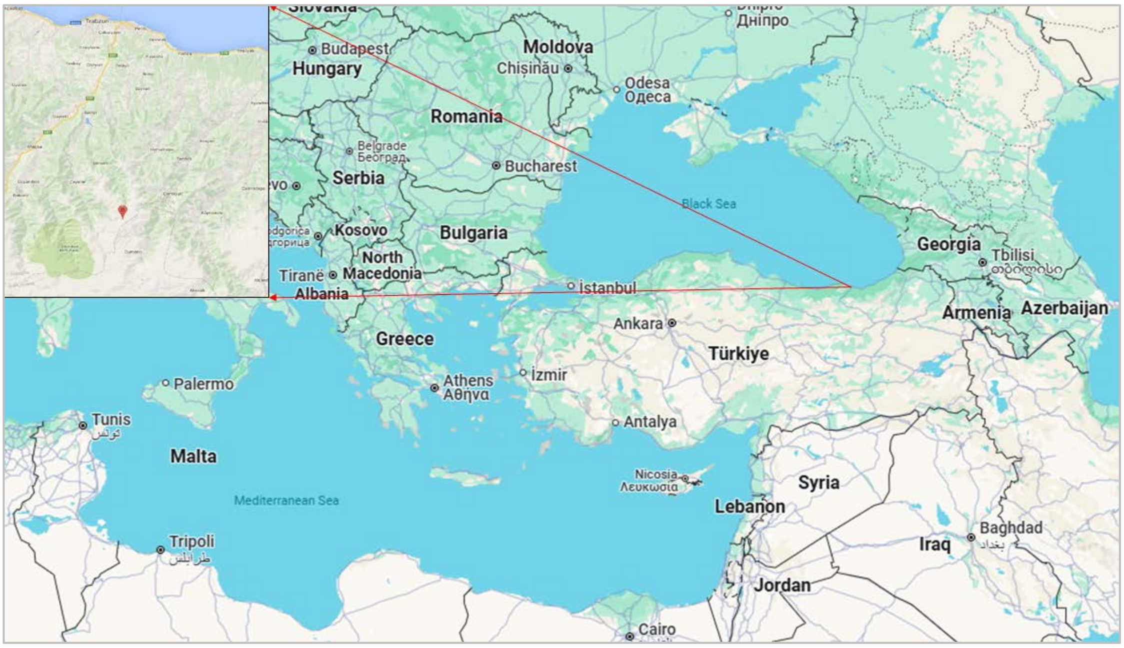

Figure 1. Geographical locations of the sample plots included in the study

Table 1
Aspect and elevation information for sample areas

Sample Area No	Elevation	Aspect
1	1790-1890	North
2	1790-1890	Northwest
3	1891-1990	North
4	1790-1890	Northeast
5	1891-1990	Northwest
6	1891-1990	Northeast
7	1790-1890	North

2.2. Methods

In the study, a total of seven sample plots were selected within the Scots pine afforestation area planted in 2007. These plots were chosen to represent three different aspects (north, northeast, and northwest) and two elevation ranges (1790–1890 m and 1891–1990 m). In 2011, measurements were conducted on 50 seedlings from each sample plot, including seedling length, root collar diameter, the number of branches on the last shoot, lengths of the longest branches in the north, south, east, and west directions, and the number of terminal buds. Additionally, inter-nodal measurements were taken to determine annual length increments. Measurements of seedling length and annual growth increments were made using a measuring tape with centimeter precision, while root collar diameters were measured with a digital caliper with millimeter precision. In 2016, the condition of the seedlings at their 10th year was assessed through field observations, and evaluations were conducted.

For data analysis, SPSS 26.0 statistical software was used to perform variance analysis, Duncan's test, t-tests, and correlation analysis. One-way analysis of variance (ANOVA) was employed to determine the significance of differences in morphological characteristics of seedlings across different aspects, and groupings were identified using Duncan's test. Differences in morphological characteristics between seedlings from different elevation ranges were analyzed using t-tests. Additionally, correlation analysis was conducted to examine the magnitude, direction, and significance of relationships among the measured traits (Ercan 1997; Özdamar 1999; Özkan 2003).

3. Result and Discussion

The mean seedling lengths and standard error values for the sample plots selected in the study are presented in Table 2.

Table 2
Average seedling length (SL) and standard deviation values of sample areas

Sample Area No	2y-SL (cm)	3y-SL (cm)	4y-SL (cm)	5y-SL (cm)
1	24.92±0.88	37.93±1.38	48.90±1.82	61.59±2.71
2	18.90±0.91	29.57±1.17	39.80±1.40	50.00±1.55
3	27.30±1.24	41.26±1.85	52.63±2.25	64.53±2.46
4	18.07±0.91	28.57±1.12	38.30±1.44	51.87±1.43
5	25.90±1.36	38.65±2.01	50.15±2.60	61.87±2.76
6	28.87±1.37	41.27±2.07	52.37±2.72	63.45±3.31
7	21.68±0.84	33.57±1.19	48.02±1.72	60.92±2.02
Ort.	23.66±0.48	35.83±0.68	47.16±0.85	59.07±0.97

2y-SL: Length of 2-year-old seedlings, 3y-SL: Length of 3-year-old seedlings, 4y-SL: Length of 4-year-old seedlings, 5y-SL: Length of 5-year-old seedlings

The highest average length values for 2-year-old and 3-year-old seedlings were recorded in sample plot 6, at 28.87 cm and 41.27 cm, respectively, while the highest average length values for 4-year-old and 5-year-old seedlings were observed in sample plot 3, at 52.63 cm and 64.53 cm, respectively. Scots pine seedlings exhibited length increases of 51.4%, 31.6%, and 25.3% consecutively after planting. As shown in Figure 2, the length growth of the seedlings was found to decrease over the years.

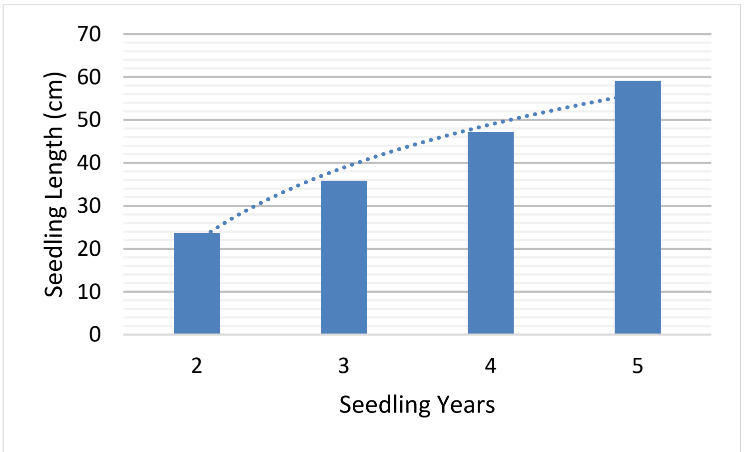

Figure 2. Average length values of Scots pine seedling by year

The mean seedling length values are presented in Figure 3 according to different aspects and altitudes. Additionally, the significance of differences in mean seedling lengths among various aspects was determined using variance analysis, and groups were identified through Duncan's test. The significance of differences in mean seedling lengths between different altitudes was assessed using the t-test (Figure 3).

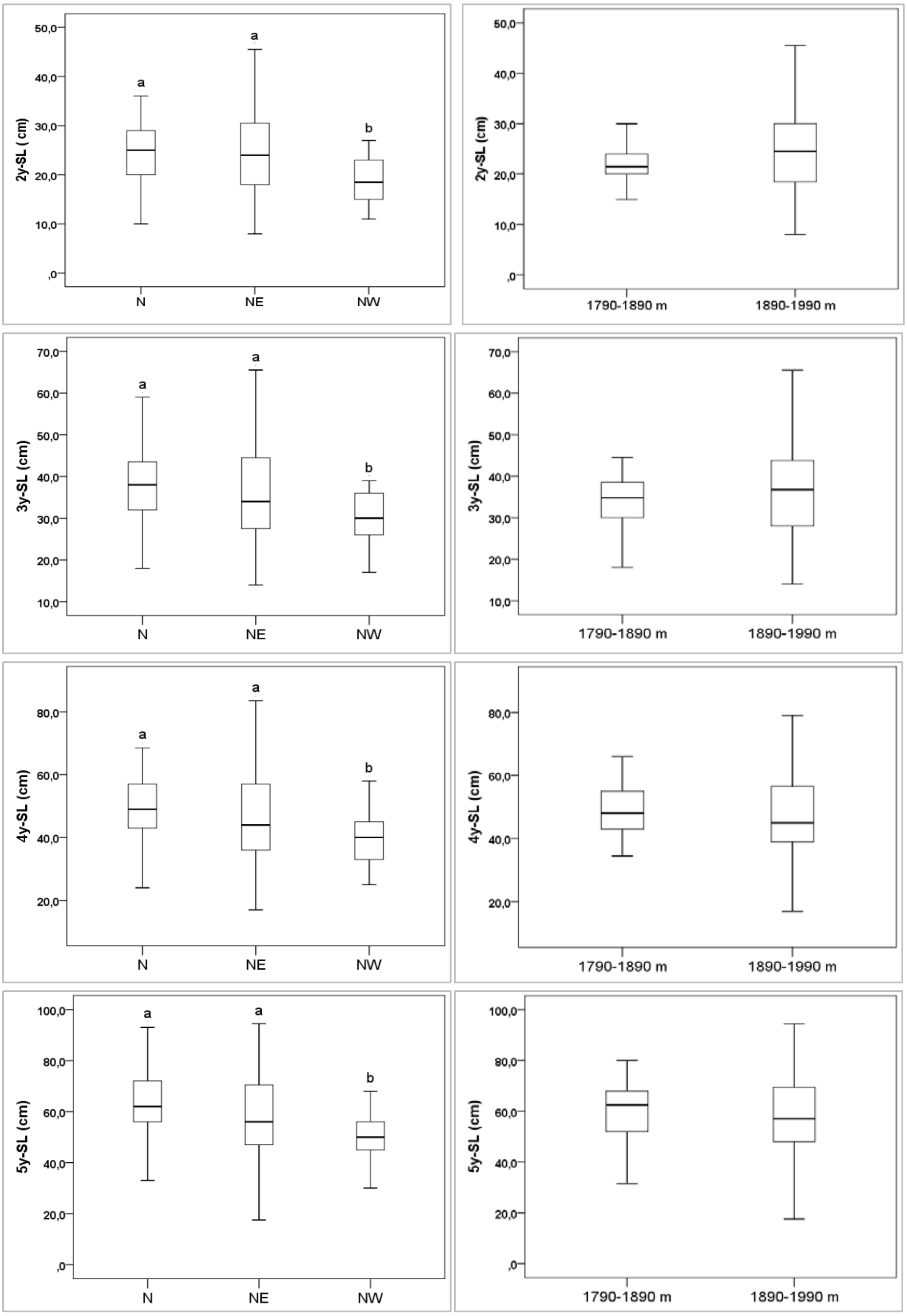

Figure 3. Mean seedling length values according to different aspects and altitudes

The differences in seedling lengths among various aspects were found to be statistically significant for each age group ($p<0.01$). Results of Duncan's test revealed two distinct groups in terms of seedling length across all ages. For each age group, the north and northeast aspects formed one group, while the northwest aspect constituted a separate group. Furthermore, the highest mean length values were observed in seedlings located in sample plots on the northern aspect. In terms of elevation, seedling lengths did not show statistically significant differences for any age group (p>0.05). However, for 2-year-old Scots pine seedlings, the mean length was lower at lower elevations (21.68 cm). By the third year, greater length growth at lower elevations resulted in a mean length (36.21 cm) close to that of seedlings at higher elevations. Length growth rates for 3-, 4-, and 5-year-old seedlings were 55%, 43%, and 27% at lower elevations, and 51%, 30%, and 25% at higher elevations, respectively, with the mean lengths being higher at lower elevations in contrast to the second year (Figure 4). A study by Çepel et al. (1977) examining the relationship between the growth of pure Scots pine forests and certain edaphic and physiographic factors across Turkey concluded that temperature was the limiting factor for Scots pine growth in Northeastern Anatolia. They identified a negative correlation between altitude and length growth. Another study on Scots pine plantations in Artvin-Ardanuç analyzed the annual length increments of seedlings between 1987 and 1996. Regression analysis showed that Scots pine length growth was positively correlated with temperature and negatively correlated with precipitation (Ölmez and Aslan 1997).

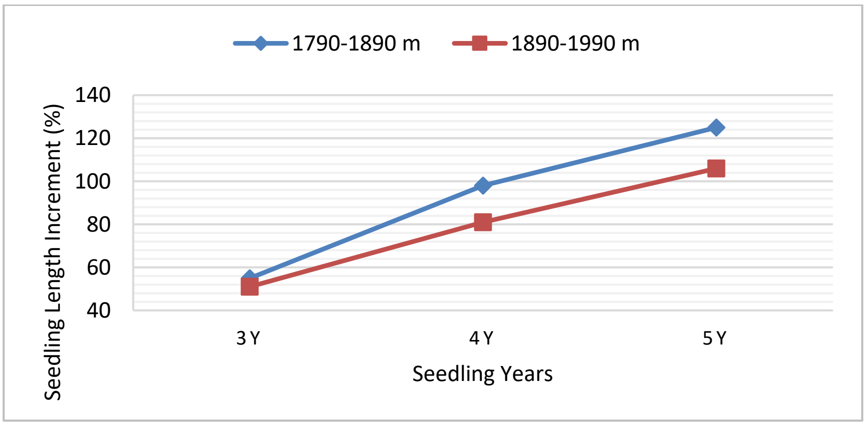

Figure 4. Length growth values (%) based on elevation and age

The mean root collar diameter (RCD) values for 5-year-old seedlings are presented in Figure 5 according to different aspects and altitudes. The significance of differences in mean RCD values among various aspects was assessed using variance analysis, which indicated no statistically significant differences (p>0.05). The average RCD values were recorded as 2.26 cm on the northern aspect, 2.09 cm on the northeastern aspect, and 2.05 cm on the northwestern aspect. In contrast, the significance of differences in mean RCD values between different elevation ranges was evaluated using a t-test, which revealed statistically significant differences at a 95% confidence level. The average RCD value was found to be 2.43 cm at elevations of 1790–1890 m and 2.11 cm at elevations of 1891–1990 m. These results indicate that, similar to seedling length, higher RCD values were observed at lower elevations and on northern aspects.

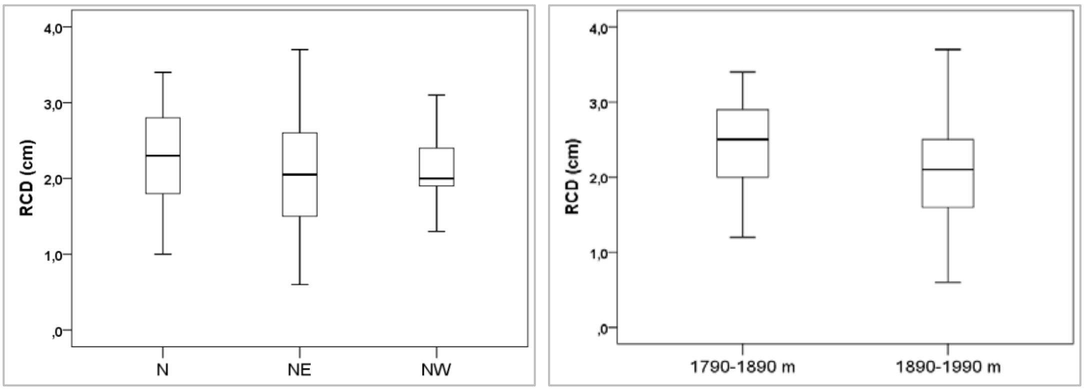

Figure 5. Mean root collar diameter (RCD) values for 5-year-old seedlings based on different aspects and elevations

In 5-year-old Scots pine seedlings, the effects of different aspects and elevations on the number of lateral branches on the last shoot (LBL) and the number of terminal buds (NTB) were analyzed using variance analysis. The results, including maximum, minimum, and standard deviation values, are presented in Table 3. For LBL, a statistically significant difference was found based on elevation, whereas no significant difference was observed among different aspects. For NTB, no significant differences were identified based on either aspect or elevation.

Table 3
Variance analysis results for LBL and NTB based on different aspects and elevations

			Minimum	Maximum	Mean	St. Error	ANOVA
LBL	Aspect	North	2	11	4.38	1.31	F:0.146 P:0.864
		Northeast	2	10	4.36	1.34	
		Northwest	3	6	4.50	0.82	
	Elevation	1790-1890	2	6	4.04	0.95	F:9.948
		1891-1990	2	11	4.56	1.38	P:0.002
NTB	Aspect	North	3	9	5.81	0.84	F:0.500 P:0.607
		Northeast	1	9	5.69	1.61	
		Northwest	4	8	5.63	0.89	
	Elevation	1790-1890	3	7	5.71	0.768	F:0.167
		1891-1990	1	9	5.77	1.311	P:0.683

p<0.05, LBL: On the number of lateral branches on the last shoot, NTB: The number of terminal buds

The lengths of the longest branches in four directions (north, south, east, and west) were measured for 5-year-old seedlings in the Scots pine afforestation trial plots (Table 4). According to the mean values for all trial plots presented in Table 3, the longest branch growth was observed in the east direction, although the branch lengths in all directions were generally similar. The average length of the longest branches was determined to be 24.86 cm.

Table 4
Longest branch lengths of Scots pine seedlings

Sample Area No	North (cm)	South (cm)	East (cm)	West (cm)	Mean (cm)
1	22.53	23.90	23.60	24.60	23.66
2	25.40	22.77	22.33	21.57	23.02
3	27.23	26.57	29.40	26.70	27.48
4	22.13	24.13	25.17	24.07	23.88
5	19.55	16.33	21.47	19.27	19.15
6	26.38	30.35	29.65	28.40	28.70
7	27.18	25.82	30.80	28.78	28.15
Mean	24.35	24.27	26.06	24.77	24.86

The results of the correlation analysis for the nine measured traits are presented in Table 5. The correlation analysis indicates that the data for all traits exhibit statistically significant positive correlations at the 99% confidence level.

Table 5
Correlation analysis results for morphological traits of Scots pine seedlings

	5y-SL	RCD	LBL	NTB	LBN	LBS	LBE	LBW	LBA
5y-SL	1	0.552*	0.371*	0.390*	0.476*	0.524*	0.619*	0.556*	0.647*
RCD		1	0.355*	0.384*	0.594*	0.623*	0.675*	0.604*	0.740*
LBL			1	0.327*	0.342*	0.344*	0.353*	0.379*	0.414*
NTB				1	0.294*	0.368*	0.290*	0.312*	0.371*
LBN					1	0.621*	0.634*	0.556*	0.812*
LBS						1	0.641*	0.652*	0.859*
LBE							1	0.739*	0.882*
LBW								1	0.864*
LBA									1

* Correlation is significant among traits at the 99% confidence level
LBN: Longest branch north, LBS: Longest branch south, LBE: Longest branch east, LBW: Longest branch west, LBA: Average length of the longest branches

In 2016, assessments were conducted in the trial plots before the vegetation period to evaluate the success of the afforestation efforts. Since the planting area is located near the alpine forest boundary, the overall seedling survival rate was determined to be adequate. While some areas exhibited scattered mortality, other areas showed high survival rates in rows. It was observed that Scots pine seedlings experienced forking and were significantly affected by extreme climatic conditions in terms of both survival success and seedling quality.

Across most of the sites, no understory vegetation (e.g., ferns, blackberries, rhododendrons, bearberry) was present at levels that would negatively impact seedling growth. However, localized observations indicated that some seedlings were affected by snow pressure on understory vegetation. Further examination of seedling pits in areas with dead Scots pine seedlings revealed that some were planted on impermeable bedrock, exposing them to stagnant water, while others were affected by grazing damage (Figure 6). A study by Tetik (1986) investigated various factors influencing the distribution of pure Scots pine forests in Northeastern Anatolia and outlined the ecological conditions required for Scots pine. It was suggested that in areas where the natural balance has been disrupted, afforestation efforts should be delayed until good grass development is achieved before proceeding with planting.

Figure 6. Scots pine seedlings affected by understory pressure and seedling pits showing mortality due to high groundwater levels and waterlogging

In the 2016 measurements, the afforestation site was found to exhibit extreme living and survival conditions characteristic of a high mountain environment, with highly adverse biological, physiological, sociological, and site conditions. Despite surviving under these conditions, the seedlings showed clear responses to damage. In general, terminal shoots had broken or dried out, leading to lateral shoots branching and forming multiple-stem structures. Observations revealed that 80% of the seedlings had forked and deviated from their normal form. In some Scots pine individuals, damage to the terminal shoot resulted in the best-developed lateral shoot taking over as the main stem, continuing its growth. It was also observed that the needles of Scots pine seedlings commonly exhibited reddening and shedding. Nevertheless, the seedlings remained vital, with some continuing to grow in a straight form while others developed in a forked form (Figure 7).

Figure 7. Scots pine individuals with maintained vitality but deformed stem structure

In high mountain ecosystems, key climatic and edaphic factors include solar radiation, air and soil temperature, precipitation (rain and snow), wind, frost, transpiration, vegetation period, and biological soil content. These factors are not independent but are in constant interaction with one another. Understanding these interactions is crucial during the assessment phase, as they play a significant role in restoring disrupted ecological balances (Turna, 2005).

In Scots pine (*Pinus sylvestris*) afforestation, it was observed that seedling growth was normal during the initial years following planting (2–3 years). However, in subsequent years, extreme climatic conditions caused various deformities, such as drying, branching, and distortion of the apical shoot. Based on data obtained from afforestation efforts conducted in high mountain areas, it was determined that both the root collar diameter (RCD) and seedling height increment were higher on north-facing slopes and at lower altitudes. Although Scots pine seedlings showed higher average height in high-altitude sample plots up to the age of 2, by the age of 5, seedlings in the lower-altitude sample plots exhibited greater height growth, resulting in higher average heights. This outcome can be attributed to the relatively harsher conditions of the higher-altitude experimental site, which, despite the lack of significant elevation differences between the sample plots, may have slightly hindered seedling development. Measurements conducted in 2010 revealed that the average seedling height was 59.64 cm, the average root collar diameter was 2.16 cm, and the average annual height increment was 13.92 cm. In 2016, measurements showed that the average seedling height had increased to 93.85 cm, the average root collar diameter to 3.43 cm, and the average annual height increment to 21.84 cm.

The Scots pine (*Pinus sylvestris* L.) seedlings used in this study originated from Sarıkamış, a region with distinct climatic and edaphic characteristics. Given that seedling origin can significantly influence afforestation success, it is crucial to compare the growing conditions of Sarıkamış with those of the project area in order to interpret the results more accurately. Factors such as temperature fluctuations, soil composition, and precipitation patterns may have affected the adaptation and growth performance of the seedlings in the Galyan afforestation site. Differences in climatic conditions between the origin and planting sites could have influenced seedling survival, growth rates, and morphological development, potentially contributing to the observed variations in performance across different aspects and elevations. Therefore, while evaluating the afforestation success, it is essential to acknowledge that the ecological characteristics of the seedling origin may have played a role in shaping the observed results.

In terrestrial ecosystems, all organisms achieve their highest levels of growth and development, as well as superior competitive abilities against other species, under living conditions that align with their physiological optimum. As conditions deviate from this optimum, these two advantages diminish. An organism with reduced competitive ability becomes a minority within the system and simultaneously grows more sensitive and vulnerable to external factors (Asan 2006). Figure 7 illustrates individuals that, despite maintaining their vitality, exhibit stem deformations caused by external factors. Additionally, the development of lateral branches as a result of terminal shoot dieback or deformation is also shown.

Studies on high mountain afforestation provide valuable insights into ecological challenges and solutions. Schoenenberger (2001) evaluated afforestation practices at high altitudes, highlighting the effectiveness of clustered planting strategies, particularly in subalpine and high-altitude regions. This method considers varying micro-site conditions, supports diverse forest structures, reduces seedling mortality rates, and enhances resistance to wind, snow pressure, and insect attacks. Additionally, clustered planting minimizes maintenance needs, increases seedling survival rates, and strengthens the ecological adaptation of forest areas in harsh mountain conditions. Nadal-Romero et al. (2023) examined the impact of afforestation on abandoned agricultural lands in Mediterranean mid-mountain regions. Their findings indicated improvements in soil properties, organic carbon accumulation, water retention capacity, and erosion reduction, although some adverse effects on the hydrological system, such as reduced annual water yield, were also observed. The study emphasized the importance of using local species and adopting sustainable strategies. Grätz et al. (2023) analyzed afforestation areas in high-altitude regions of Austria, focusing on their protective functions against avalanches and natural hazards. Using AI-assisted remote sensing, the study accurately identified critical zones affecting avalanche protection capacity, finding that Norway spruce (*Picea abies*), Swiss stone pine (*Pinus cembra* L.), and other high-altitude-adapted species were effective in reducing avalanche risks. Conversely, areas dominated by pastures were less effective in providing protection. Another study explored the potential of *Pinus nigra* in afforestation efforts in semi-arid regions of Turkey, concluding that subspecies of Anatolian black pine demonstrated better growth in high-altitude regions and significant adaptation to local environmental conditions (Ayan et al., 2021). In high mountain afforestation efforts, as highlighted in this study, adopting a nature-compatible approach and focusing on nature conservation will enhance success rates. Indeed, nature conservation-oriented afforestation should prioritize maintaining ecosystem integrity, considering the habitats of all organisms, and ensuring the preservation of biodiversity (Güney and Turna, 2005; Turna et al., 2021).

4. Conclusion

This study, focusing specifically on Scots pine plantations within the scope of the Galyan Project, provides critical insights into afforestation efforts in high mountain ecosystems. Over a ten-year observation period, it was found that initial seedling growth was generally robust; however, significant challenges emerged in subsequent years due to extreme climatic conditions such as frost, snow pressure, and soil waterlogging. These conditions led to physiological deformities such as terminal shoot dieback and excessive branching.

The research identified that site-specific factors, including aspect and elevation, significantly influenced seedling growth and survival. Northern aspects and lower elevations were particularly favorable for seedling development. These findings emphasize the importance of careful site selection and management in high-altitude afforestation projects. Moreover, integrating ecological research with practical forestry practices is essential for achieving sustainable forestry in mountainous regions.

In conclusion, while forestry in high-altitude regions is fraught with challenges, it offers immense potential for ecological restoration, biodiversity enhancement, and carbon sequestration. Future efforts should prioritize the development of robust, site-specific methodologies that incorporate ecological, physiological, and climatic factors to optimize forest success and sustainability.

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Author Contributions

İbrahim Turna: Planned and designed the study, collected data during fieldwork.

Abdurrahman Semercioğlu: Designed the study, collected data during fieldwork, and conducted analyses.

Fahrettin Atar: Collected data during fieldwork, performed the statistical analyses of the study, and wrote the article.

Deniz Güney: Collected data during fieldwork and contributed to the editing of the article.

Conflicts of Interest

The authors declare no conflict of interest.

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