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The Relationships among Tree Mixture, Management Type, Stand Density and Diameter Increment in Kazdağı Fir (*Abies nordmanniana* subsp. *equi-trojani* [Asch. & Sint. ex Boiss] Coode & Cullen) Forests

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Highlights:
- Species richness may influence stand productivity
- Stand dentiy can affect diameter increment
- Productivity may vary based on stand structure

Keywords:
- *Fagus*
- Kazdağı fir
- Mixed stand
- Productivity
- Tree growth
- Sustainability

ABSTRACT:

Tree mixture may increase stand productivity while forest tree density mostly negatively influence the tree growth. However, several research have indicated that the knowledge on the corelation between tree mixture and stand productivity is still limited. In this study, the relationships among tree mixture, stand type (i.e., even-aged versus uneven-aged), density and diameter increment of Kazdağı fir (*Abies nordmanniana* subsp. *equi-trojani* [Asch. & Sint. ex Boiss] Coode & Cullen) were examined. The research was conducted within the Ayancık Forest Management Directorate, Sinop Regional Directorate of Forestry. Four different stands were selected; a) uneven-aged fir stand, b) even-aged fir stand, c) uneven-aged mixed fir-beech stand, and d) even-aged mixed fir-beech stand. Five-year diameter increment in these four different stand types was determined and compared. Random effects regression analysis was utilized to examine the influence of the mixture and tree density on the diameter increment. Statistical relationships were found among tree mixture, stand density and the diameter increment ($p<0.05$). Moreover, diameter increment varied among the stand types

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INTRODUCTION

Carbon storage, tree nutrition, biodiversity, ecosystem functioning, and forest productivity are all often influenced by tree species mixture and stand structure (Richards et al., 2010; Pádua and Chiaravalotti, 2012; Zhang et al., 2012; Huang et al., 2018; Mensah et al., 2020). Furthermore, by improving and maintaining mixed forest production following the complementary resource use, tree mixture can lessen the negative consequences of global warming (del Río et al., 2017). Several research have indicated that altering species mixture, stand structure, and stand density can mitigate the effects of climate change (Bottero et al., 2021; Kara and Özden Keleş, 2023). Though it is generally accepted that tree mixture, stand structure, and productivity are strongly related, the fundamental mechanisms of the relationship have not been well defined (Ammer, 2019).

The relationship between stand productivity and tree mixture in various forest ecosystems has received more attention recently (López-Marcos et al., 2021), as previous research has found inconsistent relationships between these variables (Forrester and Bauhus, 2016). Tree mixture may often impact forest production favorably (Vitali et al., 2018). On the other hand, other research indicates that the tree mixture may potentially have an adverse influence on stand productivity (Wang et al., 2016). Moreover, some studies have discovered non-significant relationships between tree growth and tree mixture (Long and Shaw, 2009). Our understanding of the links between stand productivity and tree mixture appears to be limited based on the results of earlier studies (Ratcliffe et al., 2017). Thus, further research is required to accurately measure and comprehend these relationships for various forest ecosystems.

Kazdağı fir (*Abies nordmanniana* subsp. *equi-trojani* [Asch. & Sint. ex Boiss] Coode & Cullen) is is widely distributed in the northern part of Türkiye. Being one of the main tree species of the country, it has economic and ecological importance in Turkish forestry because it provides high quality wood and represents rich biological diversity (Yıldız and Özden Keleş, 2023). In Türkiye, Kazdağı fir constitute both even-aged and uneven-aged forests, while the species has both pure and mixed forests in these two management types. Oriental beech (*Fagus orientalis* Lipsky) is one of the tree species that may form mixed forests with Kazdağı fir (Kara, 2022). It is also a tree species that is economically and ecologically valuable in Türkiye (Özden Keleş, 2020). Both pure and mixed forests of these two tree species cover large areas in Türkiye. These species' mixed forests are significant ecosystems with respect to their ecological, social, and economic functions (Aktürk et al., 2020). Regarding the impacts of tree mixture and stand type on stand production in fir forests, there is still uncertainty. Forest managers would be able to adapt treatments that increase stand productivity through silvicultural treatments if they were aware of the relationships between tree mixture, stand type, and stand productivity (Odabaşı et al., 2004).

Studies on the influence of tree mixture on diameter increment are quite limited on a global scale. It is clear that there is a need to conduct more studies on this issue in the forests of Türkiye. There is not adequate study on how tree growth in Kazdağı fir forests varies according to tree mixture. Moreover, there is no enough research on how tree mixture-growth relationships vary according to management type (i.e., even-aged versus uneven-aged). Therefore, the main goals of this study are i) to compare the diameter growth of Kazdağı fir in pure fir forests and mixed fir-beech forests, ii) to determine how the relationship between tree mixture and diameter growth differs according to stand type, and iii) to determine how stand density affects diameter growth in different stand types.

MATERIALS AND METHODS

Study Area and Study design

The research was conducted at Sinop city's Ayancık area in northern Türkiye (Figure 1). The research area is within the native distribution of Oriental beech and Trojan fir, and it is situated inside the Euro-Siberian phytogeographic region. The research region experiences typical continental weather, which includes cold winters and rainy summers. The dominant vegetation in the region where the study took place is forest. Plant diversity is quite rich. Black pine (*Pinus nigra* Arnold), Scots pine (*Pinus sylvestris* L.), and oaks (*Quercus* spp.), Anatolian chestnut (*Castanea sativa*) are also present across the region. Moreover, *Rhododendron*, *Rubus*, *Cornus* are some of the understory plants.

Figure 1. The location of the study area

Four different stands were selected within the study area; 1) uneven-aged fir stand (UEF), 2) even-aged fir stand (EAF), 3) uneven-aged mixed fir-beech stand (UEMix), and 4) even-aged mixed fir-beech stand (EAMix). For the UEF forest, a GA stand located in compartment 3 with an area of 37.2 ha was studied. The last timber production in this stand was occured in 2013. The EAF forest was in compartment 6, and was a Gcd3 stand. The stand was 18.3 ha in total. The last timber production in this stand occurred in 2018. For UEMix forest, a GKnA stand located in compartment 2 with an area of 4,6 ha was studied. The latest treatment was in 2018 in this stand. The EAMix forest was in compartment 5, and was a GKncd3 stand, with an area of 18.3 ha in total. There has not been any timber production recently in this stand. The sections where the study plots were taken had an average slope of 25%, canopy closures of 70-100%, and an altitude of 1550-1650 m.

Confounding variables that may affect the correlations between diversity and production include climatic characteristics, local environmental circumstances, forest structure, and density (Bravo-Oviedo et al., 2021). To reduce the impacts of sampling and distinguish the influence of the confounding parameters from the effects of tree richness, it is imperative that the studied stands have similar climatic conditions, terrain, and elevation (Forrester and Bauhus, 2016). Please take note that the chosen stands were in close proximity.

Sampling and Masurements

In each stand type, fifteen plots in size of 400 m^2 (20x20 m) were installed. Experimental plots were randomly located within the studied stands. While determining the plot areas, aspects, slopes and elevations were chosen by paying attention to their similar characteristics.

Tree diameters at breast height (DBH) (cm) of all trees larger than 8 cm were measured, and the species were noted during the inventory, which were carried out in the autumn of 2022 for the current study within each sampling plot. Stand density (i.e., basal area [SBA]) (m^2 ha^{-1}) and number of trees per ha were determined as well, because they can influence diameter increment of trees as well. The percentage of mixture in SBA of beech trees in all stands was also calculated.

Increment core were taken from 3 dominant trees in pure fir stands with the help of an increment borer (Haglof Inc. USA), and the ring widths of the last 5 years in the increment cores were measured and noted with the help of a tree core reader (Haglof Inc. USA). In mixed stands, 3 dominant trees from each species (i.e., fir and beech) were selected, and their five-year diameter increments were measured using the same procedure.

Analyses

The relationships among tree mixing, tree density, and the increment were determined by utilizing a random-effect regression test (i.e., formula 1).

$$\mathrm{Di} = \beta_o + R_v + X^T + E \quad (1)$$

where Di is the dependent parameter, β0 is the intercept, R_v is the random parameter, X^T is the transposed matrix of the fixed effects, and E is the error term. Five-year diameter increment was used as the dependent variable (i.e., diameter increment) in the formula. Moreover, we considered stand type (i.e., pure versus mixed), SBA, percentage of mixture, and interactions as fixed parameters (Zeller et al., 2018). The plots were treated as random effect nested within the stands. The influence of stand type (i.e., uneven-aged versus even-aged) on the diameter increment was examined using analyses of variance (ANOVA). Tukey-HSD test was utilized to observe the differences among the stand types. During the statistical tests, R-Statistical software (R Development Core Team, 2021) were performed.

RESULTS AND DISCUSSION

RESULTS

Summary data about the selected stands is given in Table 1. The values of the given parameters in the table were calculated based on the average of the measurements taken within the sample plots located in each stand type. It was determined that the highest average SBA was in the EAMix stand, and the lowest average SBA was in the UEMix stand (Table 1). There were no significant differences among the stand types in terms of the number of trees (ha) ($p>0.05$). When the 5-year diameter increment of the stands were compared, it was determined that the highest increase occurred in the EAF stand and the lowest increase occurred in the EAMix stand (Table 1).

Table 1. Summary data regarding the selected stand types. UEF, EAF, UEMix and EAMix refer to uneven-aged fir, even-aged fir, uneven-aged mixed fir-beech andven-aged mixed fir-beech stand, respectively

Stand type	Parameters	Mean	Max.	Min.
UEF	SBA (m^2 / ha)	73.9	104.9	53.5
	Increment (mm / 5 yr)	5.98	7.01	4.66
	Number of trees (ha)	778	1100	600
EAF	SBA (m^2 / ha)	91.4	114.1	55.01
	Increment (mm / 5 yr)	6.17	7.01	5.01
	Number of trees (ha)	781	1175	650
UEMix	SBA (m^2 / ha)	57.7	82.9	45.01
	Increment (mm / 5 yr)	4.82	5.66	4
	Number of trees (ha)	708	875	600
EAMix	SBA (m^2 / ha)	110.4	142.1	67.4
	Increment (mm / 5 yr)	4.07	6.33	3
	Number of trees (ha)	990	1400	625

The diameter distributions of trees in each forest stand type were shown in Figure 2. UEF stand had more trees in 10 and 40 cm diameter classes. The stand does not show a reverse J shape, which is typical of an optimal uneven-aged forest. Even though EAF has been managed under even-aged methods, its structure differs from normal distribution (Figure 2). This is likely because the thinning treatment has not been done timely, and with appropriate intensity. EAMix stand shows close to normal distribution, which is typical of even-aged forests. Larger diameter classes were dominated with firs in this stand type. As for UEMix, it does not show optimal uneven-aged structure either. There is lack of trees in smaller diameter classes in UEMix stand (Figure 2).

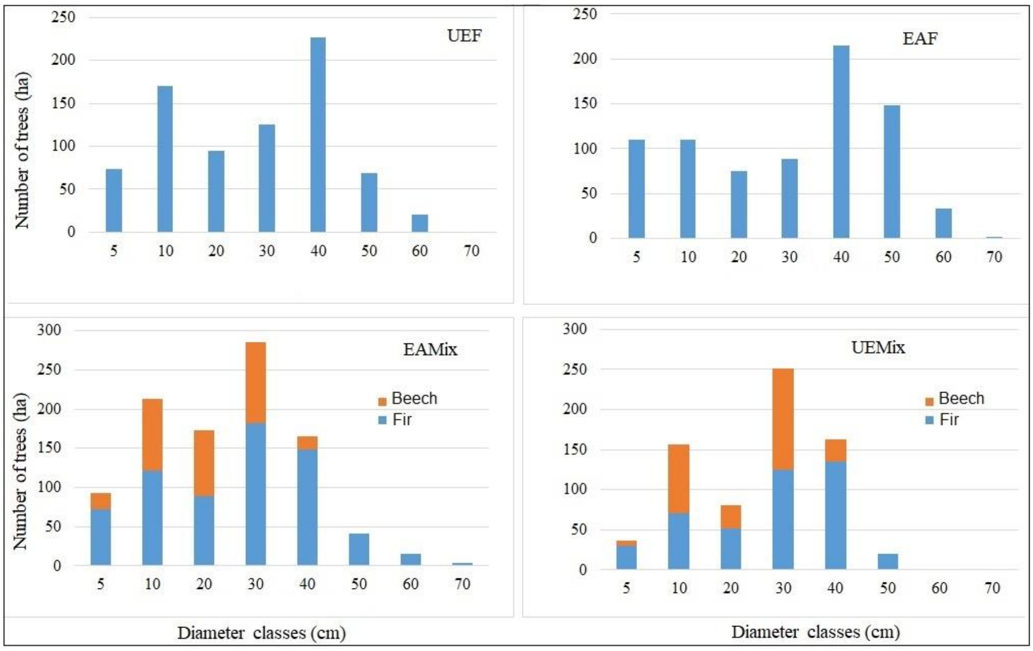

Figure 2. Diameter distributions of trees in each forest stand type

Figure 3 shows the change in 5-year average diameter increment values according to stand types. Accordingly, while the highest diameter increment was examined in the EAF stand, the lowest increase was observed in the EAMix stand. In general, a greater diameter increment was attained in pure fir stands compared to mixed fir-beech stands (Figure 3). However, it should be noted that there was not statistically significant difference between UEF and EAF stands in terms of 5-year diameter increment (p=0.832) (Figure 3).

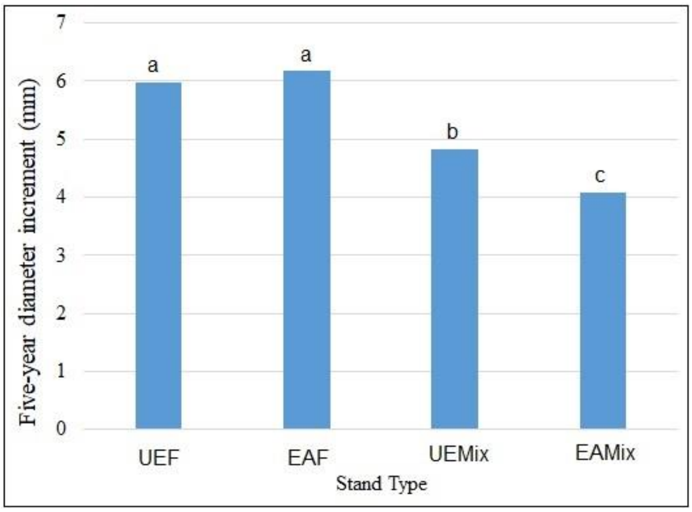

Figure 3. Five-year diameter increment in each forest type

As stated above, tree density varied across the studied stands. It is known that tree density also affects diameter increment. Therefore, comparing the 5-year diameter increment according to stand types itself would be misleading. For this reason, stand density (i.e., SBA) were included in the analyses. Given the analyses, it was determined that tree mixture and SBA had a statistically meaningful influence on the 5-year increment according to the mixed-effect regression model (Table 2). There was an opposite association between tree mixing and the increment. In other words, the increase in species diversity by introducing beech into the mixture in fir stands caused the 5-year diameter increment to decrease. That is, the introduction of beech into the mixture in fir forests negatively affected the diameter increment (Table 2).

There was also an opposite correlation between SBA and the 5-year increment (Table 2). Increasing SBA (i.e. tree density) resulted in a decline in 5-year increment of diameters. The most important reason for this is that trees can not find sufficient growing space due to increasing SBA and the competition between trees increases. It was determined that the other parameters, the percent mixture, did not have a statistical influence on the 5-year increase ($p>0.05$) (Table 2). The main reason for this is that the beech rates (%) did not seem to differ much among the selected stands.

Table 2. Influences of mixing and tree density (i.e., SBA) on 5-yr diameter increment. SE is standard error

Variables	Value	SE	t-value	p-value
Intercept	6.3028	0.3310	19.0400	<0.0001
Tree Mixing	-0.0124	0.0056	-2.2307	0.0312
Stand Density	-2.6024	0.5135	-5.0671	<0.0001
Percent Mixture	0.0301	0.0163	1.8436	0.0725

DISCUSSION

The main objective of this study was to examine how diameter increment in pure fir and mixed fir-beech forests is affected by tree mixing, stand type, and density. Diameter increment was influenced by the mixture, density and stand type. Beech and fir are shade-tolerant tree species (Kara and Lhotka, 2020; Kara, 2022), thus, they were present in the small size diameter classes as well. Quantitative approaches that relate tree mixture, stand type and stand density to diameter increment are mainly crucial since this mathematical information would improve our knowledge on the tree mixture control. It is also important to reveal these relationships because recent studies have obtained inconsistent findings among these variables (Kessler et al., 2014; Whittaker and Heegaard, 2003).

Previous studies have shown that tree mixture may have positive effects on stand productivity (Pretzsch et al., 2017). For example, Zeller et al. (2018) monitored the influence of tree mixing on forest productivity in Germany and the USA and found a positive relationship between mixture and productivity. In a similar study, Gamfeldt et al. (2013) observed the relationships between stand productivity and tree mixture in boreal and temperate forests and found that tree growth increased with increasing species diversity. Mixed forests consisting of trees with variable shade-tolerance can usually establish layered canopy and root distribution in the subsoil (Pretzsch et al., 2017). Thus, complementary subsoil resource use between tree species in these mixed forests can often lead to higher tree growth at the stand level (Kelty, 2006; Oliver and Larson, 1996).

In this study, it was found that tree mixture negatively affected 5-year diameter increment. Although it has generally been found that tree mixing positively increases tree growth (Danescu et al., 2016; Liang et al., 2016), some studies have revealed that tree mixing may negatively influence the stand productivity as well (Wang et al., 2016). Waide et al. (1999) examined nearly 200 studies on tree mixture and stand productivity relationships, and as a result it was stated that in 12% of these studies increasing species mixture reduced tree growth, while in 32% of them, there was no significant relationship between tree mixture and stand productivity. Long and Shaw (2010) found no effects of tree mixture on productivity in Ponderosa pine (Pinus ponderosa C. Lawson) forests in the western USA. These data coincide with the findings we obtained in this study.

Waide et al. (1999) stated in their study that the negative effect of species mixture on tree growth may be a result of competition between different species. This is more likely when tree species of the mixture have similar root structure, because this may reduce the complementary subsoil resource use. Moreover, this situation is also more common in infertile soils. Similarly, Coomes and Grubb (1998) found that tree mixture negatively affected tree growth in tropical forests when the soil was infertile. The fact that increasing species mixture does not have an effect on tree growth can be explained by the fact that an increase in the number of individuals of a species causes a decrease in the number of other species (Tilman, 1999).

The current study also found that stand density had a negative impact on diameter increment. One of the most important reasons for this is the increase in competition between trees with increasing stand density. In other words, as the stand density increases, the water, plant nutrients and light available to individuals may become more limited, and therefore a slowdown and decrease in the growth of trees would be observed.

CONCLUSION

The results obtained in this study may have been affected by the region where the study was conducted. Akgöl Forest Planning Enterprise has historical importance for Turkish forestry. The stands within the boundaries of this enterprise have been exposed to excessive exploitation for many years in the past, and the natural stand structures in these stands have been severely damaged. One of the reasons why the stand structure of the stands in the study area is not as expected, for example, the selection forests are far from optimal structure, may be due to these excessive exploitations in the past. Therefore, conducting such similar studies in different regions of our country will help to better understand the relationships between mixture and tree growth.

As seen in this study, the introduction of beech into the mixture in fir stands may have a negative effect on diameter increase. However, this study should not imply that mixed fir-beech stands should be converted to pure fir stands. Because, as stated above, mixed forests have many functions, and these mixed forests are not operated only for wood production. In the light of the findings obtained in this study, it can be suggested that the creation of mixtures with beech in pure fir forests, where the primary purpose is wood production, should be carefully evaluated economically. Similarly, in mixed fir-beech forests where the primary purpose is not wood production, converting the stand into a pure fir forest may mean giving up the other benefits of mixed stands. For this reason, in determining and regulating species diversity in forests, it would be logical to plan not only by considering efficiency and growth issues, but also by evaluating the relevant stands on their own and other products and services provided by those stands.

One of the shortcomings of this study is the short observation period. Long-term data is important in diameter increment studies. However, it is not easy to find stands that have not been subjected to long-term intervention in our country. For this reason, only five-year diameter increase was observed in the study. This may be a disadvantage to the study's findings. In the light of the findings, the mixing of beech with fir may seem to create a negative situation in terms of diameter increase, but the long-term effects of this relationship are unknown.

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Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author's Contributions

FK conceived the idea and conceptualized the project. GÖ collected data and compiled the literature. FK conducted analyses. FK and GÖ conducted writing and editing. All authors reviewed manuscript drafts and gave final approval for publication.

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