Impact of Thinning on Sexual Symmetry and Gene Diversity in *Pinus brutia* Ten. Plantation

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Abstract: Thinning is widely used in the context of sustainable forestry, but its impact on the gene diversity of the next generation remains unclear. In this study, we evaluated some commonly proposed genetic parameters for managing gene diversity in seed orchards. In this framework, we checked whether sexual symmetry, fecundity variation, and linked metrics (i.e., effective population size and gene diversity) can be used to optimize gene diversity through thinning in production forests. We divided trees in a Brutia pine plantation in southern Türkiye into three different canopy cover classes: the control group, the moderately thinned group, and the heavily thinned group, and monitored them. The results of our research revealed the impact of thinning on genetic parameters and showed that these metrics can be used to manage gene diversity in production forests. We believe that this study can function as a prototype for future studies using different thinning intensities in various regions and for different species to determine the most appropriate thinning intensities for sustainability.

Keywords: East Mediterranean, Forest tending, Parental balance, Reproduction, Silviculture

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1. INTRODUCTION

Thinning, an important component of sustainable forestry, has recently gained traction in the battle concerning climate change. Many studies have provided strong evidence that thinning to reduce competition among trees for essential resources provides benefits such as reduced drought-related mortality (Sohn and Saha, 2016; Cabon et al., 2018; Bello et al., 2019; Wang et al., 2019; Steckel et al., 2020; Zamora-Pereira et al., 2021), minimized wild-fire risk (Collins et al., 2014; Kalies and Kent, 2016; Palmero-Iniesta et al., 2017; Hevia et al., 2018; Tardós et al., 2019), and enhanced resistance to insect-pathogen outbreaks (Menkis et al., 2015; Bulman et al., 2016; Morris et al., 2021; Steel et al., 2021). Research has shown that the positive effects of thinning become stronger as the intensity of thinning increases and that heavy thinning, which involves lifting greater than 40% of the basal area, is particularly impactful (Collins et al., 2014; Kalies and Kent, 2016; Sohn and Saha, 2016; Cabon et al., 2018; Wang et al., 2019; Bello et al., 2019; Steckel et al., 2020; Zamora-Pereira et al., 2021). Although heavy thinning may offer greater short-term advantages, it may lead to a genetic bottleneck in future generations as it reduces the number of possible parents in the stand (Ellegren and Galtier, 2016).

In the literature, approaches to addressing gene diversity in the context of sustainable forestry have generally focused on seed orchards. Seed orchards are specifically engineered to grow genetically polymorphic (i.e., diverse) seeds for use in regeneration activities (Kang and Bilir, 2021). Burczyk and Chalupka (1997) and Kang and Lindgren (1999) have drawn attention to the delicate balance between male and female individuals in a population in the context of genetic diversity. Recent research has focused on measuring this balance via the maleness index (Cercioglu and Cetinkaya, 2021a; Jiao et al., 2021; Park et al., 2023; Kim et al., 2024). Defined as the proportion of male strobili that facilitate plant pollination, this index provides information on the sex distribution of a population (Burczyk and Chalupka, 1997; Kang and Lindgren, 1999). However, the impact of thinning on the gender balance (through maleness index) has not been investigated, yet.

Another research focus in the context of genetic diversity has been the monitoring of fertility or fecundity variation

and linked metrics (i.e., estimation of effective population size and gene diversity) (Özel and Bilir, 2016; Bilir et al., 2017; Park et al., 2017; Teodosiu et al., 2022; Xie et al., 2022; Wang et al., 2023). Fertility or fecundity variation is defined as a genetic parameter reflecting disparities in reproductive success among individual trees (Kang et al., 2003) Seed orchards target low fertility variations (Kang and Bilir, 2021). This implies that the trees in the gene pool are represented in a balanced way, i.e., that each tree contributes roughly the same number of offspring for the next generation (Kang, 2001). High variation indicates that some genotypes are disproportionately represented, thus potentially jeopardizing gene flow (Bilir and Kang, 2021). Effective number of parents refers to the minimum quantity of trees within a stand that can maintain genetic diversity (Bilir and Kang, 2021). By chance, allele frequencies in a population can fluctuate. This concept helps us understand the impact of this randomness, known as genetic drift (Kang et al., 2023). Previous research has not established a clear link between fecundity variation and commercial thinning, which is commonly used in production forests. By understanding the impacts of density reduction on gene diversity, we aim to contribute to the improvement of optimal management strategies for sensitive forestry operations.

The Mediterranean basin is a region suffering intensely from climate change (Pachauri et al., 2014; Cramer et al., 2020; Acarer, 2024). Brutia pine, which has a wide distribution area in Türkiye, stands out as one of the species at high risk in the region and as one of the species that may be most affected by climate change due to the latitudinal effect (OGM, 2020). Here, short-term approaches such as afforestation or thinning can be functional. However, in the long term, the intensity of thinning should be carefully calibrated so that the species' natural adaptation mechanisms (through gene diversity) are not disrupted.

Based on this background information, the present study addresses the changes in strobilus yields and gene diversity under different thinning practices in *P. brutia* plantations. Specifically, the following questions we focused on were: (1) How do different degrees of thinning interventions impact strobilus yields? (2) How do different degrees of thinning interventions impact sexual symmetry, fecundity variation, and the effective population size? (3) Can these genetic metrics developed for seed orchards be integrated into natural Brutia pine forests through thinning to improve conservation and management strategies? (4) What is the optimal thinning intensity for *P. brutia* in terms of gene diversity? Our findings are supposed to constitute a scientific foundation for the sustainable improvement of production forests.

2. MATERIAL AND METHOD

The investigation was implemented on an Brutia pine plantation (37° 07' 34"N, 36° 33' 04"E) in Hasanbeyli District of Osmaniye Province, Türkiye (Figure 1). The plantation is located on the Nurdagi pass, which serves as a connection between Çukurova and the eastern region. It is characterized by low hills, ranging from 750 to 800 meters

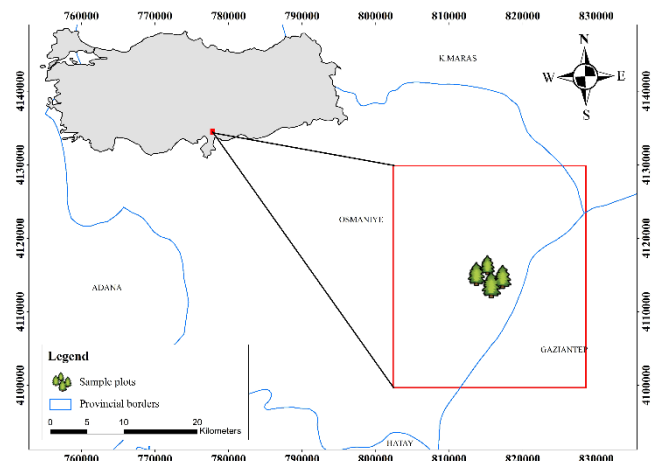in height, and has a subtropical dry summer Mediterranean climate (MGM, 2018).

Figure 1. Location of the study area

Plantation was established in 1987, was planted at 3 m × 2 m spacing, and originated from a single provenance. The plantation was thinned two times in 2000 and 2010, and its density is irregular. In 2020, sample trees were stratified into three canopy cover classes (CCCs): S1, S2, and S3 stands. No thinning activity was organized in S1, which served as a control plot. The experimental activity was organized in S2 as a medium-thinning intensity plot and in S3 as a heavy-thinning intensity plot. Thinning treatments were conducted in S2 and S3, with an intensity of 30% and 60%, respectively. S2 and S3 were thinned from below by intervening in poorly formed crowns, twisted stems, and co-dominant and suppressed trees. While timber and cutting residues were removed after the thinning intervention, no vegetation below the main vegetation layer was removed, neither during nor after thinning. Measurements were performed 3 years after the last thinning. We chose strategically neighbouring positions for all three stands to minimize environmental impacts and ensure that only the effect of thinning is visible.

To determine the growth dynamics of the trees, measurements of height (abbreviated as H) and diameter at breast height (abbreviated as DBH) were carried out. Between March and May 2023, the count of female (abbreviated as Nf) and male (abbreviated as Nm) strobilus in each individual was recorded. Each Nf was counted individually using binoculars. The generation of Nm was examined using the conventional branch approach (Krouchi et al., 2004). For Nm, each individual tree was marked with four typical branches: one located to the east, one to the south, one to the west, and one to the north. The strobili on these branches were tallied and multiplied by total number of branches that have strobili (Bilir and Kang 2021; Park et al. 2023). The total strobilus number (abbreviated as TSN) was obtained by summing number of female and male strobili in every single individual.

Data underwent the Kolmogorov-Smirnov test originally. Given the non-normal pattern of the data set, Kruskal-Wallis test was run to assess differences among groups in the dependent variables. The Kruskal-Wallis test results were visualized as weighted boxplots that not only

summarized this information using quartiles, medians, and min/max values but also compared medians and distributed the data by group (MacFarland and Yates, 2016). Correlations among the growth and reproductive characteristics of the subject trees were examined using Spearman's correlation. All statistical tests were conducted using RStudio v. 2023.03.0-386 (RStudio Team, 2020).

The maleness index (M_i), which represents individual and/or collective contributions to the pollen gene pool during pollination in the forest, was calculated as (Burczyk and Chalupka, 1997; Kang and Lindgren, 1999):

$$M_i = \frac{pm_i}{pm_i + pf_i} \qquad (1)$$

where pm_i and pf_i represent the male and female strobilus yield ratios for the ith subject tree, respectively.

Fertility or fecundity variations reflecting inequalities in the number of trees involved in reproduction were calculated separately for female (Ψ_f) and male strobilus (Ψ_m) yield, respectively, as follows (Kang et al., 2003; Park et al., 2017):

$$\Psi_f = N \sum_{i=1}^{N} f_i^2 \qquad \Psi_m = N \sum_{i=1}^{N} m_i^2 \qquad (2)$$

where N is the number of subjects, f_i is the fecundity for female strobilus yield of the ith tree, m_i is the fecundity for male strobilus yield of the ith tree.

To analyze the combined fecundity variation (Ψ), we initially examined the Spearman correlation coefficient (r) among female and male strobilus yields and then employed the following formulation (Bilir and Kang, 2021):

$$\Psi = 0.25(\Psi_f + \Psi_m) + 0.5\left[1 + r\sqrt{(\Psi_f - 1) + (\Psi_m - 1)}\right] \quad (3)$$

Effective number of parents (N_p), a concept that represents the count of adults contributing to the gene diversity of the next generation in a stand and is calculated by examining the relatedness of trees within the stand, was linked to fertility variations as follows (Kang et al., 2023):

$$N_p = \frac{N}{\Psi} \qquad N_p^{(f)} = \frac{N}{\Psi_f} \qquad N_p^{(m)} = \frac{N}{\Psi_m} \quad (4)$$

Gene diversity (GD) was computed according to fecundity variations and the number of subject trees as follows (Yazici and Bilir, 2023):

$$GD = 1 - \frac{0.5\Psi}{N} \qquad (5)$$

Tree slenderness coefficient (TSC), which is often utilized as a common metric in the context of stability against windthrow on a tree or stand basis, was calculated as follows (Zhang et al., 2020):

$$TSC = \frac{Total\ tree\ height}{Diameter\ at\ breast\ height} \qquad (6)$$

where the variables involved in the division must be of the same unit type (e.g., cm/cm or m/m).

3. RESULTS

3.1. Impact of Canopy Cover on Strobilus Yield of Trees

Strobilus yields (Nf and Nm) both differed significantly ($p < 0.05$) among canopy cover classes (Table 1 and Figure 2).

Table 1. Strobilus yields of *Pinus brutia* at different densities of canopy cover classes

CCCs *	RO **	Mean	Range
S1	Nf	20–800	257.26
	Nm	90–2610	1045.60
S2	Nf	291–1489	829.72
	Nm	300–8214	3329.18
S3	Nf	694–1915	1232.78
	Nm	750–9000	4712

* CCCs was canopy cover classes, S1 was control, S2 was medium thinning, S3 was heavy thinning; ** RO was reproductive output, Nf was female strobilus, Nm was male strobilus.
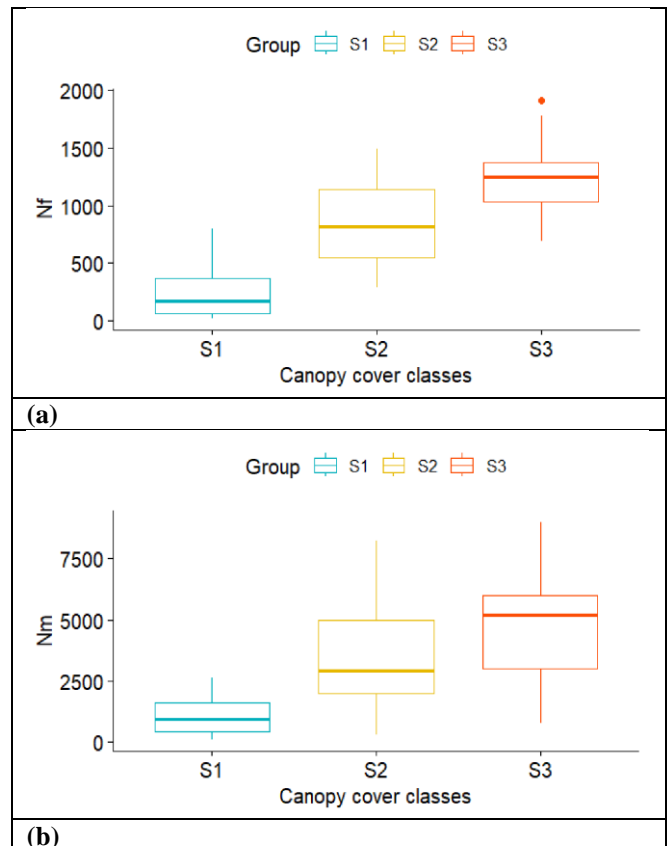

(a)

(b)

Figure 2. Female **(a)** and male **(b)** strobilus yields in canopy cover classes

The yearly Nf production of the two thinning densities was 222.52% and 379.20% ($p < 0.05$) greater than the control, respectively. The yearly Nm production of the two thinning

densities was 218.40% and 350.65% ($p < 0.05$) greater than the control, respectively. The yearly TSN of the two thinning densities was 219.21% and 356.29% ($p < 0.05$) higher than the control, respectively. In the control group, some trees were found to contribute asymmetrically to reproduction with extreme yields. For instance, in stand S1 (control), the five most fertile trees (10% of the subject trees) generated 22.83% of the TSN. In contrast, for S2 (medium thinning), this percentage was 20.12%, while for S3 (medium thinning), it was 16.08%.

3.2. Impact of Canopy Cover on Growth-Reproduction Correlations of Trees

As can be seen in Figure 3, there were overall significant ($p < 0.05$) positive correlations in terms of strobilus yields both within and among populations, as assessed by Spearman correlation analysis. There was no significant correlation between H and DBH and strobilus yields within groups, whereas there was a correlation between H and DBH and strobilus yields among groups, which was caused by the group effect. In this case, significant ($p < 0.05$) and positive correlations emerged among strobilus yields and diameter at breast height, while significant ($p < 0.05$) but negative correlations were observed among tree height and strobilus yields. In addition, the correlation analysis showed a moderate relationship with height and diameter for strobilus yields, while it showed an almost strong relationship (mean, $r = -0.68$) with the height-to-diameter ratio (i.e., slenderness).

Figure 3. Scatter plot matrix for growth and reproductive outputs. Diagonal graphs show the distribution of outputs across canopy cover classes; graphs below the diagonal show the scatter and trend of measured outputs; and above the diagonal show the overall and within-group correlations between outputs.

3.3. Impact of Canopy Cover on Sexual Symmetry, Fertility Variation, and Linked Parameters

Maleness (M_i) and femaleness indices (F_i) fluctuated among canopy cover classes (Table 2). The M_i of the two thinning densities stabilized, decreasing by 5.26% and 3.90%, respectively, compared to the control. However, although sexual symmetry was approached in thinned stands compared to the control, a perfectly linear relationship was not detected in terms of maleness and femaleness indices in stands depending on the thinning

intensity. Stand S2 was the one that approached sexual symmetry the most.

Table 2. Fecundity variation (Ψ), effective number of parents (N_p), maleness index (M_i), femaleness index (F_i), and genetic diversity (GD) in stands.

CCCs *	S1	S2	S3
Ψ	1.70	1.33	1.14
Np	29.41	37.59	43.86
Mi	0.80	0.76	0.77
Fi **	0.20	0.24	0.23
GD	0.983	0.9867	0.9886

* CCCs was canopy cover classes, S1 was control, S2 was medium thinning, S3 was heavy thinning; ** Fi = 1 - Mi.

The Ψ of the two thinning densities stabilized, decreasing by 27.82% and 49.12%, respectively, compared to the control. The N_p of the two thinning densities stabilized, increasing by 27.81% and 49.13%, respectively, compared to the control. The effective population size had a positive linear relationship with the degree of thinning in S2 (75% productive trees) and S3 (88% productive trees) and demonstrated linear growth in comparison to the control (59% productive trees). Gene diversity (GD), which is linked to effective population size and fertility variation, also increased from S1 to S3. Gene diversity loss was reduced by 0.0037 and 0.0056 in the two thinning densities, respectively, compared to the control.

4. DISCUSSION

4.1. Impact of Canopy Cover on Strobilus Yield of Trees

Adjusting the spatial arrangement of forests is a crucial component of the sustainable forestry approach. Thinning is a frequently employed technique for making this adjustment. We addressed the impact of thinning on fecundity so as to create a polymorphic seed bank for forest sustainability. The results showed that thinning significantly ($p < 0.05$) and exponentially increased strobilus yields in *P. brutia*. This finding is in line with the recognized notion that trees in more open canopy positions (with increased light availability due to thinning) produce significantly more reproductive structures compared to trees in the control group with denser canopies (Moreno-Fernández et al., 2013; Nguyen et al., 2018; Matsushita et al., 2020). This is consistent with and can be explained by the findings of Saatçioğlu (1971), who reported that a large nutrient expenditure in the mast year may result in poor seed formation the following year; that an increase in the carbon/nitrogen ratio in the tree is likely to increase flower formation; that hot summers reduce the uptake of nutrient salts due to soil drought and that sunny weather increases carbohydrate production; and that the tops of trees that receive light from all directions and are fully exposed produce the most flowers and fruit. Furthermore, the yield of male and female strobilus in thinned stands showed a linear increase. This suggests a consistent increase in reproductive effort following thinning.
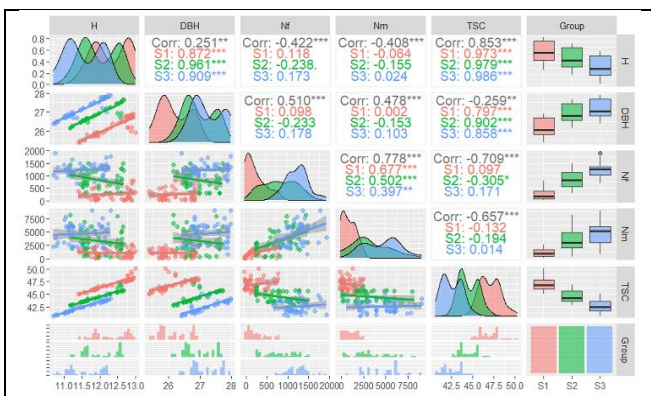
Our study is in accordance with the research published by Ayari et al. (2012), who reported that trees with larger trunk diameters produce larger cones, that thinning practices can increase this production, and that this is perhaps one of the biggest advantages of thinning. Similarly, Ayari et al. (2011), looked at 79 Aleppo pine forests in Tunisia and detected a negative association between canopy cover intensity and seed and cone yield ($r_{seed} < -0.418$, $r_{cone} < -0.471$ ($p < 0.001$)). These findings are supported by other studies showing that thinning treatments have an ameliorative effect on trunk diameter, total height, and crown development (Prévosto et al., 2011; Adamopoulos et al., 2012; Ruano et al., 2013). The effects of thinning on the production of reproductive structures have been documented in Aleppo pines in various geographical locations, such as Tunisia (Ayari et al., 2012), Italy (Mencuccini et al., 1995), and Spain (Arista and Talavera, 1997), and in various forest tree species, such as *Pinus ponderosa* (Krannitz and Duralia, 2004), *Pinus pinea* (Moreno-Fernández et al., 2013), and *Pinus koraiensis* (Nguyen et al., 2018). In conclusion, with our results (i.e., the observed increase in fecundity and more even distribution of reproductive effort), we would like to emphasize once again that thinning is a valuable tool to promote successful reproduction in Brutia pine stands.

4.2. Impact of Canopy Cover on Growth-Reproduction Correlations of Trees

In terms of correlations, the most remarkable outcome we found was the almost strong (mean, $r = -0.68$) correlation between TSC and strobilus yields. Typically, research in the literature has focused on examining correlations between growth patterns and reproductive yields (i.e., strobilus and cones) and has found evidence of positive, negative, or neutral relationships. For example, Bilir et al. (2006) conducted a study in three clonal *Pinus sylvestris* seed orchards and found that although flower yield was not very high in general, it was positively affected by growth characteristics, and this was especially related to the diameter at the base. Gonçalves and Pommerening (2012) reported a significant positive relationship between cone yield and crown diameter in *Pinus pinea* and Çerçioğlu and Çetinkaya (2021b) in *Pinus brutia*. Çerçioğlu and Bilir (2018) reported that height had no effect on female flower yield in 2015 but had a positive and significant effect on male flower yield and 2016 overall flower yield in *Pinus nigra* Arn. subsp. *pallasina* (Lamb.) Holmboe. In the same study, crown diameter was found to have a positive effect on flower yield in 2015 and a negative effect on flower yield in 2016. In addition, it was emphasized that height and diameter at breast height were more effective on the number of seeds and cones, while the growth traits that were effective on reproductive traits were listed as height, crown diameter, and diameter at breast height. Chen and Willis (2023) reported that diameter was neutrally correlated with cone production. Similarly, Yücedağ et al. (2019) reported that there was no correlation between flower yield and growth traits in *Tilia tomentosa*.

In this study, unlike other studies, we employed TSC as the dependent variable and obtained a stronger correlation coefficient with TSC than with H and DBH. This finding suggests that TSC could be measured metrically and used as a criterion for plus tree selection, or that slenderness-reducing interventions such as crown pruning could be used to increase seed yield in seed orchards (Han et al., 2008). Indeed, TSC provided a realistic representation of both the diameter and height of a tree and showed that trees with larger diameters and proportional heights (i.e., not thin trees) generally had the largest reproductive outputs. Put simply, the most evenly growing non-thin trees appear to be the best reproducers. Based on our results, we believe that TSC is highly correlated with reproductive output production. Slenderness may explain why some trees produce a good reproductive output at very old ages. For example, Genç (2004) stated that *Cedrus libani*, which is predominantly distributed in Türkiye, produces both the desired quality and amount of timber and sufficient seed yield for regeneration studies only after reaching 100 years of age, so the rotation period should not be less than 100 years. Indeed, the Turkish General Directorate of Forestry uses rotations of 120–140 years for rich areas and 160–180 years for poor areas. For Taurus cedar, this period marks a period of weakened height development: good seed production and slenderness seem to go hand in hand.

4.3. Impact of Canopy Cover on Sexual Symmetry, Fertility Variation, and Linked Parameters

As mentioned above, although the beneficial effects of thinning on reproductive structures have been demonstrated in many studies, the existing literature lacks sufficient information regarding the impact of thinning on fertility distribution. In this study, we investigated how thinning practices may affect some genetic parameters that are widely recommended for managing gene diversity in seed orchards. In this framework, we first addressed the impacts of thinning on sexual symmetry, whose importance on gene diversity has been reported in many studies (Cercioglu and Cetinkaya, 2021a; Jiao et al., 2021; Kang et al., 2023; Park et al., 2023; Kim et al., 2024). In monoecious species such as pine, sexual asymmetry (i.e., numerical variations of male and female strobili) is common (Burczyk and Chalupka, 1997; Cercioglu and Cetinkaya, 2021a; Kim et al., 2024). Maleness and femaleness indices can help us get better insight into reproduction, and they reveal paternal and maternal contributions, respectively. If M_i is 0.5, female and male fertility are equal (Kang et al., 2023). The femaleness index can be calculated as $1 - m_i$, and describes the breeding success of female parents (Kang and Lindgren, 1999). Our results showed that thinning generally tends to produce gender balance. We found that maleness and femaleness indices fluctuated among canopy cover classes and showed a dynamic response to thinning intensity. The decrease in the maleness index after thinning treatments reflected a trend towards sexual symmetry, while no direct linear relationship was found between thinning intensity and indices. This suggests that source, plant interactions, or genotypic factors may influence sexual distribution.

Secondly, we discussed the effects of thinning on fertility variation (Ψ), whose importance for gene diversity has been recognized in many studies (Özel and Bilir, 2016; Bilir et al., 2017; Park et al., 2017; Teodosiu et al., 2022; Xie et al.,

2022; Wang et al., 2023). Fecundity variation is the residual variance in the fertility levels due to the among-individual variances (Kang, 2001). Fertility is related to individuals' reproductive capability and success, often measured as the number or ratio of offspring produced (Bilir et al., 2017; Park et al., 2017; Cercioglu and Cetinkaya, 2021a). If all trees in the stand produce an equal number of offspring, the fertility variation value is 1 ($\Psi = 1$) (Kang et al., 2003). Kang (2001) reported that a fertility variation value of 2 is normal for seed orchards and up to 3 for natural populations. In this framework, we found that thinning treatments led to a significant reduction in fecundity variation compared to the control, indicating more balanced reproductive success. This finding suggests that thinned stands show a greater balancing effect and relatively low fecundity variation. Low fecundity variation indicates more equal reproductive success among trees, while high variation causes heterogeneity between genetic and phenotypic success processes (Yazici and Bilir, 2023). Consistent with Kang's (2001) study, low values of fecundity variation suggest that genetic diversity can be increased in thinned stands.

Our third focus was the effective number of parents (N_p). Low (i.e., balanced) values of fertility variation indicate that the trees in the population are represented in the gene pool in close proportions and that the population size involved in reproduction is increasing (Cercioglu and Cetinkaya, 2021a; Bilir and Kang, 2021). We found that the thinning treatments provided a significant increase in this parameter. The increase in the number of effective parents indicates a potential increase in genetic diversity within the thinned populations (Table 2). The thinning treatments provided a stronger balancing effect compared to the control, indicating a more balanced representation of trees in the population in the gene pool. However, the difference in balancing between S2 (75% productive trees) and S3 (88% productive trees) was small, suggesting that thinning intensity has a limited effect on this parameter above a certain level.

Overall, this study has demonstrated the potential of thinning practices to increase and control genetic diversity in production forests. Fertility is critical for forest management and plays a key role in achieving maximum potential genetic gain. Uneven fecundity among parental trees is likely to affect gene diversity in the next generation (Park et al., 2023; Wang et al., 2023). The more equal the offspring of the parents are, the more likely it is that the next generation will have a wider range of genes (Kang et al., 2023). Species with too little gene diversity may find it increasingly difficult to reproduce properly, and offspring may have to deal with the same health problems observed in inbreeding (Ellegren and Galtier, 2016). Reduced genetic diversity can increase a population's vulnerability to certain types of diseases and epidemics (Kang and Lindgren, 1999). Especially in times of climate change, the importance of gene diversity increases even more. We emphasize that thinning has a significant impact on fecundity variation and that gene diversity can be tracked with the parameters used in our study when determining the degree of thinning in production forests.

4.4. Balancing Effect, Thinning Intensity, and Future Prospect

GD increases from S1 to S3, indicating that genetic diversity increases with decreasing closure. N_p also increases from S1 to S3, which means higher genetic representation with less closure. Ψ decreases from S1 to S3, indicating more balanced reproductive success with less closure. In S1, GD and N_p are the lowest, while Ψ is the highest. This indicates that the stand should be thinned to increase genetic diversity and the number of effective parents. In S2, GD and N_p are at intermediate levels, and fertility variation is lower than in S1. This suggests that some positive effects are seen, but further thinning could be beneficial. In S3, GD and N_p are at their highest levels, and Ψ is at its lowest. This maximizes the positive effects of thinning. The results obtained in S3, together with sexual symmetry, show the most successful results in increasing genetic diversity and increasing the number of effective parents. However, when it comes to management practices, it is often crucial to determine the optimal level rather than completely reducing them. Therefore, keeping the degree of thinning at 50% may be the most effective approach to increasing genetic diversity and ensuring more balanced reproductive success. This rate would result in substantial enhancements in genetic variety and the number of successful parents, while also minimizing the disparities between S2 and S3. This recommendation is modeled from the statistical mean, trends, and patterns observed in the data that is currently accessible. Nevertheless, further research and meta-analysis are required to reach a meaningful and conclusive outcome in the context of integration into global forestry.

CONCLUSIONS

Effective forest management requires a comprehensive approach that considers the impact of silvicultural practices such as sustainable forestry and thinning on both yield and ecosystem health. The results of this study show that stand density is critical not only for the amount of fertility but also for genetic diversity. The genetic parameters analyzed in this study can be valuable tools to assess the impact of thinning on gene diversity. Thinning has the potential to increase reproductive success by controlling tree density and optimizing pollination. This could lead to the conservation of valuable gene diversity and the creation of a healthy seed bank for future generations. Our results show that a thinning intensity that includes keeping it in the 50% band offers a balance and is acceptable. This emphasizes the importance of considering genetic diversity when determining thinning intensity in forest management plans. By supporting these findings with studies of different tree species in different age classes and incorporating them into regional forest management strategies, we can move towards a more sustainable future for forests. This approach ensures that the ecological well-being of forests and their ability to provide valuable gene resources for future generations are maintained. This study can be considered a prototype and can be supported by future studies with different thinning intensities and species in different regions. These studies will contribute to a holistic

understanding and help determine the most appropriate thinning densities, especially in response to climate change. In summary, we believe that this study can significantly contribute to the development of future forestry policies centered on natural regeneration by demonstrating the essential role of maintaining genetic diversity and manageability to ensure sustainable forest management amid global challenges such as climate change and habitat loss.

Ethics Committee Approval
N/A

Peer-review
Externally peer-reviewed.

Author Contributions
All process steps such as conceptualization, research, analysis, visualization, methodology, and writing were carried out by Mahmut Çerçioğlu. The author has read and accepted the published version of the article.

Conflict of Interest
The author has no conflicts of interest to declare.

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