Can High-Quality Oak Be Produced at Lower Planting Densities?

A Study of Oak Group Planting Mixed with Birch

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Can High-Quality Oak Be Produced at Lower Planting Densities? A Study of Oak Group Planting Mixed with Birch.

Kan man odla ek av hög kvalitet med lägre planttäthet? En studie av ekgrupper planterade tillsammans med björk.

Malin Svensson

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Keywords:	Cluster planting, group planting, broadleaf silviculture, climate adaptations, *Quercus robur, Betula pendula,* oak management, mixed management.

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Abstract

Climate change poses a severe risk to conventional coniferous monocultures in southern Sweden, requiring a management shift toward more resilient broadleaves like oaks (*Quercus* spp.) and birch (*Betula* spp.). However, traditional oak establishment is limited by high initial costs. Here group planting of oak in mixtures with birch offers a cost-effective alternative. Yet, long-term knowledge regarding stand and tree level growth in these mixtures and competitive dynamics remain limited in Scandinavia. This study evaluated how three management intensities affect oak and birch development in a group-planting system in southern Sweden.

An experimental trial established in 2008 in Tönnersjöheden was inventoried in 2021 and 2025 (ages 16 and 20). Three treatments were compared: (T1) Unthinned control; (T2) pre-commercial/ crown thinning around oak crowns; and (T3) intensive value production thinning.

Despite heavily reduced standing volume in the thinned plots and a slightly lower site productivity in T3, statistical analyses only showed some statistically significant differences in oak growth increment across the three treatments. Furthermore, T3 generally promoted larger birch trees and improved oak stem straightness. Overall, the results demonstrate that treatment effects depend on the production objective. The study highlights the potential of group planting of oaks within mixtures of birch as an alternative to traditional row planting, as initial growth and quality variables seem strong.

Keywords: Cluster planting, group planting, broadleaf silviculture, climate adaptations, *Quercus robur, Betula pendula,* oak management, mixed forests

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Abbreviations

BAI	Basal Area Increment
PCT	Pre-Commercial Thinning
DBH	Diameter at Breast Height
ANOVA	Analysis of variance

1. Introduction

Swedish silviculture today is characterised by coniferous monocultures dominated by Scots pine (*Pinus sylvestris* L.*)* and Norway spruce (*Picea abies* (L.) H.Karst) (Riksskogstaxeringen, 2025). This limited species composition poses an economic and ecological risk under the future projected climate scenarios. Given that forest rotations span 50 – 100+ years, there is a risk that current stands will reach their limits as climatic conditions may shift beyond their adaptive capacity before harvest (Schulte et al., 2026). Sweden has experienced a clear shift towards a warmer climate in recent years, increasing the risk and intensity of extreme weather events such as droughts (SMHI, 2026). Spruce is particularly vulnerable to these changes due to its shallow root system (Caudullo et al., 2016). Declining tree vitality further increases susceptibility to other pests and pathogens such as *Heterobasidion annosum* and bark beetle (*Ips typographus)* attacks (Caudullo et al., 2016).

Due to the climate change, tree species are predicted to shift in their distribution range. For spruce, on the one hand, modelled projections indicate a potential drastic reduction in suitable growing sites in Sweden for both a moderate emission scenario (RCP 4.5) and a high emission scenario (RCP 8.5) (Buras & Menzel, 2019). This is particularly true in the southernmost region of Götaland (Mauri et al., 2022). A great proportion of broadleaved tree species, on the other hand, are expected to be favoured by climate change in southern Sweden, with projections under RCP 8.5 indicating increased tree species diversity (Buras & Menzel, 2019). Birch (*Betula* spp.*)* is for example increasingly recognised as an important feature in Swedish forestry due to its rapid growth, ecological value and greater tolerance to climatic variability compared to spruce (Slepetiene et al., 2025, Oksanen, 2021). Also, oaks *(Quercus* spp.) are likely to become even more important with increasing temperatures, as the species demonstrates greater tolerance to drought and relatively warm climates (Nosenko et al., 2025).

A key challenge in Swedish forestry is the mismatch between the current tree species composition and projected climate conditions. There is a need to balance climate adaptation with economically viable management systems. While both oak and birch may represent important components of future forest composition, oak establishment remains costly and presents risks due to browsing pressure and high regeneration cost. At the same time, birch is often undervalued in production systems despite its high growth potential and ecological benefits. This creates a management challenge regarding how to design mixed-species stands where oak can be maintained as a high-value target species while also utilising for example birch as a supporting tree species without competing with oak development.

1.1 Tree species

1.1.1 Oak in Sweden

Pedunculate oak (*Q. robur L.*) is one of the most common oak species in Sweden (Drössler et al., 2012), and has a long history in Swedish forestry, landscape, and culture. Oaks entered Sweden in southern Götaland approximately 9000 years ago (Berglund et al., 1996) and is distributed south of the 'limes Norrlandicus', which marks the northern boundary of the temperate forest zone (Löf et al., 2016). During the 1700s, it was exclusively owned by the Crown, with the purpose of securing timber for naval shipbuilding (Brunet, 2005). Today typical uses include veneer, flooring and barrels for wine, whiskey and sherry (Skogskunskap, 2026). Despite strong demand for hardwood timber in Europe and Asia, where high-quality timber is highly valued, the Swedish sawmill industry for hardwood timber is currently very limited to a few actors mainly processing oak and, to some extent, birch (Skogsstyrelsen, 2025).

Oak is also very valuable from an ecological perspective and is one of the tree species that supports the highest number of host-dependent species (Sundberg et al., 2019). It is a key host for nearly 900 species, of which almost 300 are red-listed, and is additionally utilised by a further nearly 900 species (Sundberg et al., 2019). The number of oak associated species might be attributed to the long lifespan of oaks where it develops several microhabitats such as coarse bark structures (Sundberg et al., 2019).

Oak occurs in both mixed forests and open landscapes and is adaptable to a wide range of soil types, although it generally prefers moist and nutrient-rich soils (Eaton et al., 2016). On good soils, pure oak stands can produce up to 6 m^3 per hectare and year while on poorer and drier soils the growth is much lower with volume growth around 1 m^3 per hectare and year (Löf et al., 2026). In mixed stands in Scandinavia, oaks are commonly found with spruce, in spruce-birch mixes or with pine. Overall, oak is in Sweden mainly found in older stands, with relatively few young pure oak stands (Drössler et al., 2012).

Oak is typically regenerated by planting or sowing (Löf, et al., 2015). Seeding rate for oak should be between 40 – 70 kg of acorns per hectare (Birkedal & Möller Madsen, 2007), although, obtaining high quality seeds can be challenging due to the irregularities of acorn production limiting seed orchards' ability to supply seed at time required by landowners (Löf et al., 2015).

Planting often includes large bare-root seedlings as they are a better option on land where the competing vegetation is high (Löf et al., 2015). Successful seedling regeneration typically includes about 2.000 to 10.000 oak seedlings per hectare (Löf et al., 2026). It is possible to decrease number of seedlings with the use of fast-growing nurse trees. For oak, the nurse seedlings are typically birch and are established at the same time as the oak. With nurse trees present, 2.000 to 3.000

seedlings of oak may be sufficient together with 500 to 1000 nurse seedlings. In addition to reducing the amount of main tree seedlings needed, nurse trees also provide a degree of frost protection (Löf et al., 2015).

The following management is intensive and involves two or three initial pre-commercial thinnings (PCT) aimed at removing poor quality trees and ensure sufficient light availability. Potential future crop trees are selected around the age of 40 to 50 years and includes 50 to 70 future crop trees per hectare. Annual pruning is recommended due to the development of epicormic branches and regular commercial thinnings continue to release the crowns of the selected crop trees to avoid competition. The management cycle is typically finished at a rotation age of 100 to 150 years (Drössler et al., 2012), potentially resulting in very high timber values for oak (Löf et al., 2026).

Although oak appears to be better suited to future climate conditions, partly due to their deep tap root system, which enables access to deeper soil water while also providing greater structural stability against wind (Eaton et al., 2016), this comes at a cost. Regeneration is associated with high establishment costs due to extensive acorn predation and seedling browsing, requiring fenced regeneration areas (Madsen & Löf, 2005). This may also explain the perceived lack of young oak stands in southern Sweden. Identifying efficient and cost-effective oak silvicultural systems therefore remains an important challenge.

1.1.2 Birch in Sweden

Birch is the most common deciduous tree species in Swedish forestry, with silver birch (*B. pendula* Roth.) accounting for about 30 to 50% of the birch inventory in southern Sweden. Birch is a pioneer species with a rapid initial growth and is often the first species to appear on newly disturbed sites (Rytter et al., 2014) due to their high capacity for natural regeneration (Hynynen et al., 2009). In general, birch grows best on fresh nutrient rich soils and requires sufficient growing space to maintain rapid growth with full crown development. Top height can exceed 25 m and is typically reached before 80 years of age. Under northern European conditions, birch can achieve mean annual growth exceeding 10 m^3 per hectare and year at rotation periods of 30 to 60 years (Rytter et al., 2014).

In recent decades there has been a significant shift in interest towards birch and the standing volume of birch in young forests has nearly doubled since the 90s. Birch management has shifted from active removal of birch to the intentional creation of mixed species stands, often with coniferous species (Dahlgren Lidman et al., 2024). Naturally regenerated birch typically occurs in mixed conifer-dominated forests, where it is often managed for pulpwood production (Hynynen et al., 2009). In mixtures with spruce, birch also provides positive effects for biodiversity when compared with spruce monocultures (Felton et al., 2016). In contrast, birch intended for high-quality timber production is typically established in pure stands through planting densities between 1.600 and 2.500 seedlings per hectare. For high-quality timber, large diameter, straight and defect free stems are desired (Hynynen et al., 2009).

Early interventions are required, and PCT is essential to ensure that remaining trees maintain a green crown of at least 50% of the tree height to sustain growth potential. Following PCT, two to three thinnings are typically carried out, focusing on removing low-quality or competing stems to favour high- quality crop trees (Rytter et al., 2014).

Birch wood is strong and versatile, making it valuable for products such as plywood, flooring, furniture, pulp and more recently in bio-based textiles. Traditionally, birch bark has been used for roofing and basketry, while the wood has long been and continues to be, widely valued as firewood (Rytter et al., 2014). Recently it has also become increasingly recognised that birch plays a crucial role in climate mitigation through carbon sequestration and is often undervalued in comparison to conifers (Slepetiene et al., 2025).

1.2 Group planting

Group planting, a variation of the broader concept of cluster planting, is a silvicultural method where trees are established in smaller patches rather than uniform rows to reduce regeneration costs and improve stand. Developed in central Europe during the 80s and 90s, the method was inspired by natural oak regeneration, where trees often occur in irregular clusters (Saha et al., 2012, 2017). The approach aimed to make reforestation of windthrow and clearcut areas more economically and ecologically viable compared to traditional row planting (Saha et al., 2012).

Cluster planting generally includes two main designs, nest planting and group planting, defined by seedling counts and differing spacings. Nest planting uses clusters of 20-30 seedlings with high initial density and has often resulted in poor stem quality due to intense competition between trees (Saha et al., 2012).

Group planting uses a wider initial spacing between seedlings. In Germany, groups commonly consist of 19 to 27 seedlings for oak regeneration, sometimes combined with spruce trainer trees that provide shade to the oak stems for improved stem quality. The groups are established at wider distribution of 80 to 100 groups per hectare, with centre-to-centre spacing ranging from 10 x 10 m to 10 x 12 m (Saha et al., 2012). The clusters in both planting methods are spaced at distances corresponding to the target density of future crop trees (Saha et al., 2017). Concentration of clusters leaves open areas in the stand for natural regeneration of secondary species, which increases overall stand biodiversity (Saha et al., 2012).

1.3 Aim of study and research questions

Despite both oak and birch being considered important future tree species in southern Swedish forestry, there is still limited knowledge on how to successfully establish and manage them in mixed stands.

This study aims to investigate group planting as an alternative to traditional regeneration methods for producing high-quality oak in mixtures with birch. While birch is recognised as a potential nurse and admixture species, its role may vary between facilitation and competition depending on management strategy and stand structure. However, it remains unclear how different proportions of birch in mixed stands with oak influence oak growth and quality at both stand and individual tree level. Addressing this knowledge gap is relevant for developing silvicultural systems that promote both high-quality oak timber production and more climate adapted mixed forests at potentially reduced establishment costs. The following research questions form the basis of the study:

1. How does different group planting treatments affect the growth of oak and birch on stand level and individual tree level?

2. How does different group planting treatments affect the quality of oak and birch on stand level and individual tree level?

2. Materials and Methods

2.1 Study site

The site for the trial was situated in Tönnersjöheden, outside of Halmstad in Southern Sweden (Figure 2). The trial was carried out by SLU on a site owned by Sveaskog. The soils were sandy moraines over granitic migmatitic gneiss and granite (SGU, 2021: Soil types 1:25 000-1:100 000, Bedrock 1:1 million), with a fresh soil moisture class (Department of forest ecology and management, n.d.). The mean annual temperature in this area is + 6.7°C with a mean annual precipitation of 1158 mm. The vegetation period is approximately 215 days with a mean temperature of + 12.3°C and mean precipitation of 523.4 mm. Site index for oak varied between 24-30 at age 20 between plots (Table 1). The previous forest rotation consisted of a planted spruce stand which was wind damaged in 2005 and harvested in 2006.

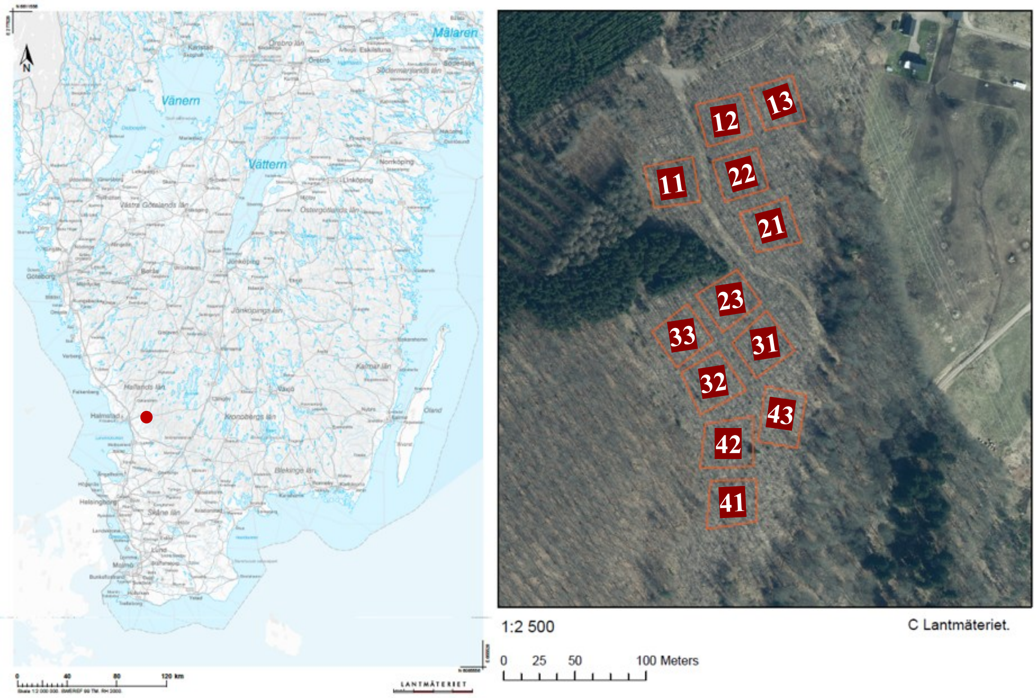

Figure 1: Maps showing site of the experiment. To the left: the red dot marks the location of the experiment © Lantmäteriet. To the right: Treatment Layout

2.2 Experimental design and silvicultural treatments

The objective of the experiment was to examine silvicultural treatments, volume production, and wood quality when oak is planted in groups in mixtures with birch. The overall aim is to assess the potential for producing high-quality oak timber under different stand compositions of birch. The experiment was established in 2008 and consisted of four blocks, each containing three plots with one of three different treatments. Each plot measured 30 x 33 m (net plot) with a surrounding 5 m buffer zone. In the spring of 2008, the site was soil scarified and fenced. In May of 2008, the plots were planted with birch (2-year-old, Asarum seed orchard) and groups of 6 oaks (2-year-old, provenance Visingsö). Both species were planted with a spacing of 2.0 x 2.5 m and the distance between oak groups were 10x10 m (Figure 2). This resulted in approximately 2000 birches per hectare and about 600 oak trees in 100 groups per hectare. In July of 2014, cleaning of birch was conducted around the oaks and in April of 2019, Pre-Commercial Thinning (PCT) of birch was performed (Johansson, 2021).

The three different treatments were as follows:

I. Un-thinned Control with no active cleaning or thinning during the rotation period. Secondary species were removed at establishment and two oak crop trees per group were selected as future crop trees.
II. Mixed planting of oak and birch with oak as the final goal. Birch will act as nurse tree for as short period as possible. Thinning, and later, crown thinning was carried out around the oak groups so that the upper crown of the oaks had at least 1 m of free space from the nearest birch. The timing and intensity of the interventions were adjusted successively according to stand development. Secondary species were removed at establishment and two oak crop trees per group were selected as future crop trees.
III. Mixed planting of oak and birch with oak as final goal and value production of birch during parts of the rotation. Secondary tree species were removed at establishment. There was selection of 400 birch crop trees per hectare and two oak crop trees per group were selected.

The two selected oak crop trees were pruned on half of each plot in all treatments. In Treatment 3, 200 birch trees per hectare were pruned to a height of 5-6 m on half the plots. The treatments were randomly assigned to each plot within a block.

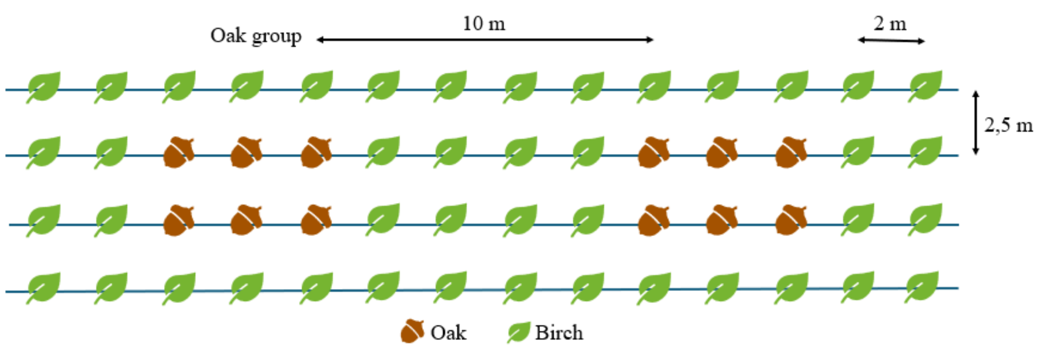

Figure 2: Group planting design

2.3 Data

Measurements were conducted on two occasions, in July and August of 2021 and in September of 2025 (Table 1), 13 and 17 years after planting. All oaks and the 400 birches chosen as future crop trees in treatment 3 were permanently numbered to enable monitoring on individual tree level over time. All other birches were measured without individual numbering to enable analyses on stand level.

Table 1: Overview of experiment. Data refers to the latest inventory made in 2025. Tree DBH and height are presented as mean values.

Block	Treat-ments	Site Index at age 20 (m)	Height Oak (m)	Height Birch (m)	Diameter Oak (cm)	Diameter Birch (cm)	Oak Stems per ha	Birch Stems per ha	Basal Area Oak (m2/ha)	Basal Area Birch (m2/ha)	Volume Oak (m3/ha)	Volume Birch (m3/ha)
1	1	30	8.7	14.5	6.9	12.4	682	1071	2.6	12.9	11.3	78.1
	2	30	8.9	13.3	7.3	11.9	464	1090	1.9	12.2	8.5	68.0
	3	25	9.2	13.9	8.1	15	517	424	2.7	7.5	11.8	42.2
2	1	30	8.8	14.4	6.4	12.5	423	1221	1.4	14.9	6.1	89.5
	2	26	7.8	13.6	6.2	11.7	370	1070	1.1	11.5	4.4	65.4
	3	25	7.4	14.1	6.3	15.4	478	411	1.5	7.6	5.7	43.5
3	1	26	7.6	13.7	5.8	11.8	479	1361	1.3	14.9	5.0	85.7
	2	26	7.6	13.1	6.1	12.0	447	1002	1.3	11.4	5.2	62.2
	3	25	7.0	14.6	5.4	15.3	429	480	1.0	8.8	3.5	51.7
4	1	26	7.1	12.9	6.1	11.8	455	1050	1.3	11.4	4.9	61.8
	2	27	7.7	12.6	6.6	11.1	410	982	1.4	9.4	5.4	50.3
	3	24	6.9	13.0	7.5	15.2	484	375	2.2	6.8	7.3	35.7

2.3.1 Growth variables

All trees have been cross calipered for the measurement of diameter at breast height (DBH) in millimetres, first with the caliper towards the mark and the second with the caliper 90° from the mark. Height measurements in meter were taken for all oaks in all treatments and for the numbered birches in treatment 3.

2.3.2 Quality assessment

Quality assessments were made in October 2025. One to two oaks in each oak group were chosen as potential future crop trees and assessed for quality. These crop trees were chosen based on growth performance and initial visual assessment of overall tree quality. Several variables were measured describing branches, crown base height and stem straightness (Figure 3). The quality assessments were based on the following variables in six categories:

I. Tree height and crown base height, measured in dm.
II. Stem straightness was assessed on the lower 3 m of the stem as deviation from a straight line from top to root on the trunk in the following classes (Figure 3):

1. Straight = maximum deviation of 0.5 stem diameter from the straight line.
2. Slightly crooked = maximum deviation of 1 stem diameter from the straight line.
3. Crooked = deviation of more than 1 stem diameter from the straight line.

III. Forking was measured in dm as height above ground to all forks on the stem.

IV. Spike knots were counted as number of spike knots in three stem sections:
1. Upper part of the living crown
2. Lower part of the living crown
3. Beneath the crown base

V. Branch thickness included diameter of the thickest branch on the stem at 1-2 m above ground measured in mm.

VI. Number of branches included number of healthy and dead branches on the stem at 1-2 m above ground, including epicormic branches in the same stem section. Epicormic branches were counted individually up to five and thereafter recorded in classes (6-10, 11-20, 21-30, etc).

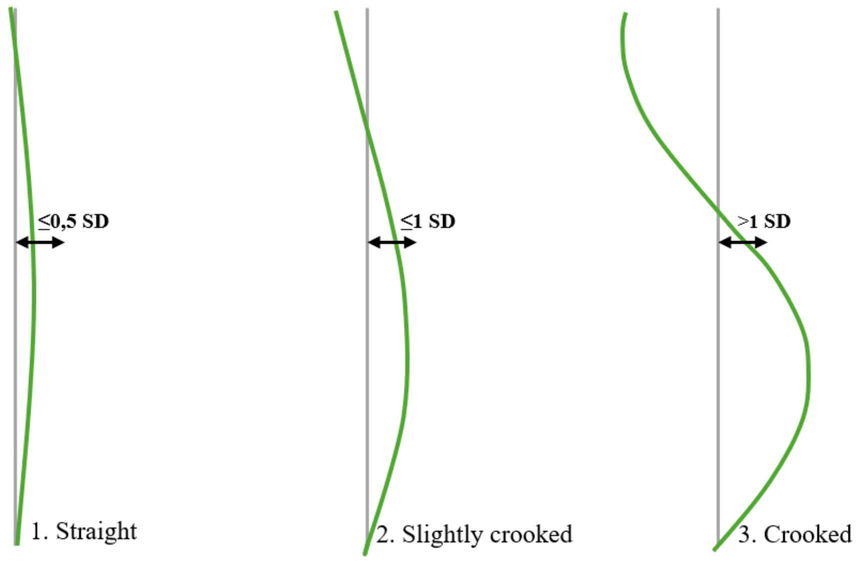

Figure 3: Classification of Stem Straightness. SD = Stem Diameter

2.4 Data analysis

Analysis of collected data was done in two parts. Firstly, the growth traits volume increment and basal area increment (BAI) were calculated on both individual tree level and on stand level between the first and second revision. Secondly, the quality parameters were calculated to see if there were quality differences between the treatments. R statistical Software was used to analyse the data as well as to develop graphs and calculate statistically significant differences between treatments (R Core Team, 2026). Package used for drawing graphs were ggplot2 (Wickham, 2016).

2.4.1 Data analysis of individual tree growth

Mean DBH was calculated for each block and treatment before any statistical analysis and volume was calculated according to SLU's Field data system for forestry field trials (Karlsson et al., 2012, s. 12). BAI was calculated using the following formula for each individual tree:

$$BAI = \frac{\pi \cdot DBH_{rev2}^2}{4} - \frac{\pi \cdot DBH_{rev1}^2}{4}$$

where rev2 was the revision from 2025 and rev1 the revision from 2021. Volume increment was calculated as the difference in stand volume between rev2 and rev1. Mean increment values were then calculated for each plot.

Treatment effects on plot level mean BAI and volume increment were assessed using a two-way analysis of variance (ANOVA) including the treatment and block as variables to account for differences between blocks. Tukey HSD post-hoc test were performed when significant differences were detected. Differences between treatments were considered significant if $p < 0.05$. One measurement was removed from the analysis due to a strong decrease in diameter between revisions, which indicated a measurement error.

2.4.2 Stand level data analysis

For stand level analysis, individual tree level values were scaled to per hectare using the plot area as follows:

$$X_{ha} = (\sum X) \cdot \frac{10000}{A_{Plot}}$$

where X represents either BAI or volume increment and $A_{Plot} = 990$ m^2. An ANOVA was applied to test for treatment effects with block included to account for differences between blocks for both oak and birch followed by a Tukey HSD post-hoc test when significant differences were detected.

To evaluate production capacity of the site, stand level site productivity (bonitet, m^3sk per hectare and year[1]) was calculated. The dominant height and age data collected were processed using the digital forestry tool at skogskunskap, "Bonitet – skogshögskolans system" (Skogskunskap, 2024). This tool applies the standardised Swedish site index curves to project the long-term average growth potential for oak and birch at stand level (Skogskunskap, 2024). This was applied for all plots of oak and for the birch plots in treatment 3, as the other treatments were missing values for dominant height.

2.4.3 Data analysis of oak quality traits

The analysed quality traits were crown base, branch thickness and stem straightness. These variables represent key quality parameters for mature oak crop trees, characterised by a straight stem, free of branches up to approximately one third of total tree height. Stem straightness was recorded for individual trees and treated as an ordinal variable describing stem form quality. Because stem straightness is a ranked score rather than a continuous measurement, statistical methods based on ranks were used instead of assuming equal spacing between values. Differences among treatments were assessed using a Kruskal-Wallis test, followed by post-hoc pairwise comparisons using Conover-Iman tests, when significant effects were detected.

Treatment effect of crown base height and branch thickness were analysed using ANOVA with block included to account for differences between blocks.

2.4.4 Data analysis of birch quality traits

Birch quality was assessed based on DBH distribution and occurrence of stem damage. These variables were chosen as no individual quality assessment were made for birch, whereas the main objective of high-quality birch timber includes large diameter, and damage free stems. For this analysis, individual tree DBH measurements from revision 2 (2025) were used to represent the current stand structure. Trees were grouped according to treatment, and differences in DBH among treatments were analysed at tree level.

An ANOVA including block were performed to account for differences between blocks was used to test for differences in mean DBH between treatments. When significant treatment effects were detected, a Tukey HSD post-hoc test were applied to identify pairwise differences between treatments.

Tree damage was assessed using recorded damage codes and. Trees with a recorded value of zero were considered undamaged, while damage codes represented different types of stem defects. Two injury codes (81 and 172) were

[1] Reference value for oak and birch was presented in m^3 per hectare and year which were assumed to be comparable with the m^3sk per hectare and year presented for bonitet at skogskunskap, representing total stem volume over bark.

removed due to missing classification information. Damage frequency was summarised as percentages and were only assessed in treatment 3, as this was the only treatment with permanently marked birch trees.

2.4.5 Data analysis of oak tree mortality

Tree mortality was assessed for oak during revision 2 using the recorded damage codes. Trees assigned the code 70 were classified as dead. Mortality was calculated as the proportion of dead trees relative to the total number of trees assessed within each treatment. As there were no mortality recorded for revision 1, mortality analysis was only based on observations from revision 2.

3. Results

3.1 Growth increments

3.1.1 Growth increment of individual tree level

Mean plot BAI differed significantly between treatments (Figure 4), where treatment 3 had a significant higher BAI than treatment 1 (p = 0.034). There were no significant differences between treatments 1 and 2 or between treatment 2 and 3 ($p > 0.05$). Individual tree BAI distribution can be seen in figure A1 (Appendix 1) Mean plot volume increment for oak did not vary significantly between treatments (Figure A3, Appendix 1). Individual tree volume increment distribution can be seen in figure A2 (Appendix 1).

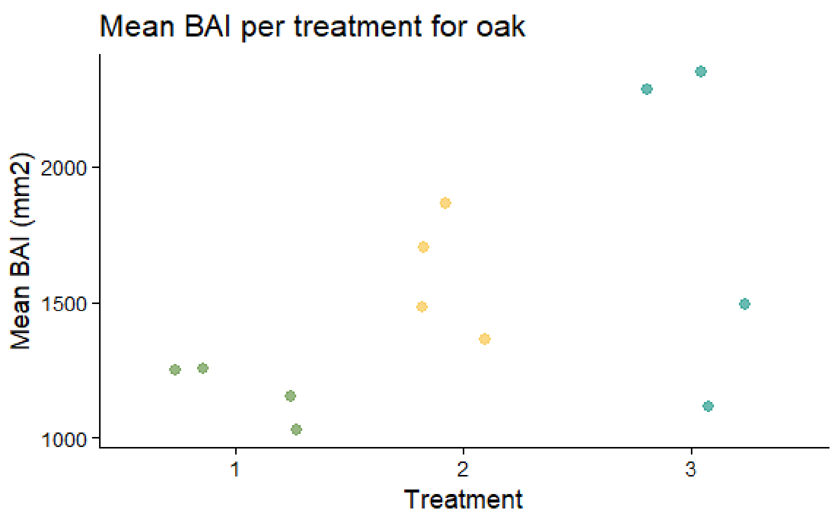

Figure 4: Mean plot BAI for oak per treatment where each point represents a plot.

3.1.2 Growth increment on stand level

On stand level, birch consistently showed higher BAI than oak. Birch BAI ranged from 3.18 to 5.7 m^2 per hectare while oak ranged between 0.5 and 1.2 m^2 per hectare (Figure 5). There was no statistical significance of BAI between the treatments for oak, however there were significant differences for birch. Treatment 3 showed significantly lower stand level birch BAI than both treatment 1 (p = 0.003) and treatment 2 (p = 0.019) . However, there were no statistically significant differences between treatment 1 and 2 (Table 2).

Table 2: p-values from Tukey HSD post-hoc comparisons of birch BAI between treatments. ***Bold = significant differences.***

P-values for birch BAI per hectare			
	T1	T2	T3
T1			
T2	0.193		
T3	**0.003**	**0.019**	

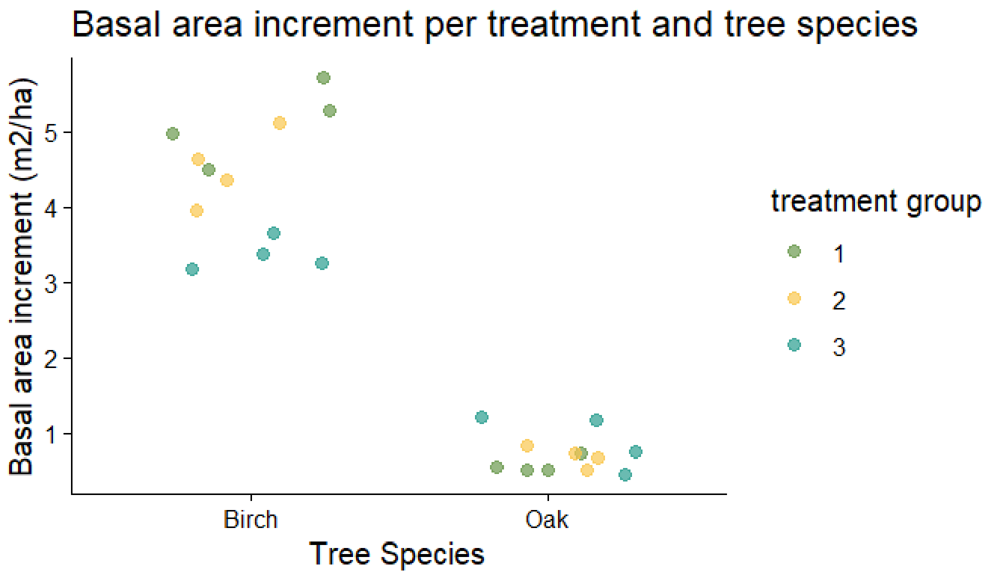

Figure 5: Basal area increments per treatment and tree species per hectare.

Volume increment for oak ranged between 1.8 to 6.3 m^3 per hectare between revisions (Figure 6). Birch consistently showed higher volume increment than oak (Figure 6), ranging from 18.6 to 42.8 m^3 per hectare between revisions. There were no statistically significant differences for stand level oak volume increment between treatments. There was a significant difference on stand level birch volume increment between treatments. Treatment 3 had significantly lower volume than both treatment 1 ($p = 0.0014$) and treatment 2 ($p = 0.023$). There were no significant differences between treatments 1 and 2 (Table 3).

Table 3: p-values from Tukey HSD post-hoc comparisons of birch volume increment between treatments on stand level. ***Bold = significant differences.***

P-values for birch volume increment per hectare			
	T1	T2	T3
T1			
T2	0.064		
T3	**0.0014**	**0.023**	

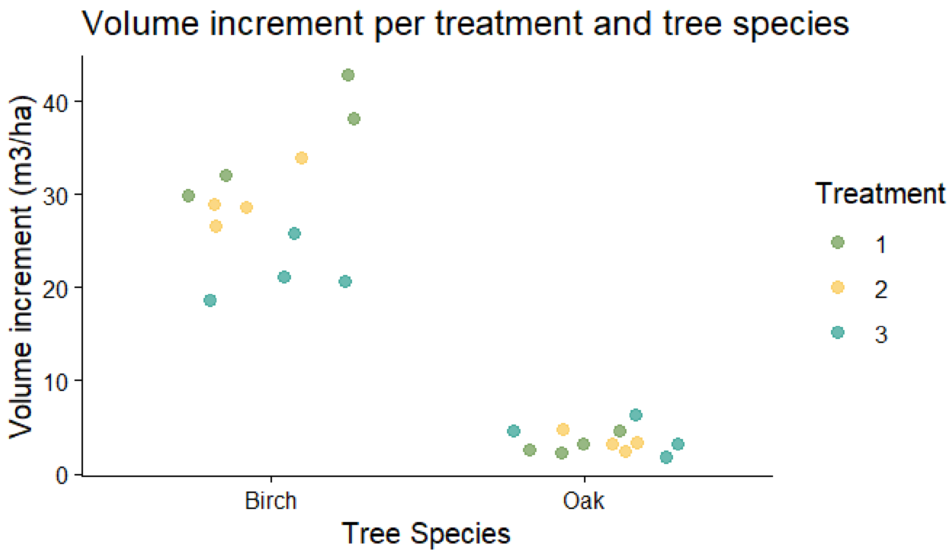

Figure 6: Volume increment per tree species and treatment per hectare

Estimated oak site productivity differed slightly between treatments (Table 4). Treatment 1 and 2 showed similar site productivity values, while treatment 3 showed lower estimated values (Table 4). Birch site productivity in treatment 3 ranged from 5.3 – 6.5 m^3sk.

Table 4: Estimated site productivity per treatment calculated via skogskunskap.

	Oak m3sk/ha and year	Birch m3sk/ha and year
T1	5.2 - 5.9	-
T2	5.2 - 5.9	-
T3	4.6	5.3 - 6.5

3.2 Oak quality traits

Stem straightness varied between treatments. In treatment 3 69% of the stems had stem straightness class 1, meaning straight stems, in comparison to treatment 1 and 2 which had 48% and 43% straightness class 1 respectively (Figure 7). There was a statistically significant difference in stem straightness between treatment 1 and 3 (p = 0.045) and an even bigger difference between treatment 2 and 3 (p = 0.0062) as can be seen in table 5. However, there were no statistically significant difference between treatment 1 and 2 (Table 5).

Crown base height and branch thickness did not vary much between treatments (Figure A4 & A5 in appendix 2) and did not express any significant differences.

Table 5: p-values from Conover-Iman post-hoc pairwise comparisons of stem straightness between treatments. ***Bold = significant differences***

P-values for stem straightness			
	T1	T2	T3
T1			
T2	0.1950		
T3	**0.0450**	**0.0062**	

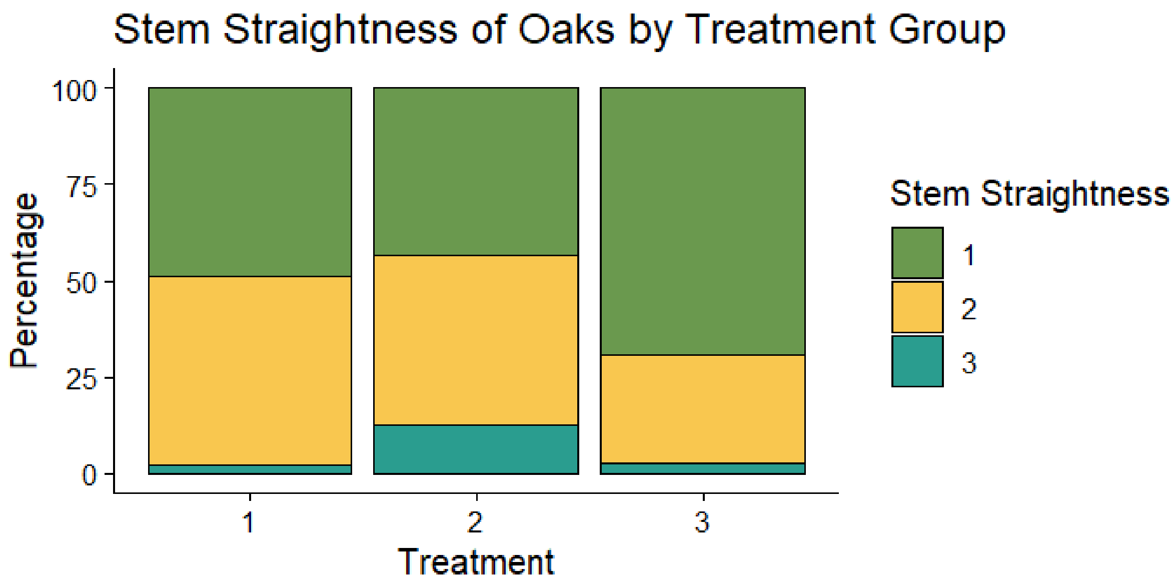

Figure 7: Stem straightness within the different treatments in percentage where stem straightness 1 is classified as straight stems

3.3 Birch quality traits

DBH distribution for birch varied among treatments with fewer but larger trees in treatment 3 compared to treatment 1 and 2 (Figure 8). All treatments differed significantly between each other. Treatment 2 had significantly smaller trees than treatment 1, while treatment 3 had significantly larger trees than both treatment 1 and 2 (Table 6).

Table 6: p-values from Tukey HSD post-hoc comparisons of mean DBH between treatments. ***Bold = significant differences,*** *and parentheses show mean differences.*

P-values for DBH (diff).			
	T1	T2	T3
T1		**0.042 (-4.94)**	***p*** **< 0.001 (+33.79)**
T2			***p*** **< 0.001 (+38.73)**
T3			

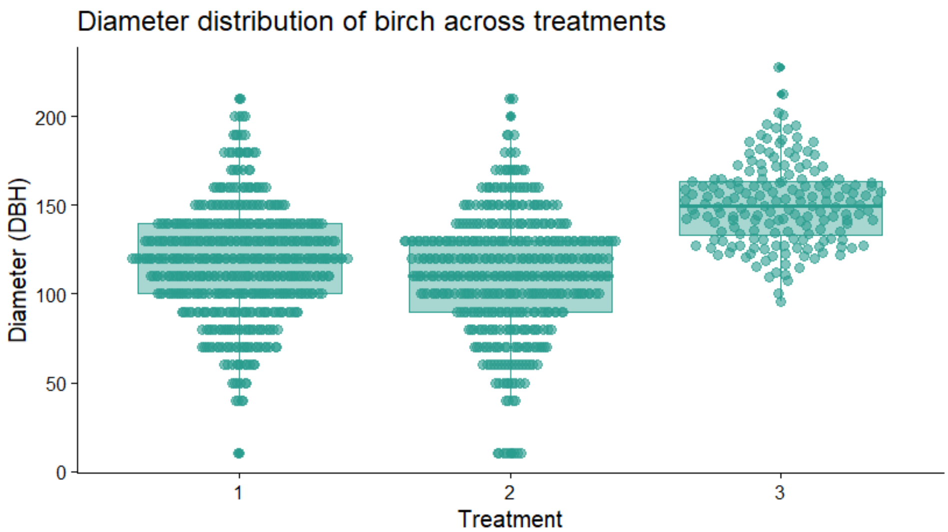

Figure 8: Diameter distribution of birch across treatments where every point represents an individual tree.

Damage assessment in birch was restricted to treatment 3 (Figure A6 in Appendix 2). The most common damage type was wolf branches, where wolf branches in the centre section of the stem were observed in 27 trees (16%). Overall, 75% of trees showed no recorded damages.

3.4 Oak tree mortality

Oak survival was high across all treatments ranging between 94% - 95%. There were only minor observed differences in mortality between treatments (Figure A7 in Appendix 3)

4. Discussion

4.1 Growth responses of oak and birch

Growth increments showed that birch consistently exhibited higher BAI and volume increments than oak at this stage of stand development. This pattern is expected and indicates the different growth dynamics of the species, given the pioneer characteristics and rapid early growth of birch (Hynynen et al., 2009, Rytter et al., 2014).

Overall, the results indicate that treatment effects on oak growth were limited. Oak volume increment did not vary significantly on either plot level or stand level. However, the mean oak BAI for individual trees differed significantly between treatments, where treatment 3 showed higher increments than treatment 1. This may indicate that the lower birch density reduces the competition enough to already promote individual oak growth in treatment 3, although these differences are not yet detectable in volume increments or stand level BAI. Therefore, these results only provide limited evidence that any treatment increase the yield of oak considerably at this stage in the rotation.

In contrast, treatment differences were more evident for birch. Individual tree level growth assessment could not be conducted for birch in treatments 1 and 2 as trees were not permanently marked. However, stand level BAI and volume increment analysis indicated higher overall birch productivity in treatments 1 and 2 compared to treatment 3. An important factor influencing this can be explained by the differences in birch density between treatment 3 and the two denser treatment 1 and 2 (Table 1). The lower birch density in treatment 3 likely reduced the competition for resources, which may also explain the higher oak BAI observed in this treatment. At the same time, treatment 3 produced the highest mean birch DBH, suggesting the development of fewer but larger birch trees under this treatment while treatments 1 and 2 maintained higher overall stand productivity and birch yield.

The lack of significant differences between treatments 1 and 2 for either oak or birch suggests that the additional management interventions in treatment 2 do not appear to provide additional production benefits compared to treatment 1. At this stage of stand development, treatment 1 appears to achieve similar production outcomes without the additional management costs involved in treatment 2.

The estimated bonitet values observed in the plots ranged from 4.6 and 5.9 m^3sk per hectare and year (Table 4), which falls within the productivity ranges reported for productive oak stands in Sweden, where growth may range between approximately 1 and 6 m^3 per hectare and year depending on site conditions (Löf et al., 2026). Although, these reference values mainly refer to pure oak stands, the results suggest that oak established in group plantings with birch can maintain productivity levels comparable to the higher reported scale of pure oak stands.

Although treatment 3 had lower stand density (Table 1) and lower estimated site productivity (Table 4), oak growth remained comparable to the denser treatments. Treatment 3 even showed significant higher mean BAI compared to treatment 1, possibly due to reduced competition from birch. In addition, treatment 3 produced straighter oak stems and larger birch diameters, suggesting that lower stand density may favour individual tree development and timber quality rather than maximising total stand level production.

While previous research has shown that birch can negatively affect diameter and height growth (Rock et al., 2004, Liziniewicz et al., 2016), no clear treatment effects were observed for oak production in the present study at age 20. This is partly consistent with observations by Rock et al. (2004) who investigated the influence of birch on relatively young oaks (approximately 8-9 years old) growing in clusters. Their study showed that competition from birch had weaker effects on diameter and height growth in smaller oaks, while negative impacts became more pronounced in stands with larger oaks. Furthermore, Saha et al., (2012), in a meta-analysis of oak stands aged between 10-26 years, found that growth of oak in group plantings were generally comparable to traditional row plantings. This indicates that differences in stand structure do not necessarily mean reduced oak growth in early stages of stand development.

4.2 Effects of treatments on quality

While there generally were limited treatment effects on oak growth, the treatment effects were more obvious in terms of stem quality. Stem straightness for oak differed significantly between treatments, with treatment 3 showing the highest proportion of straight stems (69%) and significant differences compared to treatment 1 and 2. In contrast, there were no statistical differences between treatment 1 (49% straight stems) and 2 (44% straight stems). This suggests that silvicultural treatment can influence quality traits such as stem form even when growth responses are less distinct.

Similar patterns were reported by Rock et al. (2004), who demonstrated that oak stem quality improves and likelihood of stem deformation decreases with increasing distances to neighbouring birch. Their findings further suggests that quality traits such as stem form and shifting crown centres may respond earlier to birch competition than standard growth variables.

While Saha et al. (2012, 2017) found that group plantings were superior to traditional row plantings for producing high-quality oak, they largely connected this to the presence of surrounding “trainer” trees that provided side-shade and improved stem quality. In contrast to Saha et al. (2012) where groups typically had a few trainer trees in close proximity to the oak, the present study examined the effects of extended amounts of birch around the oak group, therefore testing the threshold for optimal density, however direct comparisons of pure oak stands were not included in this study.

Saha et al. (2017) found that trainer trees can improve oak quality, but if densities become too high, they might instead act as strong competitors. This may help explain why lower birch densities in treatment 3 resulted in straighter oak stems, as the beneficial effects of birch remained without too much competition. Furthermore, Rock et al. (2004) concluded that shifts in crown centre may act as an early sign of increasing competition in oak stands and could help determine when neighbouring competitor trees should be removed.

In contrast, crown base height and branch thickness showed no clear treatment effects. This may suggest that not all quality traits respond equally to management intensity and silvicultural treatments. It may also be too early in the rotation for the treatment to have effect on these quality traits.

Birch quality traits also differed between treatments. Since large diameter and damage-free stems are the main quality traits in birch production, the significantly larger DBH observed in treatment 3 suggests more favourable conditions for producing higher-quality birch timber. The larger diameter could, however, also be the result of a thinning-from-below that was conducted in the stands, where smaller birches were removed.

Stem damage observations were only available for treatment 3, where 75% of stems were classified as damage free. Since trees in treatment 1 and 2 were not permanently numbered, comparing damage assessment between treatments were not possible. Therefore, no conclusions regarding treatment effects on stem damage can be made.

4.3 Implications for management

Overall, the treatments preformed broadly similar outcomes, with indications that treatment 3 favoured plot development. Treatment 3 resulted in significantly higher mean plot level BAI, improved oak stem straightness and larger birch diameters, indicating potential benefits for timber quality. In contrast, treatments 1 and 2 maintained significantly higher stand level birch BAI and volume production. However, these results should be interpreted with caution and require further follow up and observations. In addition, the study only evaluated oak groups within different densities of birch. Comparing the growth and quality of oaks established in group plantings with those established using traditional row planting would be valuable for assessing wether similar timber quality can be achieved at lower planting densities and therefore also at a potentially reduced establishment cost.

Suggested management recommendations may therefore depend on the production objective. If the combined production of quality oak and birch is prioritised, treatment 3 appears most favourable based on oak stem form and birch diameter development. However, if higher total volume production is the primary objective, treatments 1 and 2 may be preferred due to higher stand level growth increments. Given the lack of clear differences between treatments 1 and 2, the control treatment may be the most economically viable alternative, as it produced similar outcomes as treatment 2 without the extra interventions.

In relation to Rock et al.'s (2004) conclusion about crown shifting, the lower amount of straight stems treatment 1 and 2 may indicate high levels of competition on the oaks from birch, suggesting that thinnings may need to be performed to improve individual tree quality.

4.4 Limitations and future research

To draw definitive conclusions for future management from this study, this experiment needs to be tracked over a longer part of the rotation. Furthermore, as the treatments are grouped over a relatively small area there is a risk that the results are site specific. It would therefore be desirable to replicate the experiment across multiple sites to validate these findings for future management of oaks planted in groups. However, these initial results may provide valuable early insights for future management.

5. Conclusions

This study aimed to gather insights regarding if high-quality oak can be produced at lower planting densities, and the results partly supported this assumption. With increasing temperatures and greater risk of future drought, oak represents a viable tree species for future forest management due to its adaptability to changing climatic conditions and stability. The results indicates that oak volume production can be maintained in mixed stands at lower oak densities while preserving good individual tree quality. At this early stage of the rotation, treatment effects were more evident in quality traits than in growth, however this might change as the stand matures.

The results suggests that lower density group planting systems may provide a cost-efficient alternative for oak establishment without negatively affecting early oak growth. Overall, the lower density treatment maintained comparable oak growth despite lower stand density and estimated site bonitet, while also improving stem quality characteristics in both oak and birch, although at the cost of lower total stand level production.

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Popular science summary

Climate change is creating major challenges for Swedish forestry with increasing risk of extreme weathers including droughts. Many forests in southern Sweden are dominated by Norway spruce, a tree species that is vulnerable to drought and storms. As a result, interest is growing in alternative tree species that may be better adapted to future climate conditions. Oak and birch are two promising candidates, but establishing oak stands is often expensive because large numbers of seedlings are required and young oaks need intensive management and protection.

This study investigated whether high-quality oak timber can be produced at lower planting densities using a method called group planting. This means that instead of planting oak trees evenly in rows across a site, groups of six oaks are planted together and surrounded by birch. This is a way to reduce the number of oak seedlings required while the birch also provides shelter for the oak during the establishment phase. The experiment, established in southern Sweden in 2008, compared three different management strategies that varied in thinning intensity and the amount of birch left around the oak groups.

The results showed that oak growth was largely similar across all treatments, despite large differences in stand density and management intensities. However, the most intensive thinning produced straighter oak stems, which is an important characteristic for future timber quality. Oaks in this treatment also showed higher basal area increment. Birch responded differently, with the most intensive treatment producing fewer but larger trees. In contrast, denser stands produced more total wood volume but did not improve quality variables.

These findings suggest that group planting can be a promising alternative to traditional oak establishment methods. By using fewer oak seedlings and combining them with birch, forest owners may be able to reduce establishment costs while still achieving good growth and timber quality. Although, the experiment is still relatively young and long-term monitoring is needed, the results indicate that mixed oak and birch stands could play an important role in creating more climate adapted and high-quality forests in southern Sweden.

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Thank you to Ulf Johansson for providing all the necessary information for this experiment.

Appendix 1. Oak growth increment, individual tree level

This appendix includes graphs of growth increment for oak per treatment on individual tree level.

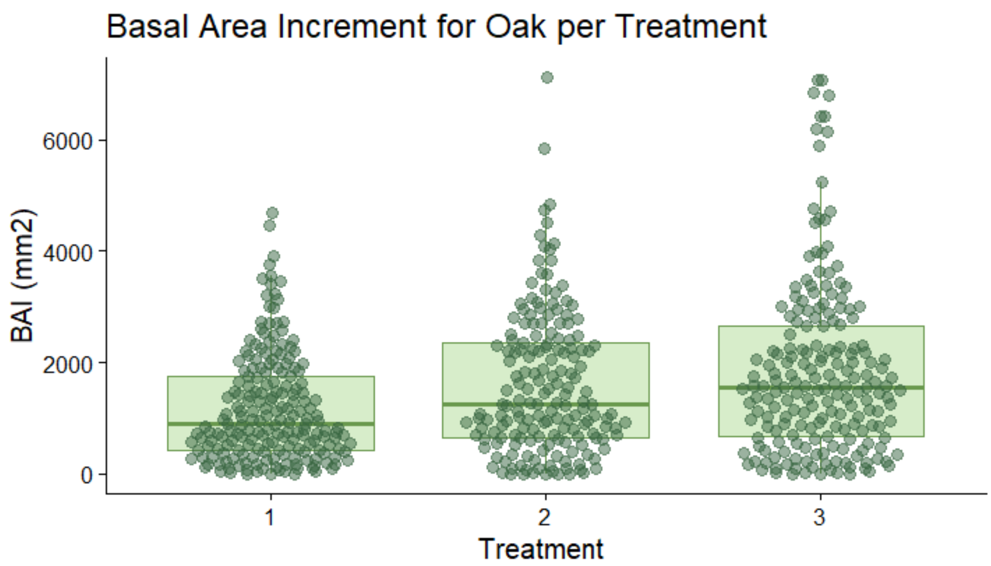

Figure A 1: Basal Area Increment for oak per treatment on individual tree level where each point represents an individual tree.

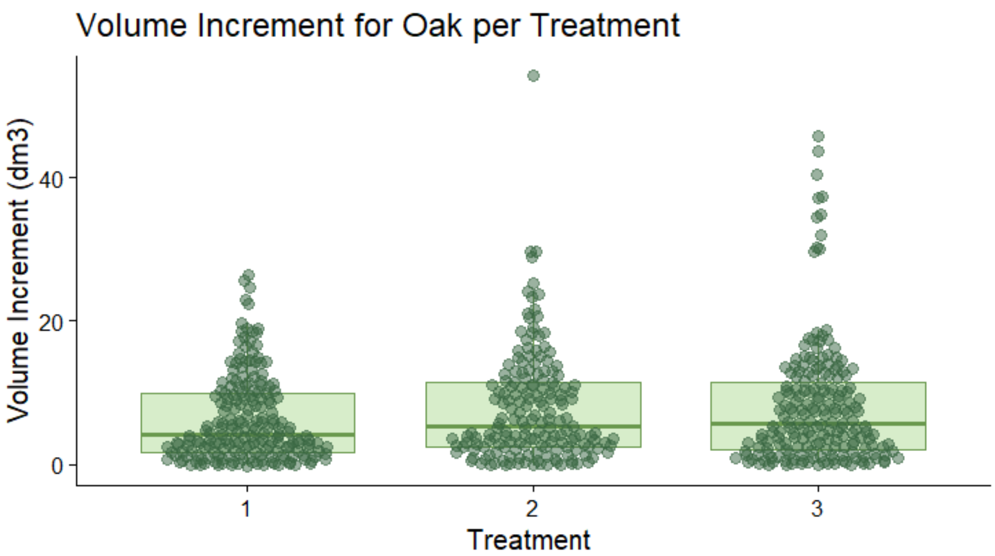

Figure A 2: Volume increment for oak per treatment on tree level where each point represents an individual tree

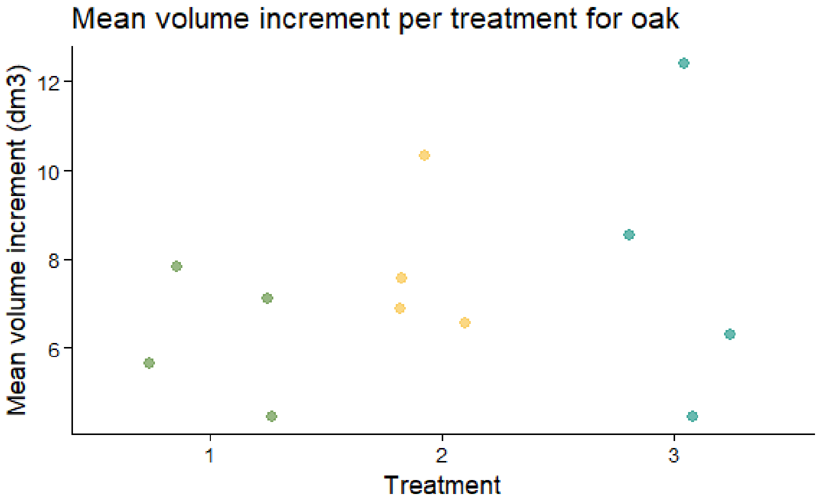

Figure A 3: Mean plot volume increment for oak, where each point represents a plot.

Appendix 2. Quality graphs

This appendix includes additional quality graphs for oak and birch.

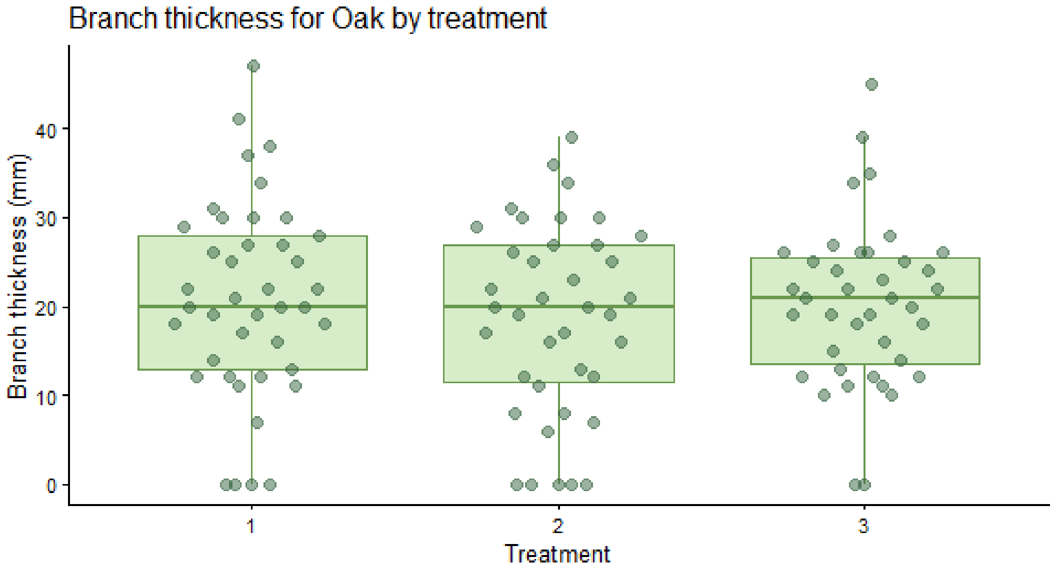

Figure A 4: Thickness of the coarsest oak branch on the stem 1-2 m above ground.

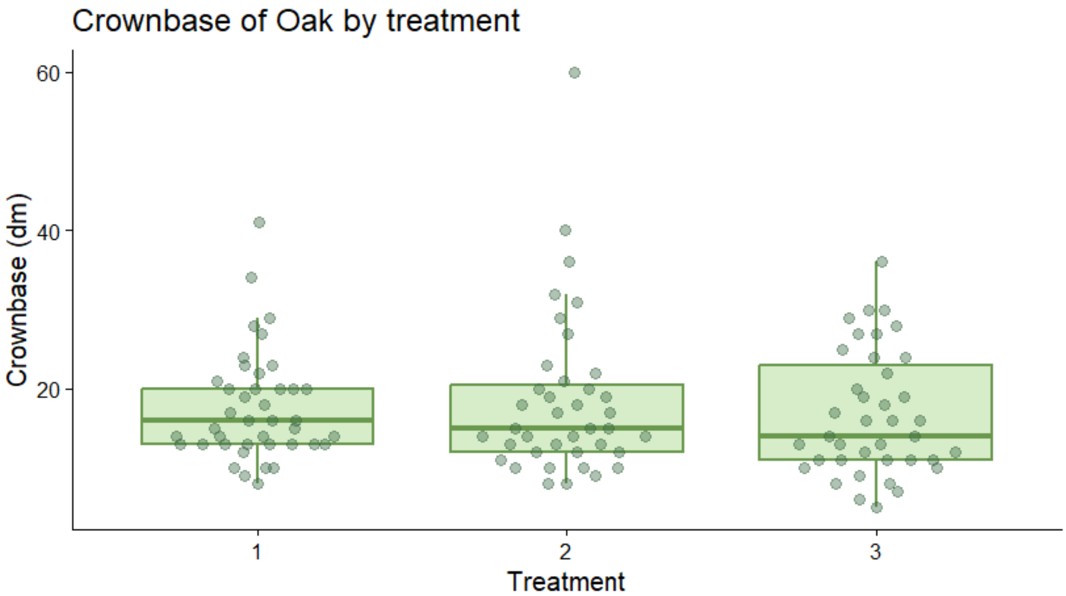

Figure A 5: Height of crown base for oak in the different treatments.

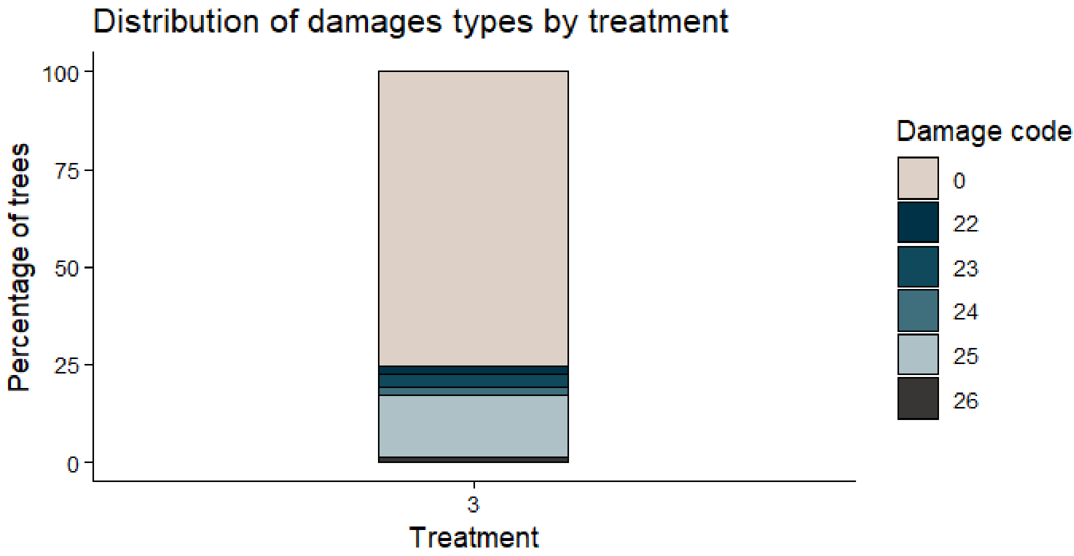

Figure A 6: Tree damage distribution within treatment 3 in percentage. Damage code classifications: 22 = Fork in the centre section of the stem (above 1/3 and below 2/3), 23 = Fork in the top section of the stem above 2/3), 24 = Wolf branch in the root section of the stem (below 1/3), 25 = 25 Wolf branch in the centre section of the stem (above 1/3 and below 2/3) & 26 = Wolf branch in the top section of the stem

Appendix 3. Oak mortality

This appendix includes a graph regarding oak mortality.

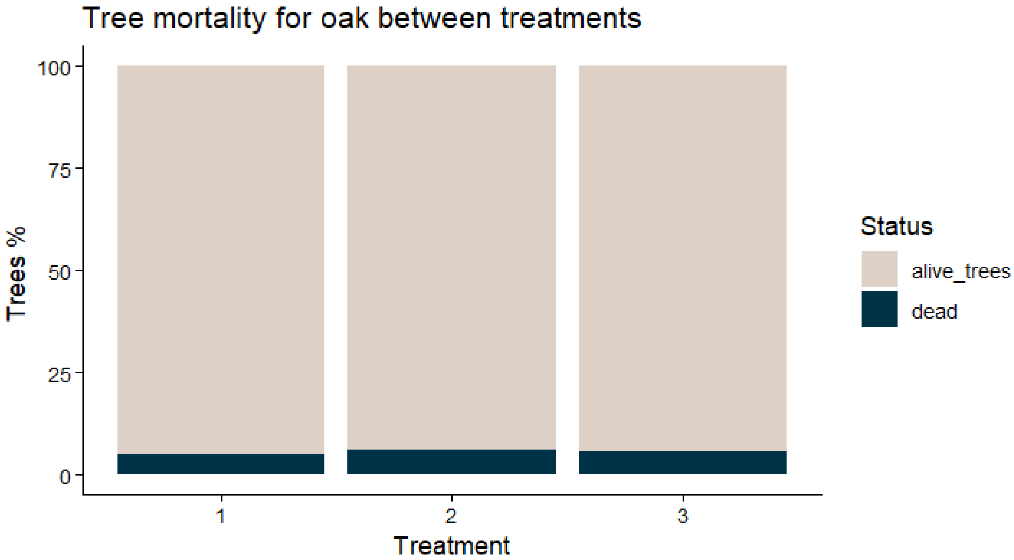

Figure A 7: Tree mortality in oaks between treatments in percentage.

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