

THE EFFECT OF ELEVATION ON FOREST STRUCTURE AND TREE COMMUNITY COMPOSITION IN TROJAN FIR FORESTS IN KAZDAĞLARI (NW ANATOLIA, TÜRKİYE)

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(Received 9th Sep 2025; accepted 24th Nov 2025)

Abstract. Elevational contrasts offer natural experiments to investigate climatic and edaphic effects on forest structure. In the Mediterranean–Euxine transition, such contrasts can reorganize species assemblages and canopy architecture, yet plot-based evaluations integrating composition, density, and stratification are rare in the region. We examined Trojan fir (*Abies nordmanniana* subsp. *equi-trojani*) forests in Kazdağları (NW Türkiye) across two elevation zones—three low (600–800 m) and three high (1200–1400 m) sites—using 36 plots (25 × 25 m) were surveyed in October 2023. All woody individuals ≥30 cm were censused, crown overlaps mapped, and used to calculate cover, density, and vertical stratification. Community composition was assessed via NMDS, and structural variables were modeled with GLMMs and zero-inflated beta models. Across 13 taxa, ordinations clearly separated high from low situated plots, with tighter clustering at higher elevations. High sites were needle-leaved-dominated, while low sites supported mixed broad-leaved associates. Species-level patterns showed stable Trojan fir cover and density, denser *Fagus orientalis* at low elevations, and more *Pinus nigra* at high elevations. Canopies were generally limited to one–two layers, with ≥3 layers uncommon—especially at high elevations—indicating reduced vertical complexity. Elevation thus emerges as a driver of assembly and structure in Trojan fir forests; conserving heterogeneity across zones may strengthen resilience to warming climate.

Keywords: *Abies, elevation, cover, density, community, forest structure, Trojan fir*

Introduction

Elevation strongly influences forest communities through gradients in microclimate, soil properties, and disturbance regimes (Körner, 2007; Lenoir et al., 2008). In mountainous landscapes, elevational gradients often produce distinct zonation in species composition, canopy structure, and functional traits (Pausas and Austin, 2001; Jurasinski and Kreyling, 2007). Such structural and compositional shifts affect ecosystem processes, including hydrological regulation, carbon sequestration, and biodiversity resilience (Kellner et al., 2009; Bruijnzeel and Veneklaas, 1998). Consequently, the effects of elevation on forest structure and community composition have been extensively studied across biomes worldwide, from tropical to boreal regions (Lieberman et al., 1996; Antonio Vázquez and Givinish, 1998; Drewa et al., 2002; Miyajima and Takahashi, 2007; Mazón et al., 2020; Wambugu et al., 2024). These studies improve our understanding on the structural variation of forest biodiversity along with elevational gradients and provide information on the forests across elevation belts.

In Anatolia, elevational range and variability are recognized as major drivers of biodiversity (Atalay, 1994; Şekercioğlu et al., 2011), and elevation strongly shapes forest vegetation and structure in both the Mediterranean (Kavgacı et al., 2021; Özkan et al.,

2024) and Euxine regions (Kavgacı et al., 2023). Despite its ecological importance, empirical studies on elevational patterns of community structure, functional composition, and vertical canopy stratification in many Anatolian forests remained limited.

Kazdağları (Mount Ida), in northwestern Anatolia (Türkiye), is one of the understudied regions of the country's biodiversity. Situated at the intersection of the Mediterranean and Euro-Siberian floristic zones, the mountain harbors exceptionally rich biodiversity, marked by high levels of endemism, relict species, and pronounced habitat heterogeneity shaped by steep elevational gradients (Davis, 1965–1985; Ekim et al., 2000). The forest ecosystems of Kazdağları play a critical role in regulating water resources, stabilizing soils, and buffering local climate, thereby supporting both ecological integrity and socio-economic functions (Atalay, 2008; Çolak and Rotherham, 2006). A defining element of these forests is the Trojan fir (*Abies nordmanniana* subsp. *equi-trojani*), an endemic and endangered conifer whose taxonomic status has long been debated but which nonetheless dominates forest stands of the region (Ata, 1975; Knees and Gardner, 2011; Usta and Tavşanoğlu, 2023).

Most existing studies in the region have focused on floristic inventories and silvicultural aspects of local forests; however, few have quantified the forest structure of Trojan fir, leaving a critical gap in understanding its structural dynamics across elevational gradients. Moreover, research on the forestry, genetics, ecology, and morphology of Trojan fir has largely been conducted in other parts of its distribution range, rendering the Kazdağları populations particularly understudied (Usta and Tavşanoğlu, 2023). These knowledge gaps limit our ability to predict how these forests will respond to climate change and to assess their role in supporting biodiversity along elevational gradients. Documenting elevation-driven variation would (i) clarify the niche breadth and competitive strategies of key taxa; (ii) reveal whether underrepresented broad-leaved species are poised for expansion under warming; and (iii) inform conservation strategies aimed at bolstering resilience across elevation-dependent gradients of structure and composition. More broadly, although elevational zonation of forest vegetation is common worldwide (Lieberman et al., 1996; Drewa et al., 2002; Miyajima and Takahashi, 2007; Mazón et al., 2020), Kazdağları represents a particularly informative system because an endemic, threatened fir coexists with a diverse pool of Mediterranean and Euro-Siberian broad-leaved species. In such a region, local floristic diversity may mediate forest responses to climate change by providing alternative, locally adapted species that can assume canopy dominance if Trojan fir declines or shifts upslope.

Here, we address this gap by examining forest composition and structure in sites dominated by Trojan fir across two elevation zones (low vs. high) in the Kazdağları region of northwestern Anatolia (Türkiye). Specifically, we (i) quantified tree community composition, including both cover and presence–absence patterns; (ii) compared cover and density across functional groups (broad-leaved vs. needle-leaved trees) and focal tree species; and (iii) evaluated vertical stratification of canopy layers as an indicator of structural complexity. Based on patterns observed in other Anatolian regions, we hypothesized that the structure and composition of Trojan fir forests would differ between low- and high-elevation zones, with lower tree diversity and structural complexity expected at higher elevations.

Methods

Study area and sites

Kazdağları (Mount Ida) is a mountain massif in northwestern Anatolia (Türkiye), spanning the provinces of Çanakkale and Balıkesir, and forming a natural boundary north

of Edremit Bay on the Aegean coast. Vegetation organized into three primary zones—forests, shrublands, and high-mountain communities—with about 800 plant taxa recorded, many of which have significant ethnobotanical importance (Uysal, 2010). Forests are characterized by broad-leaved deciduous stands at lower elevations, mixed deciduous–coniferous forests at mid-elevations, and coniferous forests at higher elevations, reflecting the strong influence of elevation on vegetation patterns (Efe et al., 2015). The area experiences a transitional Mediterranean climate, with warm, dry summers and wet winters. Annual precipitation ranges from about 850 mm on lower slopes to 1400–1500 mm in the subalpine zone, while mean annual temperatures vary from 12–16°C at low elevations (0–100 m) to 6–8°C at higher elevations (1400–1700 m). Part of the mountain was designated a national park in 1994 in recognition of its exceptional floristic richness (Uysal, 2010). Despite its ecological significance, unprotected areas of Kazdağları face growing anthropogenic pressures, including logging, forest management interventions, tourism development, mining, and land-use change, which threaten its biodiversity and ecosystem integrity (Çolak and Rotherham, 2006).

We selected six study sites (Fig. 1), three in the high elevation zone (1200–1400 m), and three in the low-elevation zone (600–800 m). High-elevation sites were Kazdağı National Park (39.7153°N, 26.8833°E; ~1400 m), Kazdağı Forest Management Zone (39.8878°N, 26.9181°E; ~1350 m), and Kirsealan Forest Management Zone (39.7720°N, 26.9922°E; 1290 m). Low-elevation sites were Çan Gene Management Zone (39.9233°N, 27.9333°E; 600 m), Koyuncu Ecotourism Zone (39.4251°N, 27.773°E; ~725 m), and Yenice Forest Management Zone (39.5410°N, 27.1510°E, ~690 m). All sites had been free from forest management interventions for at least 20 years, minimizing anthropogenic influences on forest structure and composition (Fig. 2).

Data collection

We conducted fieldwork in October 2023 across the six study sites. At each site, we established six sampling plots of 625 m² in size (25 × 25 m) in structurally representative stands to capture variation in canopy composition. Within each plot, we established two 25 m line transect by using measure tapes, spaced 10 m apart, and recorded all woody individuals taller than 30 cm on intersecting the transects and identified them to the species level. For each intersecting individual, we recorded the start and end points of crown projections to estimate cover as percentage of transect length occupied by each group. The two transects per plot were combined into a single 50 m line for plot-level cover estimates. We used these data to quantify tree composition, relative density (proportion of individuals or functional groups per plot), and vertical stratification (the arrangement of tree crowns into overlapping layers). In total, we surveyed 36 plots each with two transects for the study.

Community composition

We analyzed patterns in community composition across elevation zones using non-metric multidimensional scaling (NMDS) for both cover and presence/absence with the *vegan* package in R (R Core Team, 2023; Oksanen et al., 2025). We run two separate ordinations with the *metaMDS* function, using two dimensions ($k = 2$) and 100 random starts to ensure stable solutions. We applied Bray–Curtis dissimilarities to cover data, and Jaccard dissimilarities to presence/absence data. We evaluated differences between

elevation zones using permutational multivariate analysis of variance (perMANOVA) with *adonis2* function in the *vegan* package, applied to the same dissimilarity matrices (Oksanen et al., 2025). We visualized ordinations using the *ggplot2* package (Wickham et al., 2025).

Cover and density

To test whether elevation influenced cover (canopy cover) and density, we prepared two datasets. The first grouped species into functional types: needle-leaved (*Abies nordmanniana* subsp. *equi-trojani*, *Pinus nigra* subsp. *pallasiana*) and broad-leaved (all others). The second retained species identity but included only the three focal taxa present across all sites (*Abies nordmanniana* subsp. *equi-trojani*, *Fagus orientalis*, *Pinus nigra* subsp. *pallasiana*). Since various *Quercus* species and *Castania sativa* were common at low elevations but absent in high elevations, we excluded them from the focal taxa.

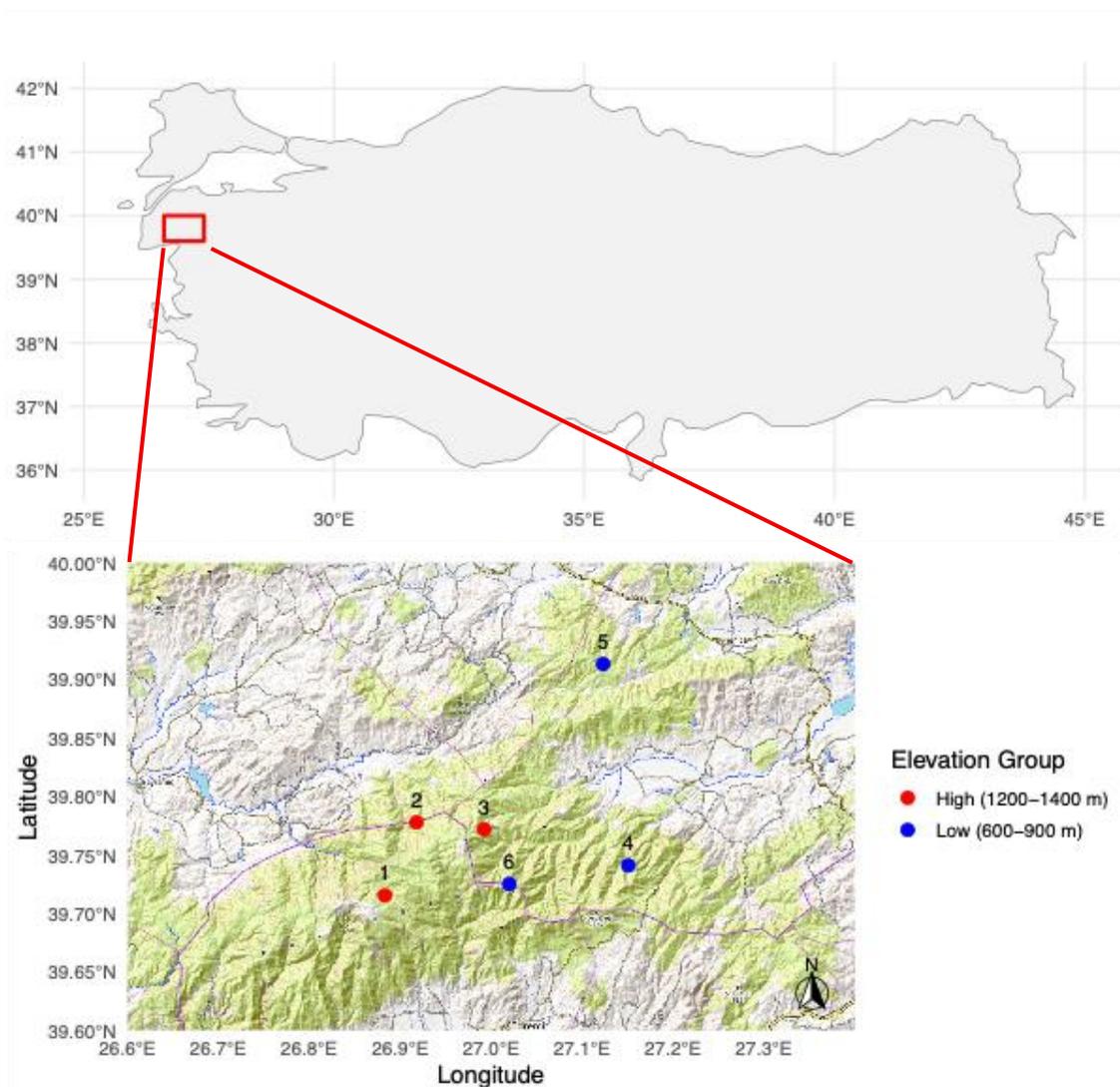


Figure 1. The location of study area in Türkiye (above map) and of study sites around the study area (below map). (1) Kazdağı National Park; (2) Kazdağı Forest Management Zone; (3) Kirsealan Forest Management Zone; (4) Çan Gene Management Zone; (5) Koyuncu Ecotourism Zone; (6) Yenice Forest Management Zone

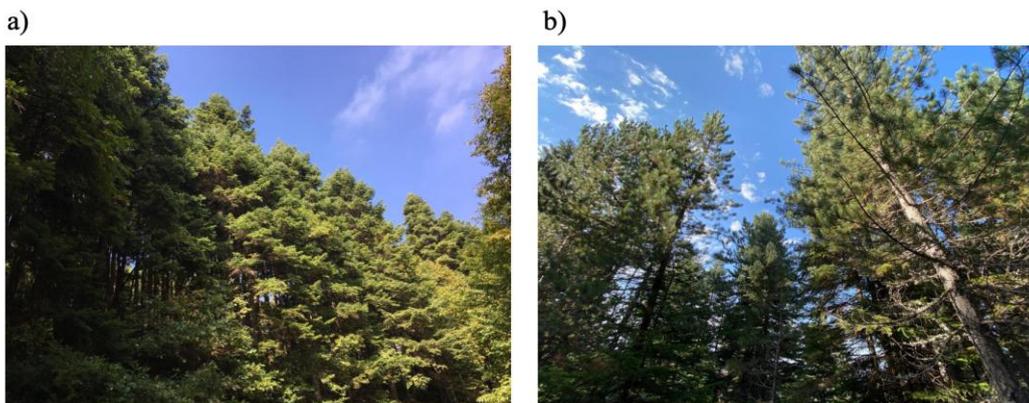


Figure 2. Forest structure of a) low elevation site (Çan Gene Management Zone), b) high elevation site (Kazdağı National Park). Pictures show both density and cover differences in elevation zones as low elevation site is denser and more diverse

For each dataset, we calculated plot-level cover by summing canopy-segment lengths per species or group and converting totals to percent cover; because crowns can overlap, cover could exceed 100%. We calculated densities as the proportion of individuals belonging to a focal species or functional group relative to the total number of individuals in the plot.

We analyzed cover and density separately at the functional group and species levels. Because normality assumptions were violated (Shapiro–Wilk test, $p < 0.01$), we modeled cover with generalized linear mixed models (GLMMs) using a Gamma distribution and log link (*glmmTMB* function, *glmmTMB* package; Brooks et al., 2025). We modeled density with binomial GLMMs, and we used a beta-binomial model when overdispersion occurred. In all models, we included elevation (high vs. low) and species or functional group as fixed factors, with plot as a random effect. We estimated marginal means and pairwise contrasts with the *emmeans* function in the *emmeans* package (Lenth, 2025). For functional groups, we compared broad- vs. needle-leaved cover and density within each elevation; for species, we compared each focal species between elevations. We assessed significance with Wald z-tests, with Tukey adjustments for multiple contrasts, and we back-transformed the results to the response scale where appropriate.

Vertical stratification

We quantified canopy vertical stratification as the number of crowns overlapping vertically above each point along a 50-m transect in every plot. For each woody individual, we recorded the transect positions where its crown projection began and ended. Overlaying all crown segments produced a one-dimensional profile of “layer count” (i.e., the number of overlapping crowns) along the transect. From this profile, we derived two metrics: (i) the vertical stratum count, defined as the maximum layer count observed on the transect; and (ii) layer-length proportions, calculated as the proportion of the 50-m transect occupied by 1, 2, 3, and ≥ 4 concurrent layers.

We modeled layer proportion as a function of elevation (low vs. high), layer count (1, 2, 3, ≥ 4), and their interaction using a zero-inflated beta GLMM with a logit link (*glmmTMB* function, *glmmTMB* package; Brooks et al., 2025), where zero inflation

accounted for plots lacking ≥ 4 layers. We included plot identity as a random effect to account for non-independence of observations from the same plot. We conducted model diagnostics using simulated residuals (*DHARMA* function, *DHARMA* package; Harting, 2024). We obtained post hoc contrasts with the *emmeans* function in the *emmeans* package (Lenth, 2025) to compare layer-count proportions within each elevation zone; *p*-values were Holm-adjusted, and we reported results on the response scale.

Results

Community composition

The presence–absence matrix (Table 1) showed that two conifers (*Abies nordmanniana* subsp. *equi-trojani* and *Pinus nigra* subsp. *pallasiana*) occurred at all six sites, indicating region-wide dominance across elevations. Among broad-leaved species, only *Fagus orientalis* was present in both zones (Table 1). Low-elevation sites supported a broader set of broad-leaved associates, including *Castanea sativa*, *Quercus frainetto*, *Q. petraea*, and *Sorbus torminalis*, yielding higher local richness (7–8 species per site). By contrast, high-elevation sites were compositionally simpler (3–4 species per site), largely conifer-dominated, with *F. orientalis* present at two of the three high-elevation sites and a few taxa restricted to the National Park (e.g., *Populus tremula*, *Sorbus umbellata*).

Table 1. Presence and absence of species in each study site

Species	Study site					
	Low-elevation zone			High-elevation zone		
	Çan GMZ	Koyuncu EZ	Yenice FMZ	Kazdağı FMZ	Kazdağı NP	Kirsealan n FMZ
Needle-leaved						
<i>Abies nordmanniana</i> (Steven) Spach subsp. <i>equi-trojani</i> (Asch. & Sint. ex Boiss.) Coode & Cullen	+	+	+	+	+	+
<i>Pinus nigra</i> J.F. Arnold subsp. <i>pallasiana</i> (Lamb.) Holmboe	+	+	+	+	+	+
Broad-leaved						
<i>Acer platanoides</i> L.	+	-	-	-	-	-
<i>Carpinus betula</i> L.	-	+	+	-	-	-
<i>Cytisus hirsutus</i> L.	+	-	+	-	-	-
<i>Castanea sativa</i> Mill.	+	+	+	-	-	-
<i>Fagus orientalis</i> Lipsky	-	-	+	+	-	+
<i>Populus tremula</i> L.	-	-	-	-	+	-
<i>Quercus frainetto</i> Tan.	-	+	+	-	-	-
<i>Quercus petraea</i> (Matt.) Liebl.	+	+	-	-	-	-
<i>Rubus</i> sp.	+	-	-	-	-	-
<i>Sorbus torminalis</i> (L.) Crantz	+	+	-	-	-	-
<i>Sorbus umbellata</i> (Desf.) Fritsch	-	-	-	-	+	-
<i>Vaccinium myrtillus</i> L.	-	-	-	-	+	-

Functional groups are NL: needle-leaved, BL: broad-leaved

The cover-based NMDS (stress = 0.205; *Fig. 3a*) showed a clear separation of plots by elevation primarily along NMDS1 ($R^2 = 0.55$, $F = 7.45$, $p = 0.001$, permANOVA). Group ellipses overlapped modestly, but high-elevation plots clustered tightly, whereas low-elevation plots were more dispersed, indicating greater among-plot heterogeneity at low elevations. No consistent clustering was observed among sites within the same elevation zone.

The presence/absence NMDS (Jaccard distance; stress = 0.145; *Fig. 3b*) accentuated this pattern ($R^2 = 0.68$, $F = 12.82$, $p = 0.001$). Elevation ellipses showed less overlap than in the cover-based ordination, with high-elevation plots again forming tighter clusters, and low-elevation plots remaining more dispersed. Individual sites were intermingled within elevation clusters, providing little evidence of site-specific grouping beyond the strong elevation effect.

Cover and density

The elevation \times functional group interaction was significant for cover ($p = 0.018$). At high elevations, needle-leaved cover exceeded broad-leaved cover ($p < 0.0001$), whereas the difference was not significant at low elevations ($p = 0.275$; *Fig. 4a*). This pattern was driven by the higher cover of broad-leaved species at low elevations compared to high elevations ($p = 0.013$), while needle-leaved cover did not differ significantly between elevation zones (*Fig. 4a*).

At the species level, cover models indicated that both *Fagus orientalis* and *Pinus nigra* subsp. *pallasiana* had lower cover than *Abies nordmanniana* subsp. *equi-trojani* at high elevations ($p = 0.015$ and $p = 0.048$, respectively; *Fig. 4c*). However, within-species contrasts showed no significant differences between elevation zones for *A. nordmanniana* subsp. *equi-trojani* ($p = 0.669$), *F. orientalis* ($p = 0.111$), or *P. nigra* subsp. *pallasiana* ($p = 0.138$).

For density, the elevation \times functional group interaction was also significant ($p = 0.0013$). At high elevations, needle-leaved taxa had much higher densities than broad-leaved taxa ($p < 0.0001$), whereas the difference was not significant at low elevations ($p = 0.069$; *Fig. 4b*). At the species level, both *F. orientalis* and *P. nigra* subsp. *pallasiana* had lower densities than *A. nordmanniana* subsp. *equi-trojani* at high elevations ($p = 0.011$ and $p = 0.002$, respectively; *Fig. 4d*). The elevation \times species interaction further indicated species-specific responses: within-species contrasts showed no elevation effect for *A. nordmanniana* subsp. *equi-trojani* ($p = 0.266$), a marginal tendency for *F. orientalis* to be denser at low elevations ($p = 0.051$), and significantly higher density of *P. nigra* subsp. *pallasiana* at high elevations ($p = 0.026$).

Vertical stratification

Across both elevation zones, canopies were predominantly single- or double-layered, with progressively lower proportions in the three- and ≥ 4 -layer categories (*Fig. 5*). The decline in proportional cover with increasing vertical complexity was especially steep in the 3-layer and ≥ 4 -layer categories, which accounted for only a small fraction of total canopy length. Model estimates confirmed these patterns: proportions in the 3-layer ($\beta = -1.63$, $p < 0.001$) and ≥ 4 -layer categories ($\beta = -2.63$, $p < 0.001$) were substantially lower than in single-layer plots, while two-layer canopies were only marginally less frequent than single-layer canopies ($p = 0.079$). A significant elevation \times layer interaction indicated that the relative scarcity of 3-layer canopies was more pronounced at higher

elevations (Fig. 5). Within each elevation zone, post hoc contrasts showed that single-layer cover greatly exceeded cover in 3- and ≥ 4 -layer categories (all $p < 0.001$).

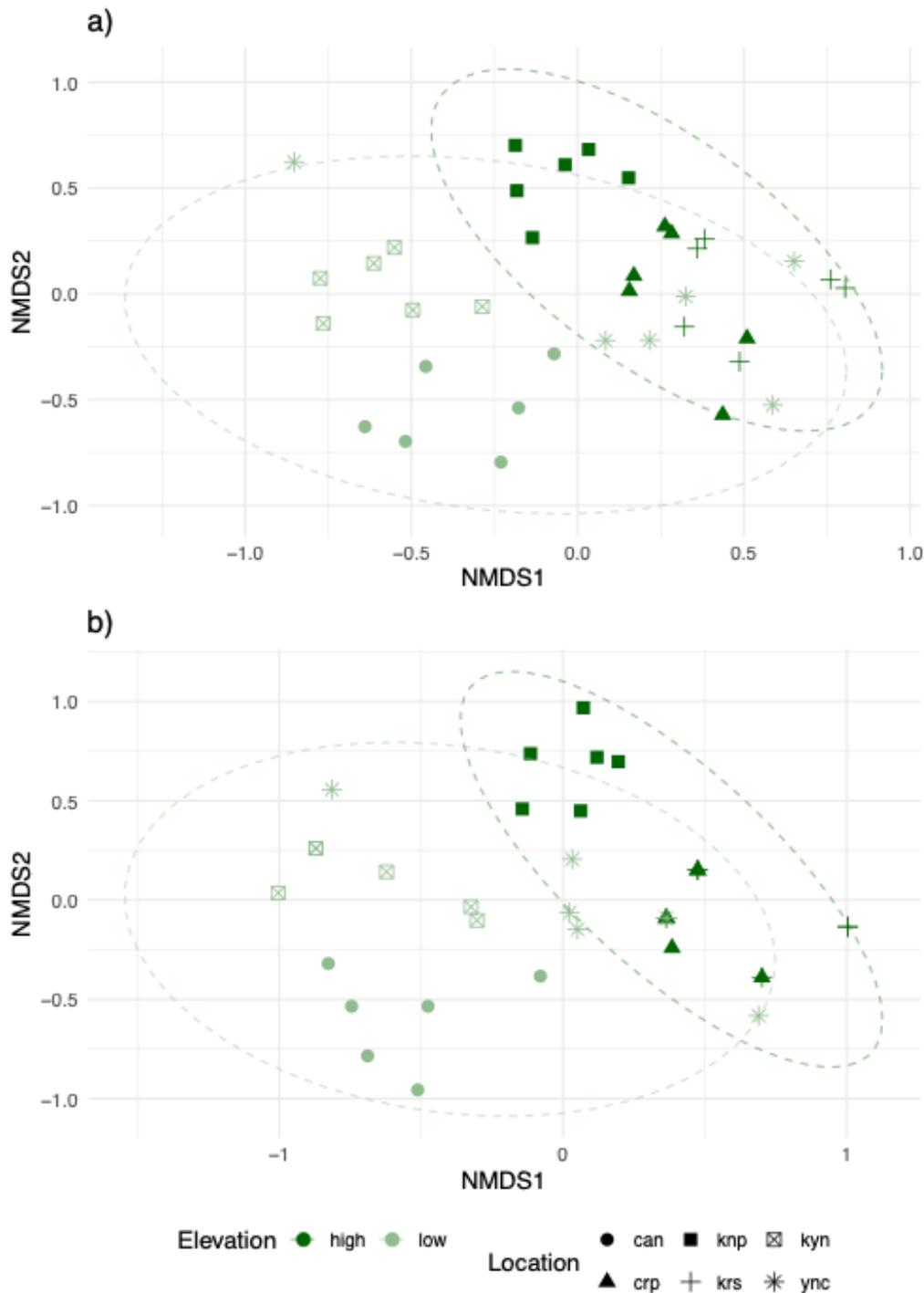


Figure 3. Non-metric multidimensional scaling (NMDS) graph based on (a) cover (stress value = 0.205) and (b) presence/absence (stress value = 0.145) of species in study sites. Data based on transects in study sites. Dark and light green points are sites at high and low elevation zones, respectively. Each study site is shown with different symbol. Eclipses correspond for [95% confidence regions/1-SD dispersion] high- and low-elevation groups in NMDS space (presence/absence, Jaccard), indicating group centroids and overlap. In both analysis, high and low elevation groups significantly differ each other ($p < 0.0001$; permANOVA)

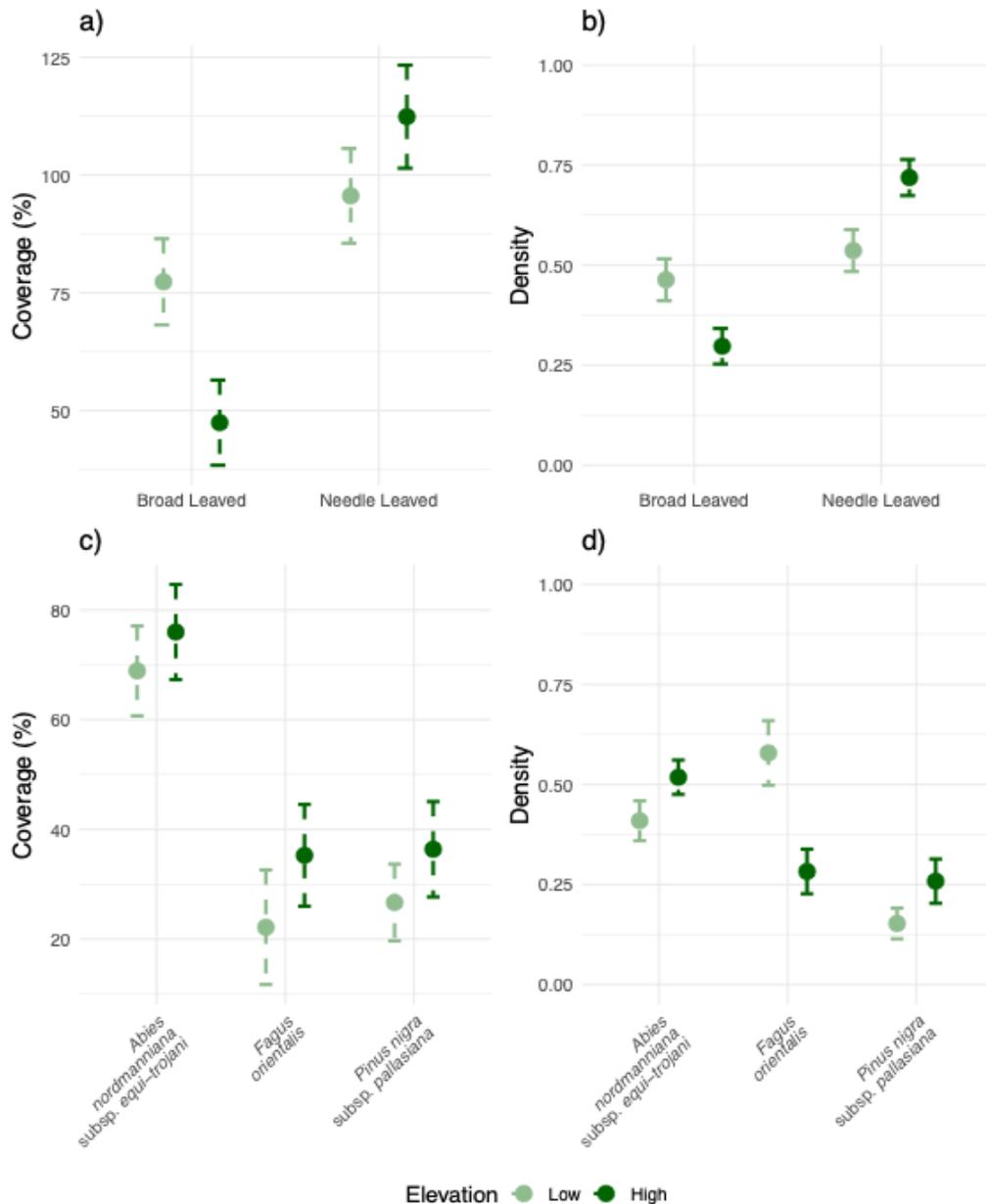


Figure 4. Elevational differences in forest composition and structure by elevation zone. Points and dashed whiskers show group means with 95% confidence intervals (light green = low elevation, dark green = high elevation). (a) Cover (%) by functional group (broad-leaved vs. needle-leaved). (b) Relative density by functional group. (c) Cover (%) by focal species (*Abies nordmanniana* subsp. *equi-trojani*, *Fagus orientalis*, *Pinus nigra* subsp. *pallasiana*). (d) Density by focal species. Cover is the percentage of the 50 m transect occupied by crown projections; density is the plot-level proportion of individuals

Discussion

Trojan fir forests in Kazdağları exhibit clear elevational differentiation in both structure and tree species composition. Elevation shapes functional-group dominance, tree species assemblages, and canopy stratification: high-elevation zones are dominated by needle-leaved taxa, especially *Abies nordmanniana* subsp. *equi-trojani*, whereas low-elevation zones have a greater contribution of broad-leaved taxa, notably *Fagus*

orientalis. Because these forests host an endemic, threatened fir embedded within a biodiversity-rich transition between Mediterranean and Euro-Siberian floristic regions, they provide a regionally unique example of how elevational zonation interacts with local floristic diversity. This pattern accords with temperate–montane zonation in the eastern Mediterranean region, where broad-leaved deciduous species gain competitive advantage at warmer, lower elevations (Barbero et al., 1992; Ruiz-Labourdette et al., 2012). Similar trends have been reported from other Anatolian forests, where elevational gradients strongly influence vegetation structure and composition (Fontaine et al., 2007; Kavgacı et al., 2021, 2023; Özkan et al., 2024).

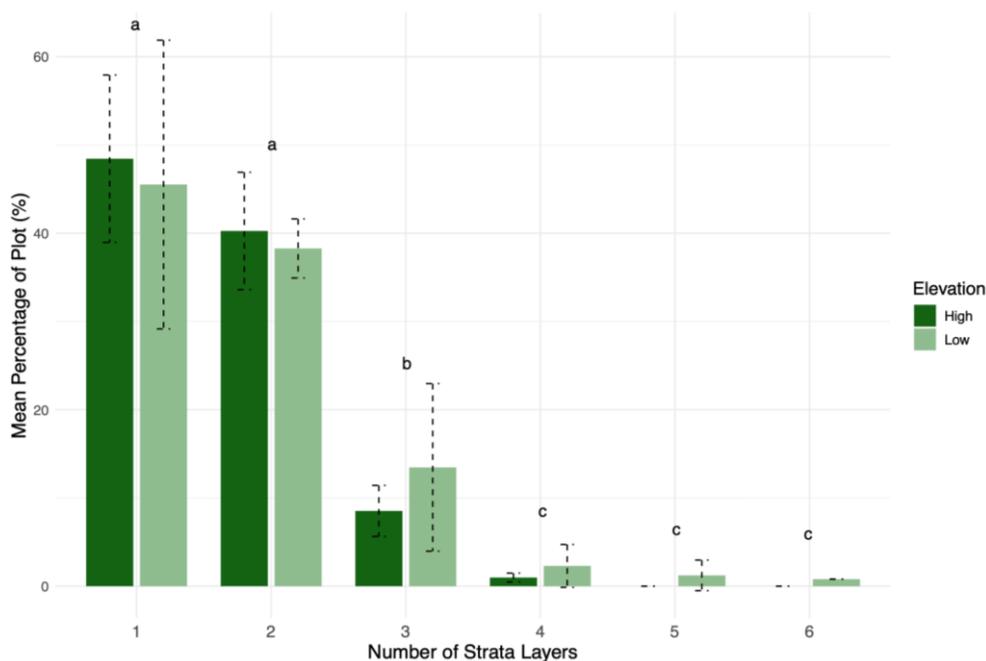


Figure 5. Vertical stratification by elevation zone. Bars show the mean percentage of transect length occupied by positions with 1–6 concurrent canopy layers (i.e., the number of crowns overlapping above each point along a 50-m transect); dashed whiskers indicate 95% confidence intervals. Different letters above bars shows significant ($P < 0.05$) difference among strata layers. There was no significant difference between high and low elevations at any stratum

The NMDS ordinations reinforced the strong role of elevation in shaping community structure. Both cover- and presence/absence–based analyses revealed a clear separation between high- and low-elevation plots. High-elevation communities formed more compact clusters, whereas low-elevation plots showed greater dispersion. This suggests that high-elevation stands share a more uniform species composition and canopy dominance, likely due to harsher climatic constraints and a narrower pool of adapted species, while low-elevation stands are more heterogeneous, reflecting broader environmental variability and competitive interactions. The tighter clustering at high elevations may also reflect the ecological dominance of Trojan fir, which limits opportunities for other species to establish (Kara and Lothka, 2020; Özçelik and Kara, 2024). In contrast, the broader spread of low elevation plots points to more variable forest assemblages, potentially shaped by microclimate, disturbance history, or soil differences (Sabatini et al., 2018; Atkins et al., 2023).

At the species level, Trojan fir maintained relatively stable cover and density across elevation zones, suggesting ecological flexibility and persistence under varying thermal and competitive regimes. While saplings perform better at high elevations (Özden-Keleş, 2020), this species is also recognized for its tolerance of warmer, lower elevations compared to other firs (EUFORGEN, 2025). In contrast, *Fagus orientalis* and *Pinus nigra* subsp. *pallasiana* displayed elevation-specific trends: *Fagus* was more frequent at lower elevations, whereas *Pinus* increased in relative density at higher elevations. At low elevations, *Fagus* exhibited relatively low cover, but high density compared to other broad-leaved taxa, implying numerous small individuals rather than large canopy dominants. This may indicate active recruitment under favorable microclimatic conditions or competitive suppression by taller canopy species, resulting in limited lateral crown expansion. Over time, these dense juvenile cohorts could contribute to increased broad-leaved dominance if canopy openings occur, potentially altering competitive dynamics with Trojan fir.

Vertical stratification plays a key role in promoting understory microclimates and enhancing ecosystem functions and services (Terschanski et al., 2024; Yan et al., 2024). In our study sites, however, multi-layered canopies (≥ 3 layers) were uncommon in both elevation zones, and particularly scarce at the high elevations. The dominance of single-layer canopies in high-elevation sites may reflect climatic constraints on growth, disturbance history, or limited understory regeneration. By contrast, the slightly greater occurrence of multi-layered canopies at low elevations likely reflect faster growth rates, a broader species pool, and more continuous recruitment. Although no recent management interventions occurred at the sites, legacy impacts of past harvesting, grazing, or selective cutting may also have reduced structural complexity.

From a conservation perspective, these findings highlight elevation as a major driver of compositional and structural variation in Trojan fir forests. Maintaining heterogeneity in species composition and canopy structure across elevation zones could enhance resilience to projected climatic shifts, particularly given modelled reductions in suitable habitat for Trojan fir under future warming scenarios (Usta Baykal, 2019). In this Mediterranean–Euxine transition zone, the coexistence of Trojan fir with multiple broad-leaved associates such as *Fagus*, *Quercus* and *Castanea* offers several potential pathways of community reassembly under warming, for example through increased broad-leaved dominance at lower and mid elevations. Our elevation-stratified baseline therefore provides a framework for evaluating how locally adapted tree species may compensate for future declines in Trojan fir or shifts in its distribution. While the relative stability of Trojan fir across elevations suggests persistence potential, reduced vertical complexity—particularly at higher elevations—may limit understory diversity, regeneration niches, and ecosystem functions such as microclimatic buffering.

Conclusion

This study provides the first integrative assessment of elevational variation in Trojan fir forest structure in Kazdağları, with implications for biodiversity conservation, forest dynamics, and climate adaptation. Future research should examine the demographic processes underlying these patterns, including regeneration, seedling survival, and species-specific competitive interactions under variable temperature and moisture conditions. Long-term monitoring and experimental approaches would help disentangle the relative roles of climate, competition, and disturbance in shaping these forests. Such

knowledge is essential for developing adaptive management strategies that conserve Trojan fir while maintaining structurally and compositionally diverse forest systems in Kazdağları.

Author contributions. Ç.T. conceived of the research idea; N.U. and Ç.T. designed sampling procedure, all authors collected data; N.U. performed statistical analyses and wrote the first draft; N.U. and Ç.T. created the final version of the manuscript; all authors critically contributed to the final version.

Acknowledgements. We thank Kahraman İpekdal for his contributions to the preliminary fieldwork and data collection. We also acknowledge the support of the Kazdağı National Park Management Office and the Bayramiç, Çan, and Kalkım Forest Management Offices. The fieldwork of the study was conducted with the permissions of the General Directorate of Nature Conservation and National Parks of Türkiye (no: 10884895) and Çanakkale Branch Directorate, Ministry of Agriculture and Forestry of Türkiye (no: 10905944). This study forms part of the first author's Ph.D. dissertation, conducted at the Institute of Science, Hacettepe University, Türkiye.

Funding. This work was conducted/funded by the Functional Ecology Laboratory, Hacettepe University. N. U. is supported by the Higher Education Council of Türkiye (YÖK) under the 100/2000 Priority Areas Program.

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