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The Effects Of The First Thinning On Stand Structure In Oak and Hornbeam Mixed Stands

Meşe ve Gürgen Karışık Meşcerelerinde İlk Aralamanın Meşcere Kuruluşuna Etkileri

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Abstract

This study, conducted in Istanbul's Belgrad Forest, examines the effects of moderate thinning on stand dynamics. In 2017, a moderate high thinning was implemented in a mixed stand of sessile oak (*Quercus petraea*) and common hornbeam (*Carpinus betulus*). Changes in diameter and basal area increments, stand stratification, and vitality (health condition) were analyzed over a two-year period following the treatment. The study employed a design with control and treatment groups. During thinning, 0% (control) and 15–20% (moderate) of the basal area were removed from the stand. The two-year results revealed that thinning significantly increased diameter and basal area increments in both species. Sessile oak, positioned in the dominant top story, exhibited greater diameter and basal area increments, compared to common hornbeam. Compared to the control plots, the treated plots displayed a 57% higher diameter increment in sessile oak and a 14% higher increment in common hornbeam. Similarly, the basal area increment was 12% higher in sessile oak and 15% higher in common hornbeam. Analyses of stratification and vitality changes indicated that moderate thinning treatments enhanced the potential for high-quality stem development in sessile oak individuals. Comprehensive evaluation of thinning effects requires long-term monitoring; nonetheless, in sessile oak stands with structural similarity and mixture with semi-shade tolerant species, the application of moderate to high thinning intensity is advisable

Keywords: Thinning, Sessile oak, İncreament, Stratification, Vitality

Özet

İstanbul Belgrad Ormanında gerçekleştirilen bu çalışmada aralamanın meşcere dinamiği üzerindeki etkileri incelenmiştir. Sapsız meşe ve adi gürgen karışık meşceresinde 2017 yılında mutedil yüksek aralama müdahalesi gerçekleştirilmiş ve bu müdahalenin çap ve göğüs yüzeyi artımı, meşcere tabakalanması ve vitalite (sağlık durumu) değişimi üzerine iki yıl içerisinde meydana gelen değişimler incelenmiştir. Çalışma deseni tesadüfi deseninde kontrol ve uygulama grubu ile gerçekleştirilmiştir. Aralama ile göğüs yüzeyinin %0 (kontrol) ve % 15-20'si (mutedil) meşcereden çıkartılmıştır. Aralama müdahalesinin iki yıllık sonuçları incelendiğinde; aralama müdahalesinin her iki tür içinde çap ve göğüs yüzeyi artımını artırdığı belirlenmiştir. Galip katta bulunan sapsız meşe türlerinin adi gürgen türlerine göre daha fazla çap ve göğüs yüzeyi artımı yaptığı tespit edilmiştir. Uygulama sahası kontrole göre sapsız meşede %57, adi gürgende %14 daha fazla çap artımı yapmıştır. Aynı şekilde göğüs yüzeyi artımı sapsız meşede %12, adi gürgende %15 daha fazla olduğu belirlenmiştir. Tabakalanma ve vitalite değişimleri incelendiğinde sapsız meşe bireyleri için mutedil müdahale gören sahanın kaliteli gövde yetiştirme olanağını arttırdığı görülmektedir. Aralamanın etkisi konusunda daha uzun yıllara ait verilerin incelenmesi gerekmekte olup, benzer yapıdaki yarı gölge ağacıyla karışım oluşturan sapsız meşe meşcereleri için mutedil yüksek aralama önerilebilir.

Anahtar Kelimeler: Aralama, *Quercus petraea*, Artım, Tabakalanma, Vitalite

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1. Introduction

The increasing demand for wood raw materials in Türkiye and the sustainable management of our existing forests are of great importance. Meeting the growing need for raw wood materials in our country can be achieved through the effective application of technical management treatments (Çiçek et al., 2007; 2013).

One of the most important management practices in stand cultivation is thinning. It is defined as continuous and planned treatment that involves periodic removals of trees, preventing the closure of the canopy, and addressing the competition between trees from the time of the dense phase until the stand enters the regeneration phase. These treatments include strong natural branch pruning and stem separation (Odabaşı et al., 2004a; 2004b; Çiçek et al., 2013).

It is well known that thinning treatments have effects on stand growth, soil properties, natural regeneration conditions, stand resilience, and forest aesthetics. Through thinning treatments, The removal of poor-quality stems and the protection of high-quality ones significantly enhance stand dynamics. The reduction in the number of individual trees and the temporary reduction of canopy closure increase the amount of rainfall and light reaching the forest floor. This situation contributes to making the soil more functional, thereby improving its production capacity (Odabaşı et al., 2004a; 2004b; Demirci, 2008). However, alongside all these positive effects of thinning, there are also some potential risks. Heavy thinning can lead to both biotic and abiotic damage. Additionally, while heavy thinning negatively affects stem quality, it can also cause the formation of water sprouts on the stems of deciduous species. In particular, water sprout formation is more prevalent in oak species compared to other deciduous species (Meadows, 1995; Dimov et al., 2006)

The timing of thinning treatments and the determination of thinning intensity, taking into account the species that make up the mixture, are crucial. In mixed stands, it is also important to consider changes in the number of tree species, in addition to the breast height diameters and the specific strata of the stand where these changes occur (Göktürk, 2013).

In Türkiye, broadleaf forests cover 32% of the forested areas, coniferous (needleleaf) forests make up 48%, and mixed coniferous and broadleaf forests account for 20%. Oak species occupy the largest area in terms of distribution (6.7 million ha), followed by red pine in second place in terms of area size. However, there is insufficient information regarding the area of distribution for each oak species (OGM, 2020).

In Türkiye, oaks, represented by 17 species, are distributed across almost all regions. Particularly, sessile oak (*Quercus petraea* (Matt.) Liebl.) has a wide distribution area in Turkey. This species is one of the most important and widespread that forms coppice and forest stands, ranking second only to coniferous forests in its distribution (Güner et al., 2012).

In the Belgrad Forest, which is the subject of this study, sessile oak forms a mixture with hornbeam (*Carpinus betulus* L.), eastern beech, and other deciduous species. Hornbeam is a semi-shade tree that mixes with sessile oak and can survive under canopy cover (Odabaşı et al., 2004a; 2004b; Sikkema et al., 2016).

Thus, hornbeam plays an important role as a secondary species in supporting the oak species; when mixed with oaks, it can pose a threat to the presence of oak trees (Kwiatkowska et al., 1997).

Similarly, although oak species in recent years, are planned individually in Forest Management Plans, the current oak yield table is used in ETA (Estimated Total Allowable) calculations. This leads to the application of the same management treatments to different oak species, which may result in an increase in the number of low-quality stems. When examining the existing examples of thinning treatments, it becomes clear that the species diversity has a significant impact on the thinning process.

This study aims to determine how moderate thinning treatments applied in mixed stands of sessile oak and hornbeam affect stand development and quality, and to determine what changes occur in stand parameters when thinning for sessile oak is neglected.

2. Material and Method

2.1. Material

The study area is located within the boundaries of the Bentler Management Unit, which is part of the Bahçeköy Forest Management Directorate under the Istanbul Forest Regional Directorate (41°10'38.34"N, 28°57'20.33"E), specifically in compartment 113 (Figure1). The study area is situated at an elevation of 100 meters and faces east. According to the Forest Management Plan, the trial site is classified as MGnb3 (a closed stand of oak and hornbeam in the pole stage) with a site quality of II (Anonymous, 2022). According to data from the Istanbul-Sarıyer Meteorological Station (located 8.5 km southwest of the study site), the region has an annual average rainfall of 1093.3 mm, an annual average temperature of 12.8°C, and an annual average relative humidity of 82.3% (Anonymous, 2016).

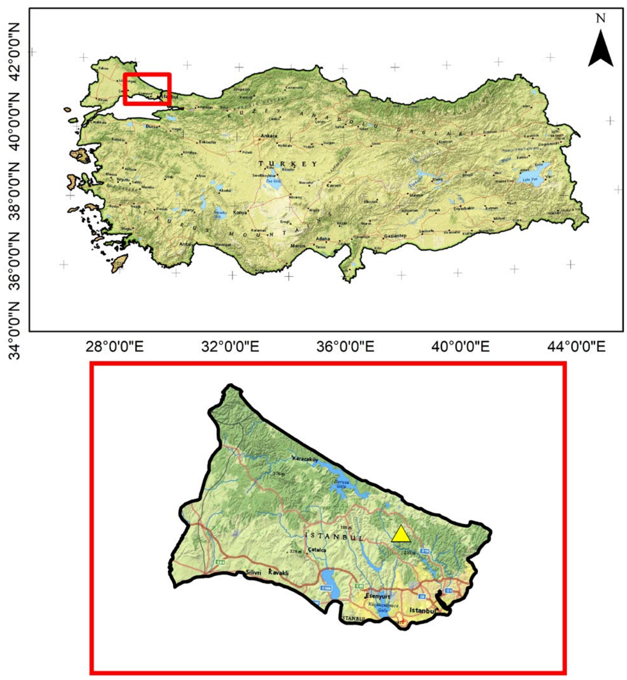

Figure 1. Location of study areas.

To conduct the study, six trial plots of 20 x 20 meters each were selected in compartment 113. When selecting the trial plots, care was taken to ensure that the six plots had the same geological and topographical characteristics. Three of the trial plots (plots 4, 5, and 6) were designated as control plots (without thinning treatment), while the remaining three plots (plots 1, 2, and 3) were subjected to thinning treatment (moderate high thinning). The trial plots are in the pole stage. The number of individuals found in the trial plots is provided in Table 1.

Table 1. The number of individuals (per hectare) found in the study areas in 2017.

Study area	Number of individuals		Total
	Sessile oak (*Quercus petraea*)	Common hornbeam (*Carpinus betulus)*	
1	2825	975	3800
2	4150	2250	6400
3	4450	650	5100
4	4175	2625	6800
5	5000	2325	7325
6	4250	3050	7300

The main material of the study consists of measurements obtained during fieldwork conducted in 2017 and 2019.

2.2. Method

In the trial plots (1, 2, and 3), moderate high thinning was applied in 2017. No thinning treatment was applied in the control plot. The determination of thinning intensity was based on the breast height diameter. The treatments were applied at control (0%) and moderate (15-20%) intensities. Measurements were taken before the thinning treatment and again in 2019 (two years after the thinning treatment) in each trial plot. The measurements included tree diameter at breast height (cm) and health status (vitality) of the trees.

In the fieldwork, the diameter at breast height was measured using a mechanical caliper. Measurements were taken from two different directions at breast height (1.30 m), and the average of the measured values was used. To determine the health status of the trees, a scoring system was applied: trees considered fully healthy were given a score of 1; those with the onset of water sprouts were given a score of 2; those with intense water sprouts and 50% of the crown dead were given a score of 3; and those with intense water sprouts and more than 50% of the crown dead were given a score of 4. Completely dead trees were excluded from measurement and their numbers were recorded.

To determine the canopy stratification of the stand using the data from 2017 and 2019, the average height of the four thickest trees in each sample plot was used to calculate the stand's top height. The top height of the stand was then divided into three equal parts to separate understory, intermediate, and top story. In each trial plot, the measured diameter values were classified as belonging to the understory, intermediate, and top story. The diameter increments over two years were calculated by subtracting the 2017 diameter values from the 2019 diameter values for each tree in the plots. The same process was applied to the measured tree heights to calculate the average height values for each stratum. The breast height diameter values for each tree in the trial plots were calculated and multiplied by a conversion factor to obtain values per hectare.

2.2.1 Data evaluation

To determine the effect of thinning treatment, the data obtained for diameter at breast height were evaluated according to the experimental design. The data were analyzed using a T-test to assess the differences between the two independent groups. Statistical analysis was not applied to the stratification and vitality data, but such analysis is intended to be applied to data from longer periods in the future. SPSS software was used for the calculations in the statistical analyses. Excel software was used to create the graphs. The percentage difference between the variables was calculated by dividing the mean value of the treatment plot by that of the control plot and expressing the result as a percentage.

3. Finding and Discussion

3.1. Average Diameter Values and Diameter Increment

The average diameter values of sessile oak in the control plot were found to be 8.49 cm in 2017 and 8.91 cm in 2019. The average diameter values of hornbeam in the control plot were found to be 3.06 cm in 2017 and 3.42 cm in 2019. Over the two-year period, sessile oak individuals in the control plot showed an average diameter increment of 0.42 cm, while hornbeam individuals showed an average diameter increment of 0.36 cm. In the treatment plot, the average diameter values of sessile oak were 7.8 cm in 2017 and 8.46 cm in 2019. The average diameter values of hornbeam in the treatment plot were found to be 2.82 cm in 2017 and 3.23 cm in 2019. Over the two-year period, sessile oak individuals in the treatment plot showed an average diameter increment of 0.66 cm, while hornbeam individuals showed an average diameter increment of 0.41 cm (Figure 2). It was determined that the diameter increment of sessile oak was higher in the plot with moderate thinning treatment compared to the control plot. In other words, the diameter increment in the moderate thinning treatment plot was 57% higher than in the control plot. It was also determined that the increment in the diameter of hornbeam was higher in the plot receiving moderate thinning treatment compared to the control plot. The diameter increment of hornbeam was 14% higher in the moderate thinning treatment plot than in the control plot. It was found that hornbeam individuals, which are generally located in the intermediate and understory, had a smaller diameter increment compared to sessile oak.

The higher average diameter value of the control plot in 2017, compared to the treatment plot, can be attributed to the removal of dominant individuals with thick diameters from the top story through moderate high thinning.

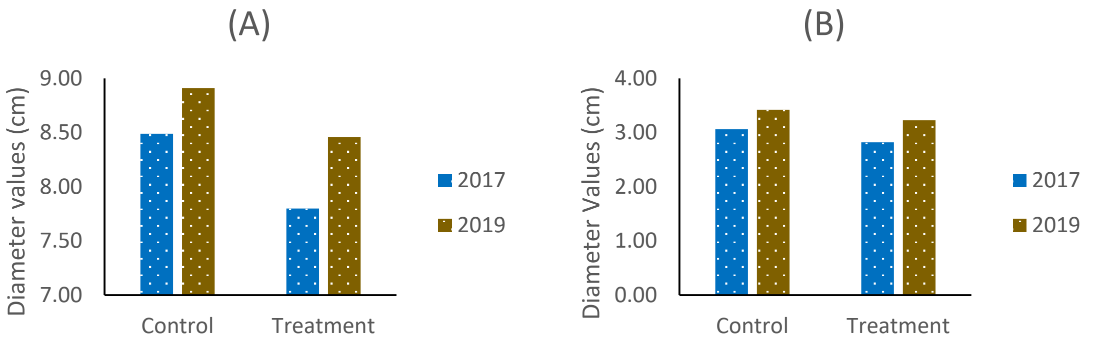

Figure 2. The data related to average diameter values. (A) Sessile oak (B) Common hornbeam.

The results of the analysis of the T-test applied to the findings of diameter increment revealed that the effect of thinning treatment was statistically significant ($p<0.05$) (Figure 3).

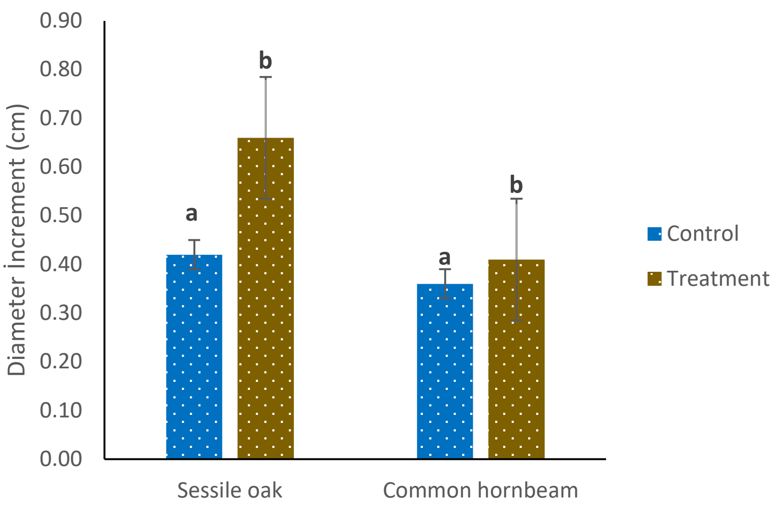

Figure 3. The result of the analysis related to diameter increment.

The greater diameter increment in the treatment plot with moderate thinning compared to the control plot can be explained by thinning, which reduces the number of trees in the stand, allowing the remaining trees to access more light, water, and nutrients. The increased diameter growth associated with thinning is closely linked to higher net photosynthesis rates, as well as increased availability of beneficial water and nitrogen (Wang et al., 1995). Similar findings have been obtained in other studies (Ceylan, 1988; Umut et al., 2000; Makinen and Isomaki, 2004a; 2004b; Meadows and Goelz, 2001; Tüfekçioğlu et al., 2005; Özbayram and Çiçek, 2018).

The greater diameter increment of sessile oaks compared to hornbeams can be explained by the fact that sessile oaks are located in the top story, with thicker diameters, taller stature, better-developed crowns, and the ability to benefit from more water, nutrients, and solar energy (Assmann, 1970; Nyland, 1996).

3.2. Average Basal Area Values and Basal Area Increment

The average basal area values of sessile oak in the control plot were 27.5488 m²/ha in 2017 and 30.6567 m²/ha in 2019. The average basal area values of hornbeam in the control plot were found to be 2.1638 m²/ha in 2017 and 2.7027 m²/ha in 2019. Over the two-year period in the control plot, sessile oak individuals showed an average basal area increment of 3.1079 m²/ha, while hornbeam individuals showed an average basal area increment of 0.5389 m²/ha. The average basal area values of sessile oak in the treatment plot were determined to be 20.6236 m²/ha in 2017 and 24.0979 m²/ha in 2019. The average basal area values of hornbeam in the treatment plot were found to be 0.8613 m²/ha in 2017 and 1.4799 m²/ha in 2019. In the treatment plot over the two-year period, sessile oak individuals showed an average basal area increment of 3.4743 m²/ha; hornbeam individuals, 0.6186 m²/ha (Figure 4).

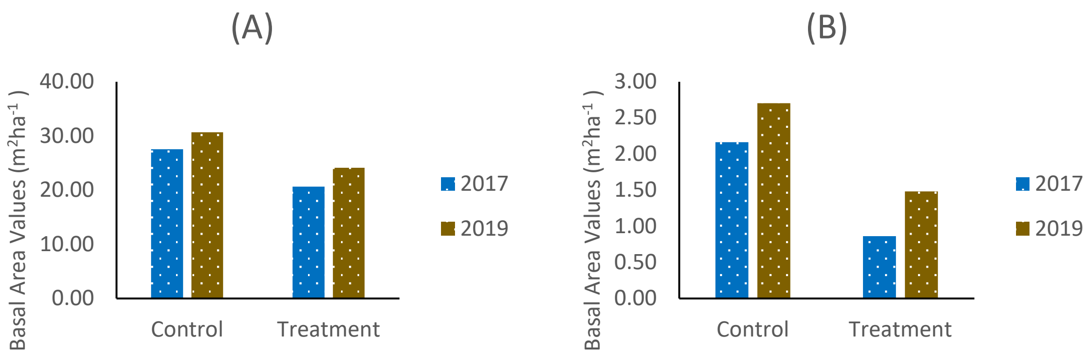

Figure 4. Average basal area values (A) Sessile oak (B) Common hornbeam.

The basal area of the stand remaining after thinning (2017) differs from the basal area measured in 2019. When examining the basal area values for both species, it was determined that the thinning treatment had a statistically significant effect on the basal area increment of the stand at a confidence level of $p<0.05$ (Figure 5).

When examining the 2019 basal area values for sessile oak, it is observed that the difference (compared to 2017) has decreased. It was found that the basal area increment of sessile oak was higher in the moderately treated area compared to the control area. When the basal area increment of hornbeam was examined, it was observed that the increment was higher in the treatment area.

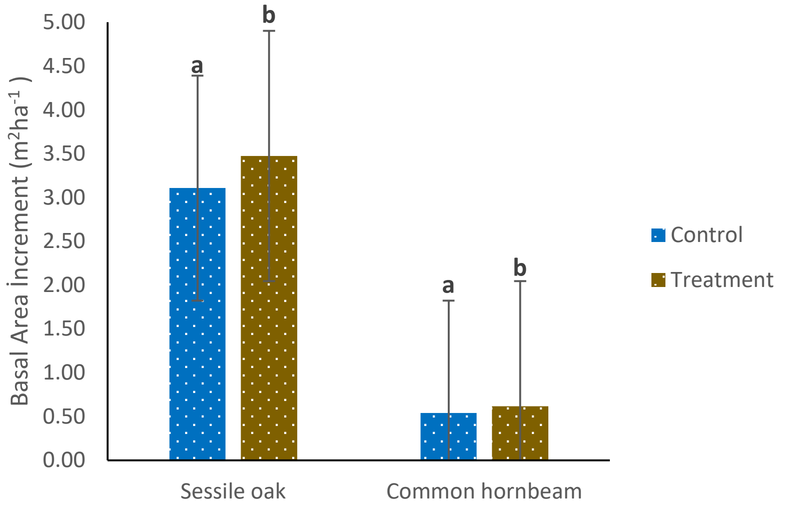

Figure 5. Analysis result for basal area increment.

Although thinned stand have a lower basal area, they have shown the same basal area increment as the control stand in one year. The remaining trees in the thinned stands increased their diameter and matched the basal area increment of the trees in the control stand. These findings are consistent with results found in similar studies (Mayor and Roda, 1993; Meadows and Goelz, 1999; Çiçek et al., 2013).

The results obtained from this study confirm the positive effects of moderate thinning on stand dynamics, particularly in mixed stands of sessile oak (*Quercus petraea*) and common hornbeam (*Carpinus betulus*). Thinning significantly increased diameter and basal area increments in both species. This aligns with earlier studies indicating that thinning reduces competition for resources such as light, water, and nutrients, thereby promoting tree growth (Assmann, 1970; Wang et al., 1995; Nyland, 1996).

Sessile oak, a light-demanding species in the dominant canopy, showed a stronger growth response than the semi-shade-tolerant hornbeam. This pattern is consistent with findings by Mäkinen and Isomäki (2004), who observed that dominant canopy species responded more positively to thinning than shade-tolerant ones. Similarly, Meadows and Goelz (2001) reported that moderate thinning in hardwood stands improved diameter growth and stem form due to enhanced crown development and resource availability.

3.3. Stratification

When examining the changes in stratification in sessile oak, it is observed that there are no trees in the understory in either treatment for both 2017 and 2019. In the control and moderate thinning treatment plots, when the two-year changes in the middle and top story are evaluated, an increase in the number of sessile oaks at the intermediate level, is seen, while a decrease is observed in the number of sessile oaks in the top story. This finding indicates that the stratification of trees among different stand layers may shift over time due to height growth, especially in mixed stands where species have different growth strategies. While a two-year period is relatively short in the context of forest development, even within this time frame, moderate thinning can lead to changes in light availability, which in turn can stimulate height growth in suppressed or intermediate trees. It appears that the sessile oak individuals from the top story have descended to the intermediate layer. In the treatment plot, in 2017, a total of 11,425 trees per hectare were present in the top story, with 11,050 individuals (96.71%). After two years, this number decreased to 10,825 individuals (94.74%). In the control plot in 2017 there were a total of 13,425 trees per hectare, with 12,225 individuals, which was 91%, and this number decreased to 11,350 individuals, which decreased to 84.5% over the two years. Although the control plot had a higher total number of trees and a higher number of trees in the top story, the proportion of trees in the top story was lower than the treatment plot. Due to the dense canopy in the control plot, 875 individuals (6.5%) moved from the top story to the intermediate story over the two years. In contrast, in the treatment plot, only 225 individuals (1.9%) moved to the intermediate level. The lower canopy density created by thinning resulted in a smaller transition of trees from the dominant to the intermediate layer (Figure 6).

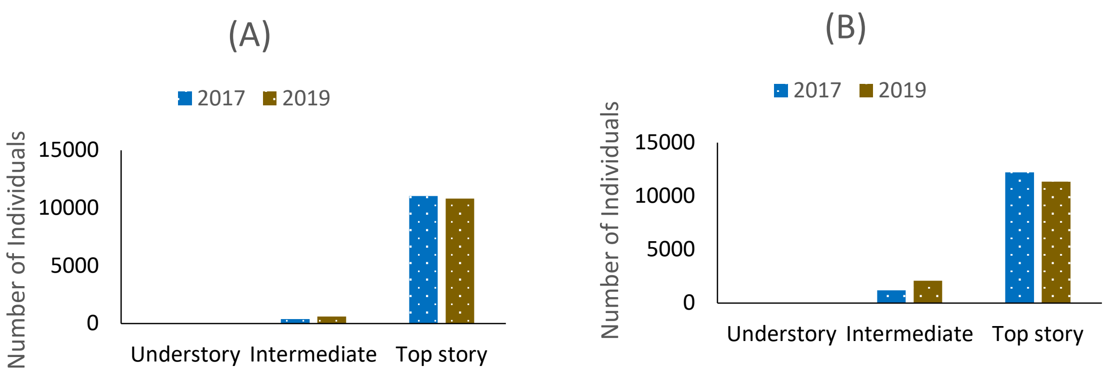

Figure 6. The stratification changes occurring over a two-year period in the sessile oak (A) Treatment, (B) Control.

When examining the stratification changes in hornbeam (C. betulus), it is observed that the number of individuals in the understory decreased in both the control and moderate thinning treatment plots, with a higher rate of decrease in the control area. In the treatment area, in 2017, there were 3875 trees/ha, with 1525 trees (39%) in the understory and 2350 trees (61%) in the overstory. After two years, the number of hornbeam trees in the understory decreased to 450 trees (11.6%), while the number in the intermediate story increased to 3425 trees (88.4%). In the control plot in 2017, there were a total of 8000 trees/ha, with 1750 trees (21.8%) in the understory and 6250 trees (78.2%) in the intermediate layer. After two years, the number of hornbeam trees in the understory decreased to 600 trees (7.5%), while the number in the intermediate layer increased to 6950 trees (87%). In contrast to what was observed in the treatment plot, 450 trees (6.5%) moved to the top story (Figure 7).

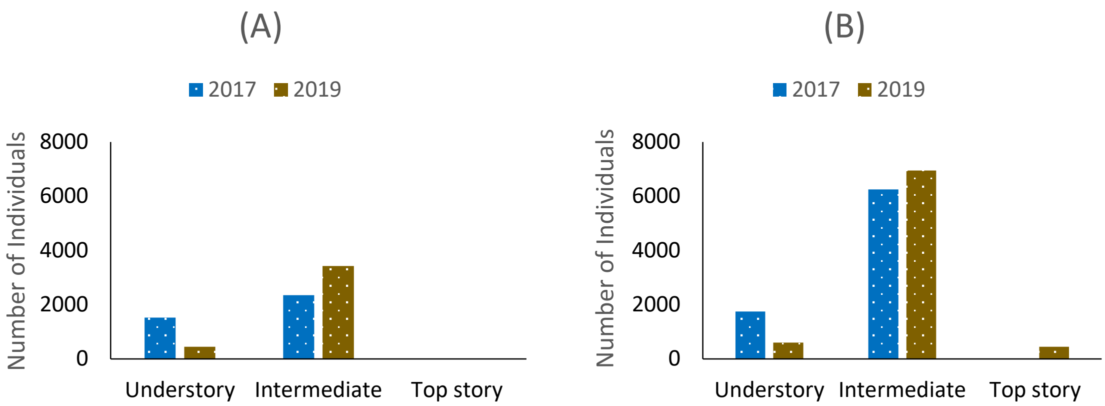

Figure 7. The stratification changes occurring over a two-year period in the common hornbeam (A) Treatment (B) Control.

The stratification dynamics observed in this study suggest that thinning reduced the downward movement of dominant trees into lower canopy layers. This outcome supports the conclusions of Smith et al. (1997), who noted that vertical stand structure is influenced by changes in light availability and crown competition.

3.4. Vitality (Health status)

In the treatment area, for the top story of sessile oaks, 11,050 trees/ha were evaluated for vitality in 2017. It was determined that 79.4% belonged to the 1st vitality group, 13.3% to the 2nd vitality group, 6.3% to the 3rd vitality group, and 1% to the 4th vitality group. In 2019, 10,825 trees/ha were evaluated. In the top story, it was determined that 78% of the trees belonged to the first vitality group, 13% to the second vitality group, 7% to the third vitality group, and 2% to the fourth vitality group in 2019. In 2017, 92.7% of the individuals in the top story were in a healthy condition (1st and 2nd vitality groups), while this ratio decreased to 91% after two years. In the intermediate stage, the vitality status of 375 sessile oak trees per hectare was examined. It was found that 50 trees (13.3%) belonged to the first vitality group, 75 trees (20%) to the second vitality group, 25 trees (6.7%) to the third vitality group, and 225 trees (60%) to the fourth vitality group. Over the two-year period, of the 600 trees per hectare, 50 trees (8.3%) were in the 1st vitality group, 125 trees (20.8%) in the 2nd vitality group, 100 trees (16.7%) in the 3rd vitality group, and 325 trees (54.2%) in the 4th vitality group. Within this short period of two years, the percentage of healthy trees (1st and 2nd vitality groups) in the intermediate category decreased from 33.3% to 29.1% (Figure 8).

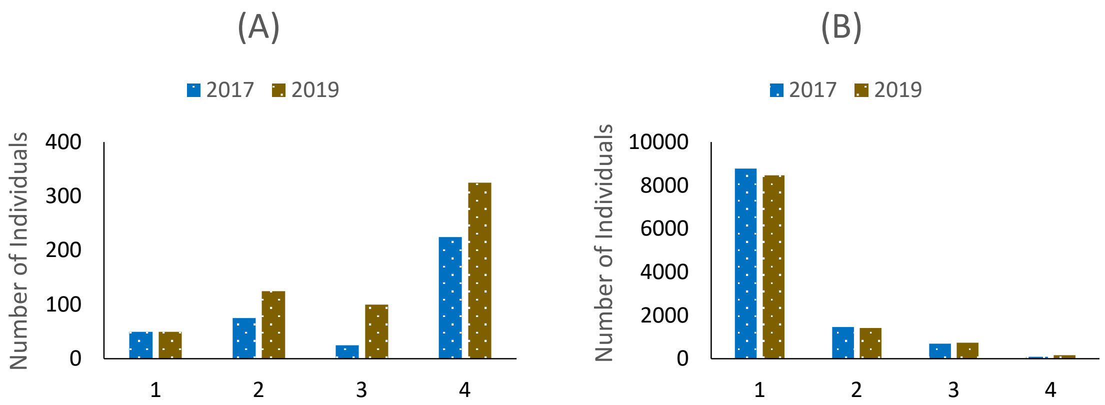

Figure 8. Vitality changes over the two-year period in the treatment area. (A) Intermediate, (B) Top story.

When the vitality of sessile oaks in the top story within the densely and irregularly closed control area was assessed in 2017, it was found that out of 12,225 trees/ha, 7,825 trees (64%) were in the first vitality group. Furthermore, 2,100 trees (17.2%), were in the second vitality group, 2,025 trees (16.6%), in the third vitality group, and 275 trees (2.2%) in the fourth vitality group. In 2019, 11,450 trees/ha were assessed, with 875 trees excluded from evaluation as they moved from the dominant to the intermediate category. Among the trees in the top story, 5,950 trees (52%) were found to be in the first vitality group, 2,225 trees (19.4%) in the second vitality group, 2,575 trees (22.5%) in the third vitality group, and 700 trees (6.1%) in the fourth vitality group. In 2017, while 81.6% of the individuals in the top story were in healthy condition (first and second vitality groups), this ratio decreased to 71.4% over a two-year period. The high density and the prevalence of oversized individuals in the area have contributed to this decline in vitality within the top story. When the vitality status of 1,200 sessile oak trees per hectare was assessed in 2017, it was found that 75 trees (6.25%) were in the first vitality group, 150 trees (12.5%) in the second vitality group, 475 trees (39.58%) in the third vitality group, and 500 trees (41.66%) in the fourth vitality group.

Over the two-year period, it was found that out of 2,125 trees/ha, 25 trees (1.2%) were in the first vitality group, 325 trees (15.7%) in the second vitality group, 750 trees (36.1%) in the third vitality group, and 975 trees (47%) in the fourth vitality group. Over the two-year period, the proportion of healthy trees in the suppressed strata decreased from 18.75% to 16.9%. In 2019, while 83% of the trees in the suppressed strata of the densely closed control area were unhealthy, this rate remained at 70.7% in the treatment area. As a result of thinnings that improved light conditions and reduced root competition, the presence of sessile oaks in the suppressed strata serving as fillers increased by 12.3% in the treatment area (Figure 9).

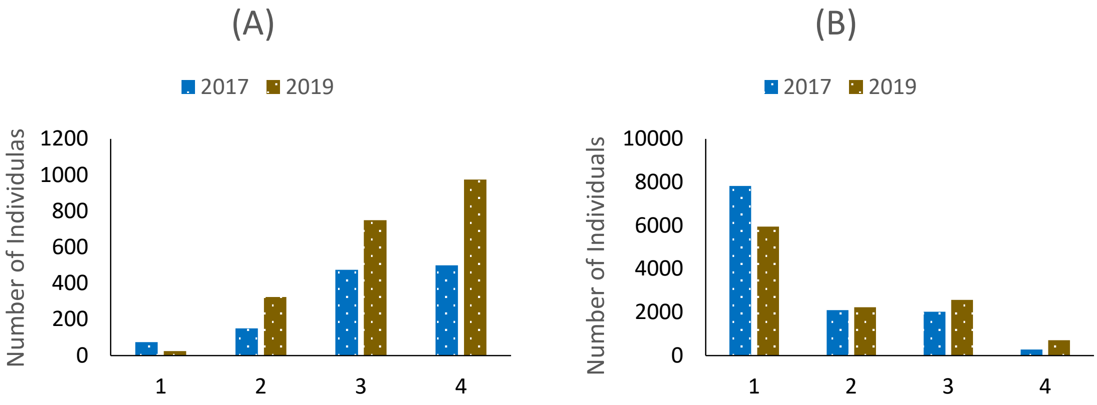

Figure 9. The change in vitality observed in the control area over a two-year period. (A) Intermediate , (B) Top story.

Vitality assessments showed that thinning contributed to maintaining better tree health, particularly for dominant sessile oaks. The proportion of unhealthy individuals was lower in thinned plots than in controls. This observation supports findings by Dimov et al. (2006) and Meadows (1995), who reported that reduced competition mitigates stress and decreases epicormic sprouting in broadleaf species.

The risk of hornbeam dominance—referred to as “hornbeamization”—was also evident in untreated plots. As Kwiatkowska et al. (1997) noted, hornbeam’s faster growth rate and shade tolerance allow it to suppress oak regeneration over time if not properly managed.

In summary, this study emphasizes that appropriately timed and moderately intense thinning is crucial for sustaining species composition, enhancing growth performance, and maintaining ecological balance in mixed oak–hornbeam stands.

4. Conclusion

Based on the two-year results obtained from this study, it was determined that the diameter increment and basal area increment in the treatment area were greater than the control area. It was found that moderate thinning treatments positively influenced stratification and vitality changes.

Based on the data obtained from stratification, it is observed that common hornbeam grows faster than sessile oak under the conditions of Belgrade Forest. While the presence of hornbeam, a semi-shade tree, in the lower and intermediate layers is an advantage for cultivating high-quality oak with good natural pruning, its growth to the upper canopy poses a threat to the existence of oak. The ascent of hornbeam to the top story should be prevented through thinning (Kwiatkowska et al., 1997; Savill, 2013). Otherwise, the hornbeamization process observed throughout the Belgrade Forest poses a risk of occurring in the study area as well.

Overall, when evaluating the vitality status, reducing light and root competition to a certain extent is beneficial for maintaining the typical light-demanding presence of sessile oak in both the dominant and suppressed strata. Therefore, thinning should be applied timely and appropriately during the pole stage, when competition is very active. Delaying this process may lead to a situation similar to that observed in the control area.

In stands where thinning operations are neglected, the amount of wood obtained is comparable to that of regularly maintained stands. In sessile oak stands, which have a tendency to become oversized, the volume of timber produced in maintained areas generally comprises first-class trunks, proportional to the stand's productivity. However, in areas that lack proper thinnig treatment, there is a dominance of oversized trunks.

Delaying thinnings or applying them at low doses makes it quite challenging to maintain the presence of oaks against hornbeam species. Based on the two-year results obtained, a moderate high thinning (15-20%) is recommended for mixed hornbeam stands combined with sessile oak. It is necessary to examine the effects of thinning on diameter increment, basal area increment, stratification, and vitality changes based on longer-term results. For a more effective evaluation, the study site should continue to be monitored, and long-term outcomes should be considered.

These findings demonstrate that moderate thinning is an effective silvicultural practice to regulate species composition, improve stand health, and promote sustainable productivity in mixed broadleaf forests. However, to validate these results and understand their long-term implications, continued monitoring and extended time-series analyses are necessary.

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