Development of planted oaks in mixed species stands - 20 years after the storm Gudrun

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Utveckling av planterade ekar i blandskogar – 20 år efter stormen Gudrun

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Abstract

The study focuses on the early development of planted pedunculate oak (*Quercus robur* L.) in mixed broadleaf stands established on sites previously dominated by Norway spruce (*Picea abies)*. Following the large-scale windthrow caused by the storm Gudrun in 2005, there were strong incentives to create more diverse and climate-adapted forests by spreading the risk among more species than spruce and pine. As a part of this effort, Sveaskog – the Swedish state-owned forest company – decided to plant 10% of their storm-damaged area (southern Sweden) with different broadleaf species, among them oak.

This thesis aimed to assess how different silvicultural strategies – precommercial-thinning, planting method (group vs. spot-wise) and fencing – influenced oak growth performance after 20 years of development. Field data were collected from a selection of Sveaskog's stands, and oak trees were measured for survival, growth (height, DBH, crown ratio, crown volume), and quality. Statistical analysis included both non-parametric tests and linear mixed-effects models.

Results showed that fencing had the most consistent positive effect on growth and quality. Pre-commercial thinning had moderate effects on DBH and crown development. The planting method had only minimal influence on the measured variable. The most prevalent quality defects were crooked stems and browsing damages, particularly in unmanaged and unfenced stands.

The findings of this study highlight the challenges related to oak production under mixed stand conditions. To evaluate if these converted stands will meet their intended ecological and economic goals, long-term monitoring and silvicultural interventions are needed.

Keywords: Gudrun, oak regeneration, conversion, reforestation, mixed broadleaf, climate adaptation

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Abbreviations

DBH	Diameter at breast height (1.3 m)
PCT	Pre-commercial thinning
LMM	Linear mixed-effect models
PG	Goal – Forest production
NS	Goal – Nature conservation with management
NO	Goal – Nature conservation without management

1. Introduction

1.1 Gudrun

Twenty years have passed since the devastating storm Gudrun swept across southern Sweden in early January 2005. This event shook many forest owners in the Götaland region, where the wind hit the hardest. Approximately three years' worth of harvest was felled, ca 75 million cubic meters (Skogsstyrelsen 2025). Around 80% of the felled volume was Norway spruce *(Picea abies L. Karst)* (Skogsstyrelsen 2005) - one of the main species favoured by the Swedish forestry industry for the last decades (Huuskonen et al. 2021).

During Sweden's industrialisation, factors such as early overexploitation, weak legislation and poor forest management resulted in a severe shortage of timber. To battle the shortages of wood supply and optimise the production, Norway spruce and Scots pine *(Pinus sylvestris L.)* appeared to be the ultimate choice for the reforestation operation (Hansen & Spiecker 2004; Löf & Oleskog 2005). The two conifer species have numerous advantages: fast growth rates, easy establishment, uncomplicated management, and the expectancy of high economic return (Löf et al. 2023). Broadleaf species, on the other hand, were considered weeds and were systematically removed using herbicides such as *Hormoslyr*, with conifers planted in their place (Karlsson 1996). This practice dominated Swedish forestry until the early 1980s, when increasing ecological awareness led to changes in forest policy. In 1983, the Swedish Forestry Act was revised to prohibit the large-scale removal of broadleaved trees solely to promote conifer plantations (Karlsson 1996; Skogskunskap 2025). In 1984, a new law – the Noble Deciduous Forests Act – was enacted to protect eight native "noble" hardwood tree species, including oak, beech, ash, elm, small-leaved lime, wild cherry, maple and hornbeam. It prohibits the conversion to other species in areas of at least 0.5 hectares (Sveriges riksdag n.d.). The widespread distribution of Norway spruce today is therefore not solely due to natural processes but also a result of human intervention (Hansen & Spiecker 2004; Löf et al. 2010). This has resulted in today's situation in Sweden where the production forest is comprising approximately 39,8% Norway spruce, 39,6% Scots pine and birch *(Betula spp.)*, 12,1% (Skogsdata 2024).

Different tree species have different susceptibility to wind damage. Broadleaves are generally more resistant due to their deeper, more robust root systems and the fact that they are leafless during the season when storms most often occur – autumn and winter – which reduces the force of the wind, and unlike conifers i.e. evergreens which keep their needles year-round and therefore pose a greater risk for windthrows (Peterson 2007; European Forest Institute 2020). Other risk factors include mature age, low wood strength, greater stand height, and recent thinning operations, which temporarily destabilise trees' anchorage (Bauhus et al. 2017; Valinger & Fridman 2011; Valinger et al. 2019). Naturally, topography and elevation also play a role (Gardiner et al. 2013).

In the aftermath of Gudrun, the Swedish forestry came under increased scrutiny as the vulnerability of conifer monocultures had been exposed, particularly Norway spruce, prompting a re-evaluation of silvicultural strategies (Ulmanen et al. 2015; Olsson 2014). In the years since, there has been a growing emphasis on building more robust and resilient forests, with risk mitigation, diversification and climate adaptation being key themes (Blennow et al. 2014). Despite the dramatic consequences of the storm, silvicultural practices, and tree species selection among private forest owners surprisingly did not change much, even a decade later (Valinger et al. 2019). The interest and curiosity for broadleaf species has, nevertheless, slowly been growing (Skogssällskapet 2022; Woxblom & Nylinder 2010).

1.2 Forest restoration and climate adaptation

Forest restoration is a broad concept that can include a wide spectrum of objectives, it is for that reason that it is yet without a universally accepted definition. However, a commonly shared goal is the restoration of ecosystem functionality, resilience and biodiversity. In some contexts, forest restoration aims to return a forest to a historical, *assumed*, natural state. In others, the focus is rather on creating new, functional ecosystems that are better adapted to climate change. This process is increasingly important for sustaining or enhancing forest vitality, particularly in light of the predicted climatic shifts (Stanturf et al. 2014; Löf et al. 2023).

Restoration can be carried out using either a passive or an active approach. Passive restoration is a more cost-efficient strategy, relying fully or partially on regeneration by adjacent trees as a seed source. This approach can be successful for pioneer species such as birch (*Betula spp.)* and aspen (*Populus tremula*). However, for slow-growing species with heavy acorns, like oak (*Quercus robur*), an active approach – typically involving planting can be more suitable (Löf et al. 2023). Active restoration also allows for the selection of planting material with desirable traits, which may be crucial for adaptive potential (EUFORGEN 2023) or achieving high timber quality.

With growing concerns about climatic stressors, increased storm frequency, as well as the susceptibility of conifers to pests and pathogens, the restoration of former broadleaved forests has become a highly topical issue. Broadleaved species are generally considered more resilient and better adapted to future climate conditions (Löf et al. 2023). By increasing the use of more tree species, the risk of total loss, both ecologically and financially, may be lowered because of species' varying susceptibility to stressors (Bauhus et al. 2017). The main target species for the restoration of European hardwood forests are pedunculate oak (*Quercus robur*) and European beech (*Fagus sylvatica*) (Löf et al. 2023).

Earlier studies support the idea that tree species diversity boosts primary production (Huang et al. 2018; Jactel et al. 2018; Liang et al. 2016) and increases stability over time (Jucker et al. 2014; Schnabel et al. 2019). The improved productivity is partly explained by the fact that different species use resources in slightly different ways and can thus share water, light and nutrients more efficiently. However, carefully matching the species composition in a mixed-species forest is still important to facilitate rather than increase unnecessary competition, although negative and positive interactions often occur simultaneously (Löf et al. 2014). This could, for example, involve integrating nurse trees (often pioneer species) alongside a slower-growing species to support structural development (Stanturf et al. 2014). Mixed-species forests have also been shown to support greater diversity and abundance of soil microbiota and mycorrhizal fungi, due to the fact that different tree species host different specialists (Huuskonen et al. 2021). These symbiotic relationships between trees and fungi are contributing to the long-term ecosystem stability as they improve nutrient cycling and soil structure (Martin & van der Heijden 2024), hence strengthening the resilience to environmental stressors.

What eventually follows after a conversion from conifer monoculture to a mixed species forest is ecosystems better adapted to withstand climate changes, while also supporting diverse wildlife, enhancing biodiversity (above as well as below ground). Nevertheless, full restoration of ecosystems that once were might not be possible due to changed climate conditions (Löf et al. 2019); therefore, having the primary goal of restoring functionality in forms of ecosystem sustainability, economic efficiency, and social values might be more achievable (Stanturf 2014). There is, however, limited knowledge about what outcomes can be expected after conversion from a monoculture into a mixed forest in terms of wood production, economic outcome and forest structure (Reventlow et al. 2021).

1.3 Sveaskog’s reforestation after Gudrun

Sveaskog, the Swedish state-owned forestry company, is Sweden’s largest forest owner, managing about 14% of the country’s productive forest land (Sveaskog 2025). Sveaskog was left with large areas of damaged forest following Gudrun. The total amount of storm-felled forest on Sveaskog's land reached 2.6

million m^3fub, which corresponds to 1.5 annual felling in the area (Götaland) (Sveaskog 2024). After Gudrun, Sveaskog decided to take steps towards more diversified forests, by reforesting (and by that, also converting) 10% of the devastated forest area with different, suitable native broadleaves instead of replanting with Norway spruce. The selected species included: pedunculate oak (*Quercus Robur*), black alder (*Alnus glutinosa*), silver birch (*Betula pendula*), small-leaved lime (*Tilia cordata*) and bird cherry (*Prunus avium*). These were planted in various combinations, often in mixtures, some of which with two species or more. These broadleaves have varying management requirements, which call for a more complex silvicultural strategy compared to what Norway spruce demands. Mixed-species stands with oak were the foundation of this study.

1.4 Challenges with oak management

Growing oak is a long-term and costly investment that requires decades of careful management if the primary goal is to produce high-quality wood (Skogskunskap 2025; Skogsstyrelsen 2015). Oak wood can be used for various purposes, for instance, construction, flooring, furniture and veneer – being the best paid assortment, hence, requiring the highest wood quality. Its versatility and strength make oak one of the most valuable woods for both practical and decorative uses (Attocchi 2015). Ideal, final oak stands are typically characterised by 50–70 future crop trees per hectare, reaching heights between 20-30 meters (depending on site index) (Carbonnier 1975), and a target diameter at breast height (DBH) of approximately 70 cm by the age of 120 years. These trees are expected to have developed straight, knot-free logs measuring between 2.6 and 2.9 meters in length (in line with industrial standards such as those of Kährs – a leading Swedish manufacturer of wood flooring that sources a significant portion of the timber from Sweden (Kährs 2025).

Equally critical to management to attain high quality, however, is the careful selection of a suitable site (Skogsstyrelsen 2015). Pedunculate oak thrives on deep soils with a fine-loamy texture, where both water and nutrient availability are sufficient (Skogskunskap 2025). The optimal soil pH ranges between 4.5 and 7 (Forest Research, n.d).

One of the biggest challenges with producing oak is the issue of browsing. Oaks are highly palatable for ungulates (Löf et al. 2021). Browsing on terminal shoots and fraying on stems can result in severe damage that disqualifies the tree from producing high-quality timber. Therefore, fencing with high-quality material is a necessity to prevent browsing and fraying. The challenge is also becoming increasingly difficult as populations of roe deer (*Capreolus capreolus*), fallow deer (*Dama dama*), and red deer (*Cervus elaphus*) continue to grow in Sweden

(Jarnemo u.å.; Löf et al. 2023). Fences are costly to install, maintain and eventually remove (Skogsstyrelsen 2015), however, 80% of the costs can be covered by subsidies from Skogsstyrelsen (including costs for fencing, planting, clearing and thinning) (Skogssällskapet 2025).

One approach that may reduce the costs of regenerating oaks is direct seeding, where acorns are sown directly into the soil, compared to conventional planting with nursery-grown seedlings. However, this approach does not come without challenges, competition from natural vegetation can hinder the early growth of oak seedlings (Löf et.al 2021); therefore, removal, i.e. cleaning, is often necessary. Predation from rodents of the buried acorns is another problem that remains hard to combat in an efficient way (Löf & Birkedal 2009; Manson et al. 2001).

An overstorey of fast-growing pioneer nurse trees could potentially address some of the challenges with oak regeneration, especially in the early developmental stages. Having nurse trees can provide benefits such as improving survival, stem form and growth (Löf et al. 2014). However, this requires that balance is achieved regarding stem density and spatial arrangement, to promote straight growth and still leave enough space to let the oaks develop large and symmetric crowns. Therefore, pre-commercial thinnings and commercial thinnings are crucial operations to regulate light and space (Skogskunskap 2025). In addition to the performance benefits nurse trees can offer, they can also provide early financial returns (Löf et al. 2014) from thinning operations, due to their shorter rotation period compared to oaks.

Epicormic branches (dormant buds on the trunk) are another common problem; if not removed, they can eventually be considered a timber defect. Epicormic branches must, for example, not occur in veneer wood (Skogskunskap 2025; Attocchi 2015). Although it is partly genetic, they are thought to also occur when the crown and root system are out of balance (Rytter 2019). To produce a knot-free bole, regular pruning of epicormic shoots is often a necessary measure (Attochi 2015). While the primary silvicultural goal is to achieve straight and knot-free timber for the future crop trees, some imperfections like crookedness and knots may be seen as decorative elements and even desirable for specific architectural or design purposes (Larsen & Aagaard, 2020).

1.4.1 Market for oak

The Swedish oak market in recent years has experienced both promising developments as well as notable challenges, depending on the segment. The demand for oak has remained strong in furniture, joinery and flooring industries.

Furthermore, in southern Sweden, new producers focusing on solid oak flooring have been established, and the market is showing signs of continued growth (Ekfrämjandet, 2024).

Companies as Kährs and Berg & Berg (another Swedish manufacturer specializing in high-quality, sustainably produced wood flooring), (Berg & Berg n.d.) reported a high need for oak logs for their production (Södra 2020). Despite domestic production, Sweden is not able to fully meet the industry's needs. In the first half of 2019, for example, imports of oak logs from Germany to Sweden more than doubled, which indeed emphasises the lack of locally produced oak wood (Skogsaktuellt 2025). As global interest in sustainably produced and renewable building materials is steadily growing (Vergarechea et al. 2023), oak with its many qualities is likely to play a part. Overall, the situation for oak in Sweden is creating good opportunities for forest owners who can supply high-quality timber.

1.5 Objectives of the thesis

The aim of my thesis is to study the performance (survival, growth and stem quality) of young oaks, 20 years after being planted at storm-felled sites following the storm Gudrun in southern Sweden. Establishing oak plantations faces several challenges, and the management is often costly and intensive. In light of the growing need to adapt forest management to climate change and extreme weather events, a better understanding of how to optimise mixed broadleaf plantations and management is highly relevant today.

In this thesis, I aim to answer the following questions:

1. Is there a difference in survival and size of young oaks between stands that have been managed (pre-commercial thinning) and left unmanaged (no pre-commercial thinning)?

2. Is there a difference in survival and size of young oaks between those which were planted in groups and those that were planted spot-wise?

3. Is there a difference in survival, size of young oaks between those which were planted with protective fences and those without protective fences?

4. Do the frequencies of quality defects of young oaks differ depending on management, fencing and planting methods?

2. Materials and methods

2.1 Study area

This study was conducted in forests owned by Sveaskog, located in Götaland, in southern Sweden. The study sites span two distinct vegetation zones: the nemoral zone, with a mean annual temperature approximately 7 – 9 °C and annual precipitation ranging from 600-1000 mm and the boreonemoral zone, with a mean annual temperature of 5 – 7 °C and annual precipitation between 500-900 mm (SMHI, 2020; Annual Precipitation Map for the Normal period 1991–2020). Due to these climatic and ecological differences, the growing conditions for the oaks may vary considerably between sites.

Several of the study sites were located within Sveaskog's Ecopark "Omberg" – a multifunctional forest landscape situated between Lake Vättern and Tåkern. The ecopark combines production forestry with high conservation ambitions and recreational values. Within the park, high biodiversity, old-growth forest remnants, rare species of fungi, insects and lichens can be found. The park is not legally protected as a nature reserve would be, however, it is governed by a long-term ecological management plan. Historically, much of Omberg consisted of open pastoral landscapes, where oaks were given space to develop into large, long-lived individuals. Today, there are approximately 400 of these large-sized oaks, but Sveaskog's long-term goal is to increase that number to 5000. Sveaskog aims to restore diverse broadleaf forests in the park, and following the storms Gudrun in 2005 and Per in 2007, many of the spruce forests have been replaced with birch (*Betula pendula*), oak (*Quercus robur*) and beech (*Fagus sylvatica)* (Sveaskog 2025).

2.2 Site selection and treatments

The stands were selected from Sveaskog's register of broadleaved plantations established on areas affected by the storm Gudrun. Although multiple species were planted, this study focused exclusively on pedunculate oak (*Quercus robur*).

In total, 33 mixed plantations with oaks were included in the study, distributed across several regions in Götaland (Figure 1). The majority of the stands had undergone one or more pre-commercial thinnings (PCT), of which 22 had production goals (PG/PF) and only two with conservation goals (NO/NS) (Table 2). However, 9 stands had not been managed at the time of data collection. Of these, 8 are nature conservation with management (NS), meaning they are managed for enhancing or maintaining biodiversity and not for production goals. Only one stand was designated as a production goal site (PG). Of the 33 sites, 18 had not been fenced, while 15 were fenced at the time of planting. By the time the measurements were conducted, all fences had been removed except for one. In total, 1137 oaks were measured, 230 in the unmanaged stands and 907 in the managed stands. The other tree species measured totalled 2888 trees.

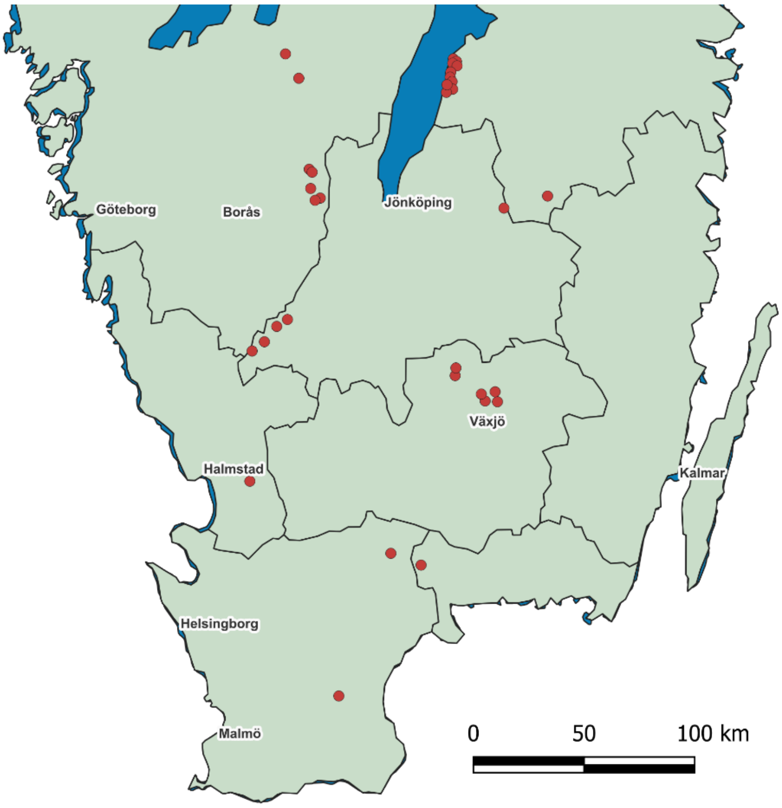

Figure 1. Map showing dispersal of all 33 surveyed sites in Götaland, southern Sweden (dots); Municipalities: Aneby, Falköping, Gislaved, Halmstad, Hörby, Olofström, Skara, Ulricehamn, Vadstena, Växjö, Ydre, Ödeshög, Östra Göinge. Map created by the author using basemap from Simplemaps and QGIS (2024).

The stands were planted between the years 2005 – 2009, making them 16 to 20 years old as of 2025. The stand size ranged from less than 1 hectare to 13 hectares (Table 2). All the stands consisted of 100% broadleaf, although they were planted with varying mixtures, where *Quercus robur* was not always the dominant species. Mixtures including birch were the most common. The stands also differed in planting density and the method used for planting. They were either planted in groups, typically four to eight oaks planted close together (1-2 m) without other species as part of the group, or spot-wise planted throughout the stand. Sites could consist of both planting methods. See *Table 2* with compiled details about the surveyed sites.

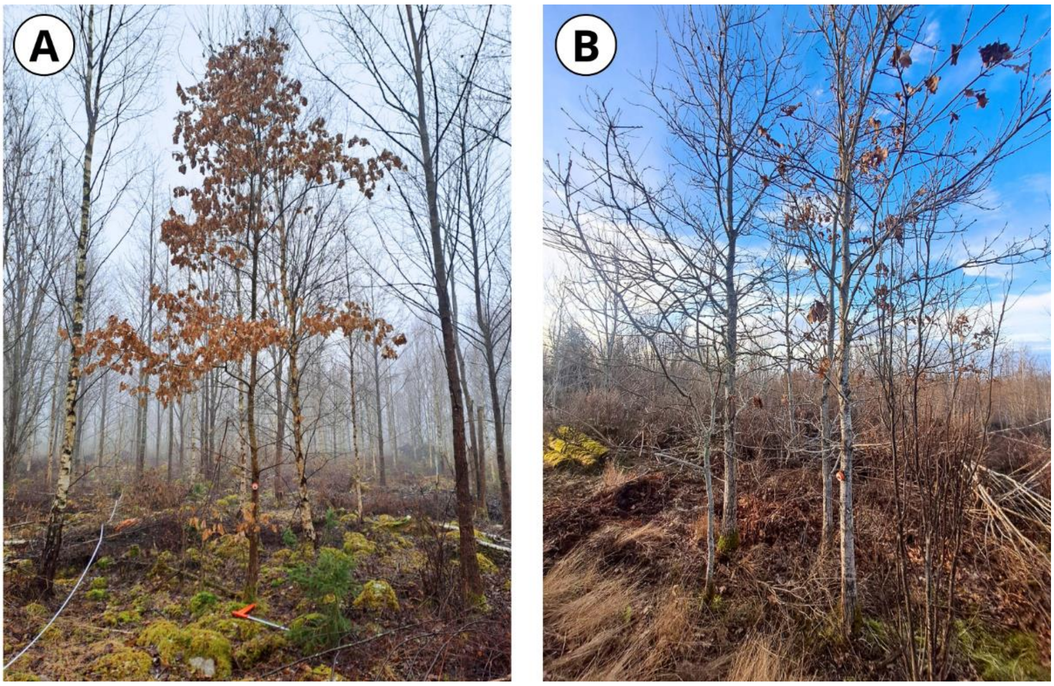

Figure 2. Example from study sites. Spot-wise planted (left), Group planted oaks (right).

Measurement plots were initially distributed systematically on a map for each site, using a grid layer, and the number of plots was determined according to the size of the stand. Measurements were only conducted where oaks were present; no data were collected if the pre-determined plot did not contain oaks. Due to the large variation in the size of the sites as well as the distribution of oaks, it was sometimes necessary to adjust the placement of the plot to the closest group of oaks. At times, the oaks were concentrated in only a part of the site, consequently, the number of plots was adjusted to the estimated area where there were oaks. Plots were carefully placed to ensure no overlap occurred.

The data were collected in circular plots with a 10-meter radius, an area of approximately 314 m^2. The number of measurement plots per stand was adjusted according to stand size, as outlined in Table 1. One plot was added for every additional two hectares of stand area.

Table 1. Number of plots carried out per site, based on stand size.

Plot Area	**Stand size (ha)**	0-1	2	3	4	5	6…
10 m radius							
(≈ 314 m^2)	**Number of Plots**	3	3	4	4	5	5…

2.3 Field survey

Data collection took place throughout February 2025.

Within each measurement plot, all tree stems of all species that met a minimum height of 1.3 meters and a DBH of at least 4 cm were counted. For all oaks, the following variables were measured: diameter at breast height (at 1.3 m) was cross-measured, for accuracy, with a calliper. Total tree height, defined as the length of the tree from the ground to the top of the tree, was measured with a Haglöfs Vertex V hypsometer. The same was done for the height of the lowest branch, i.e. the distance along the stem from the soil surface to the point of attachment of the lowest green branch, which is a part of the crown - epicormic branches were not included. Crown width was roughly assessed in all four cardinal directions (north – east – south – west), to later use these values for crown volume estimation. This was done by standing directly beneath the lowest branch and measuring the horizontal distance to the stem using a BOSCH laser distance measurer. Every oak's planting method was recorded as either "spot-wise" or "group".

Figure 3. The crown volume was estimated using a formula for the volume of an ellipsoid, assuming this is similar to the crown shape of the young oaks. Illustrated in Canva by the author.

Quality Assessment

The quality of the oaks was assessed by visual wood defects based on several criteria that degrade the timber quality (Figure 4). These defects may reduce the growth and make the wood difficult to further process in the industry, consequently resulting in low-quality timber.

- Crooked – noticeable deviation from vertical stem alignment.
- Fork – presence of two dominant stems situated below 3 meters on the stem.
- Angled sprout - strongly upward-pointing, <30°, often bark-pulling twig in trunk.
- Evidence of ungulate damage - either browsing on the crown or fraying on the trunk.

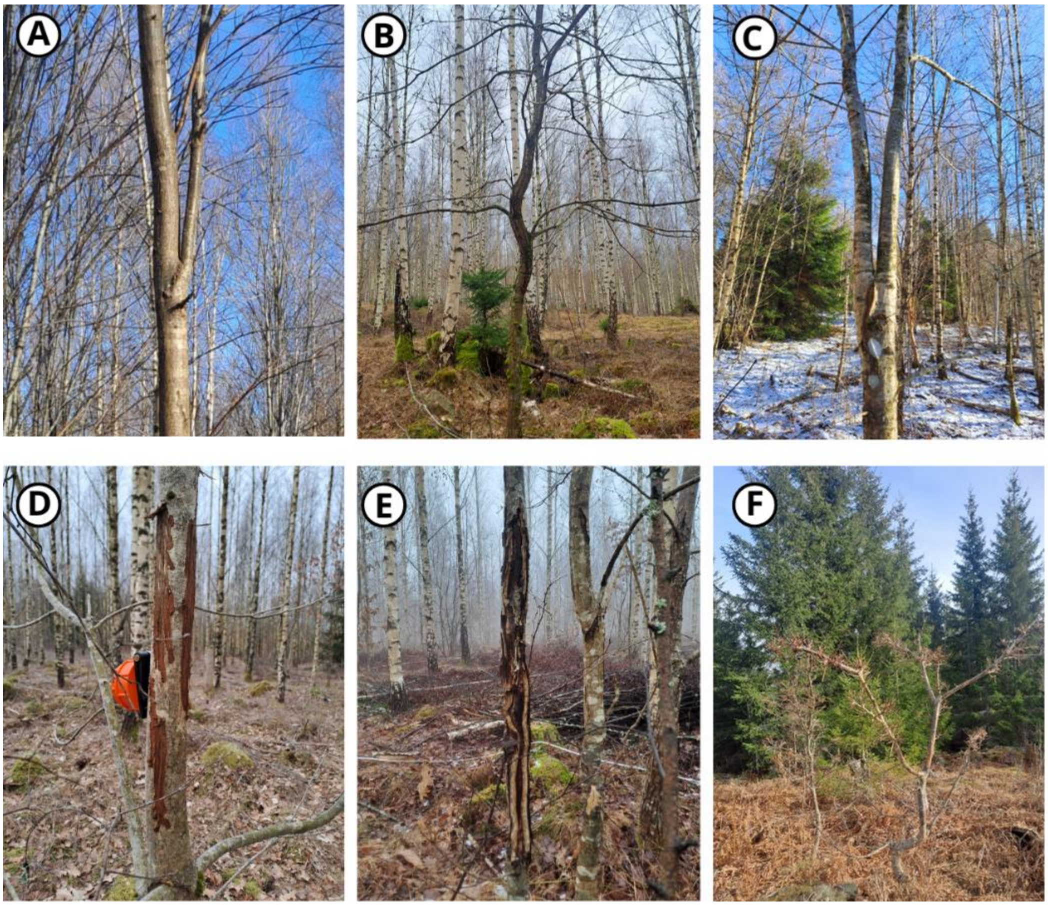

Figure 4. Examples of external defects: Angled branch (A), Crooked stem (B), Fork <3 m (C). Different types of browsing damage, to stems: (D), (E), to branches: (F). Photo by the author.

Other tree species

DBH was subsequently measured for all other tree species within the plot (with a DBH of at least 4 cm). In addition, the height of the two thickest individuals of each species was measured. To capture height variability, at least five additional trees were selected across the diameter range in the plot to represent the overall size distribution.

2.4 Site description

Table 2. Overview of surveyed sites, sorted by site number, including municipality, initial planting density ha^{-1} of oaks, stand size and management (pre-commercial thinning). Coordinates are given in SWEREF 99 TM (EPSG:3006).

Site nr	Coordinates (X, Y)	Municipality	Size (ha)	Year of planting	Planted ha^{-1}	Management	Fence
1	465 963, 6 240 617	Olofström	1.5	2007	1500	Unmanaged	No
2	495 607, 6324652	Aneby	1.9	2007	100	Unmanaged	No
3	479 235, 6 465 949	Ödeshög	1.2	2005	500	Unmanaged	No
4	419 832, 6 417 001	Ulricehamn	0.3	2008	1200	Unmanaged	Yes
5	480 275, 6 469 434	Vadstena	6.1	2009	500	Unmanaged	No
6	480 397, 6 469 854	Vadstena	3.1	2006	500	Unmanaged	No
7	480 890, 6 470 712	Vadstena	1.4	2008	980	Unmanaged	No
8	480 709, 6 470 526	Vadstena	0.8	2008	980	Unmanaged	No
9	480 894, 6 470 771	Vadstena	1.1	2008	980	Unmanaged	No
10	434 148, 6 181 759	Hörby	1	2009	1500	PCT	No
11	453 508, 6 243 860	Östra Göinge	1	2009	1600	PCT	Yes
12	385 950, 6 335 099	Gislaved	4.8	2008	908	PCT	Yes
13	387 046, 6 335 917	Gislaved	0.9	2008	908	PCT	Yes
14	388 499, 6 338 207	Gislaved	1.6	2008	950	PCT	Yes
15	388 772, 6 338 209	Gislaved	4.1	2008	750	PCT	Yes
16	422 431, 6 404 049	Ulricehamn	0.8	2007	305	PCT	No
17	419 837, 6 417 004	Ulricehamn	6.2	2008	1000	PCT	Yes
18	421 436, 6 406 427	Ulricehamn	1.9	2007	1500	PCT	Yes
19	419 218, 6 417 459	Ulricehamn	2.5	2007	1000	PCT	Yes
20	495 222, 6 323 793	Växjö	6	2006	1200	PCT	Yes
21	496 024, 6 323 334	Växjö	9.6	2007	950	PCT	No
22	496 422, 6 323 581	Växjö	6.2	2006	1200	PCT	No
23	479 561, 6 462 215	Växjö	1.5	2006	1200	PCT	Yes
24	485 629, 6 332 291	Växjö	1	2007	700	PCT	No
25	485 383, 6 332 585	Växjö	3.2	2007	700	PCT	Yes
26	523 513, 6 410 007	Ydre	0.9	2008	750	PCT	No
27	479 577, 6 462 244	Ödeshög	6.5	2008	1280	PCT	No
28	480 327, 6 466 577	Ödeshög	3.7	2007	500	PCT	Yes
29	480 827, 6 470 525	Vadstena	13.1	2008	980	PCT	No
30	480 395, 6 468 632	Vadstena	2.1	2005	2000	PCT	Yes
31	384 807, 6 286 263	Halmstad	3.7	2008	500	PCT	Yes
32	410 786, 6 453 476	Falköping	1.7	2008	789	PCT	No
33	403 922, 6 467 028	Skara	1.1	2008	900	PCT	No

2.5 Data analysis

The collected data was analysed in RStudio (version 4.3.3) using R (version 4.3.3)

A Shapiro-Wilk test was conducted to assess the distribution of the growth variables: height, diameter at breast height (DBH), crown ratio and crown volume. All variables showed strong deviation from normality ($p < 0.001$). Therefore, the non-parametric Wilcoxon Rank Sum Test (Mann-Whitney U test) was used henceforth to test for statistical significance comparisons between two groups (e.g., managed vs. unmanaged, fenced vs. unfenced, group vs. spot-wise planting). A significance level of $\alpha = 0.05$ was used throughout all statistical analyses; p-values below this threshold were considered statistically significant. The test was using tree-level data to enable direct comparisons of the individual measurements between groups and the full resolution of the dataset.

For all of the oaks, the following variables were calculated;

Survival
Survival rates of the oaks were assessed per site for the Management and Fencing comparisons. The number of observed oak individuals within each circular plot was scaled up to stems per hectare, based on the 314.16 m^2 plot area. This value was then divided by the known initial planting density (in stems per hectare) to get a proportional survival rate, making comparisons across treatments.

$$\textbf{Survival Rate} = \frac{Oaks\ observed/hectare}{Oaks\ originally\ planted/hectare} \tag{1}$$

The survival comparison between oak Group plantations and oaks planted Spot-wise required a different approach due to the lack of information on how many oaks were initially planted using each method. As a result, survival could not be calculated separately for each planting method. Instead, a site-level analysis with Spearman's rank correlation was conducted to examine whether a higher proportion of group planting was associated with higher or lower survival across sites. This non-parametric method was chosen because the data were bounded proportions and not normally distributed.

Stem density and survival.
A Shapiro-Wilk test was used to test for normality of the distribution of survival rate across sites, which showed significant deviation from normality ($p < 0.05$), however, a visual inspection of residuals from the linear models supported the use of linear regression. Therefore, to evaluate how planting density and treatment factors (management, planting method and fencing) influenced oak survival, three

linear models were fitted at the site level. Individuals of all tree species within the plots were accounted for when calculating mean stem density. The models were calculated separately to clarify whether any treatment had an additional effect on survival beyond stem density. The models were run using R's lm() function and interpreted based on adjusted R^2 and the p-values of individual predictors.

The crown lengths were calculated as the difference between total tree height (the distance from the ground to the top of the tree) and the height to the lowest living branch as part of the crown.

$$\textbf{Crown Length} = Total\ Tree\ Height\ (m) - Height\ to\ Lowest\ Living\ Branch\ (m) \tag{2}$$

$$\textbf{Crown Ratio} = \frac{Crown\ Length\ (m)}{Tree\ Height\ (m)} \tag{3}$$

$$\textbf{Crown Volume} = \frac{4}{3}\pi \cdot a \cdot b \cdot c \tag{4}$$

Where:

- a = radius in the North–South direction
- b = radius in the East–West direction
- c = vertical crown radius (i.e., half the crown length)

Mixed-Effects Models

Linear mixed-effects models (LMMs) were used to assess the effects of stand-level treatments – *management and fencing* – on oak growth, specifically for height, DBH, crown ratio, and crown volume. The planting method was excluded from the mixed models due to a lack of significant effects observed in the earlier non-parametric tests (Wilcoxon rank sum).

Management treatment (PCT conducted or not) and tree age were included as fixed effects, while plot nested within site was modelled as a random effect to account for the hierarchical structure of the data and nested variation at plot and site levels.

The general model structure for crown ratio, DBH and height was:

response_variable ~ Treatment + tree_age + (1 | Site_nr/Plot_ID)

Here, the crown volume was not included as a response variable but instead, DBH was used as a predictor for crown volume because of its known correlation with crown dimensions in pedunculate oak (Dubravac et al., 2009) and other hardwood species (Lockhart et al., 2005):

crown_volume_ellipsoid ~ Treatment + Dbh_cm + (1 | Site_nr/Plot_ID)

To evaluate the effect of fencing on crown volume, a separate LMM was used where the Fenced / Unfenced groups and DBH were included as fixed effects, and plot nested within site again served as the random effect:
crown_volume_ellipsoid ~ Fence_group + Dbh_cm + (1 | Site_nr/Plot_ID)

Analysis of Quality Defects
To assess the quality of the oaks, data recorded on four types of defects were used: Crooked Stem, Angled Branch, Fork below 3 meters and Browsing (different damages caused by ungulates), see Figure 4 above. The occurrence of each defect was summarised as a percentage of affected trees per treatment category, and comparisons were made between managed and unmanaged, fenced and unfenced and group-planted and spot-wise planted oaks.

Chi-squared (χ^2) test was used to check whether the frequency of defects differed significantly between different treatment groups. The test was based on categorical count data, comparing the number of damaged and undamaged trees in each treatment group. Significance levels were marked using standard thresholds ($p < 0.05$, < 0.01, < 0.001).

3. Results

The distribution of heights of oaks and other tree species for all 33 sites is shown in Figure 5. Oaks (blue dots) are generally lower than other tree species (red dots) and the variance is high both within plots and between sites. The three most common species within each site are listed in Appendix 3.

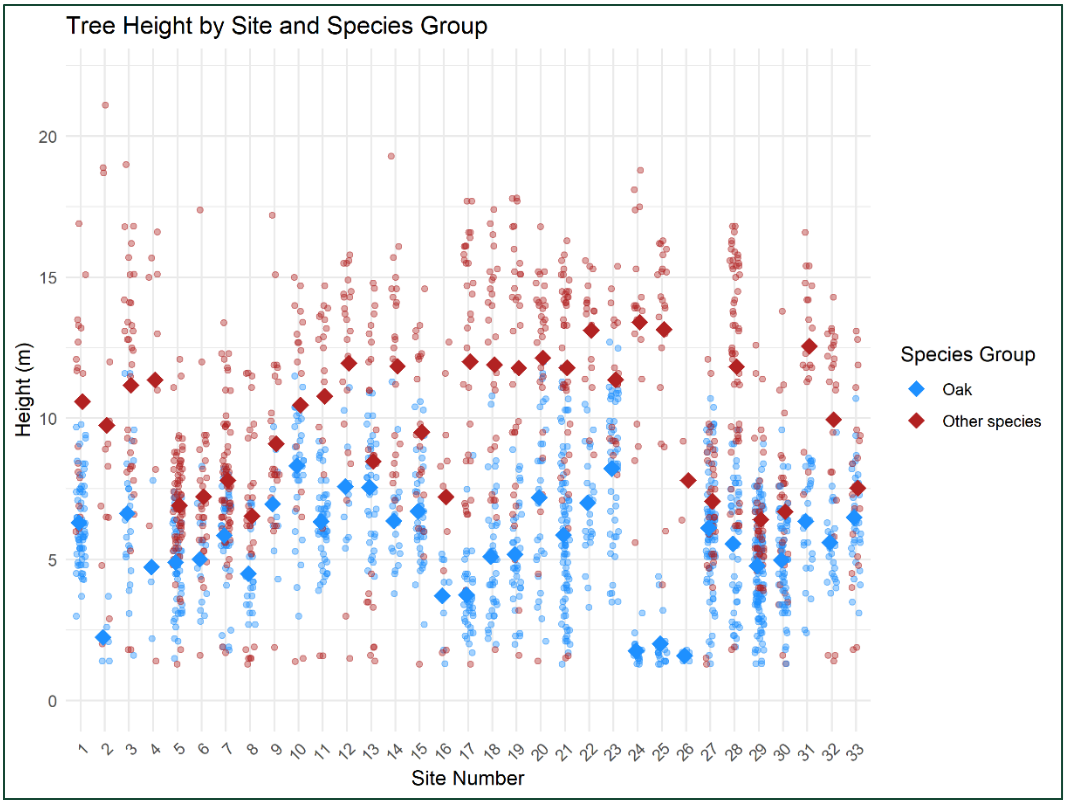

Figure 5. Height distribution of oaks (blue) and other tree species (red) across sites. Large dots mark the median height for each site.

3.1 Survival

Management and Fencing

The median survival rates were generally low (below 40%), although slightly higher in unmanaged and unfenced sites (Table 3); however, the Wilcoxon rank sum test did not show any statistically significant differences in survival between either treatment group ($p > 0.05$).

Table 3. Survival of oaks per site, comparing the groups (Managed versus Unmanaged, Fenced versus Unfenced), the number of oak plants planted per hectare and the current number of oaks per hectare.

	Managed	Unmanaged	Fenced	Unfenced
Median survival (%)	34.6%	39.0%	33.2%	39.5%
Sites (n)	24	9	15	18
Plots sampled	79	25	46	58

Planting method

The Spearman's rank correlation test showed no significant association between the proportion of group-planted oaks and site-level survival rates (ρ = -0.026, *p* = 0.90). The test did not explain any meaningful variation in survival. Thus, no observable impact on oak survival rates could be found for the proportion of group plantings.

3.1.1 Survival and stem density

Linear regression models showed that survival decreased with increasing stem density (all species included), and the negative effect was significant in all three models.

In the model including management, stem density had a statistically significant negative effect on oak survival (β = –0.00025, *p* = 0.003). This means that for each additional tree per hectare, survival decreased by approximately 0.025%. The model explained about 21.3% of the variation in survival (*adjusted* R^2 = 0.213).

In the model including fencing, stem density remained significant, with a negative effect on oak survival (β = –0.00022, *p* = 0.009). This indicates that each additional tree per hectare was associated with a decrease in survival of 0.022%. The model accounted for 19.8 of the variation in survival (*adjusted* R^2 = 0.198).

In the model including planting method, stem density again had a statistically negative effect on oak survival (β = –0.00024, *p* = 0.004). For each additional tree per hectare, survival decreased by 0.024%. The model explained about 19.9% of the variation in survival (a*djusted* R^2 = 0.199).

However, consistent with the Wilcoxon rank sum tests, none of the treatment variables (management, planting method or fencing) showed a significant effect on oak survival when accounting for stem density in the linear models ($p > 0.05$).

3.2 Size of oaks: Managed – Unmanaged stands

The Wilcoxon rank sum tests revealed a significant difference in stem diameter at breast height (DBH) and crown volume between managed and unmanaged oak stands. DBH was significantly higher in managed plots ($p = 0.024$), with a median of 5.5 cm in managed plots compared to unmanaged plots with a median of 5.0 cm. Crown volume also differed significantly between the two groups ($p = 0.014$), with managed plots showing a higher median crown volume (2.04 m^3) than unmanaged plots (1.48 m^3). Tree height did not show a significant difference ($p = 0.585$). Crown ratio likewise showed no significant difference ($p = 0.777$) (Figure 6).

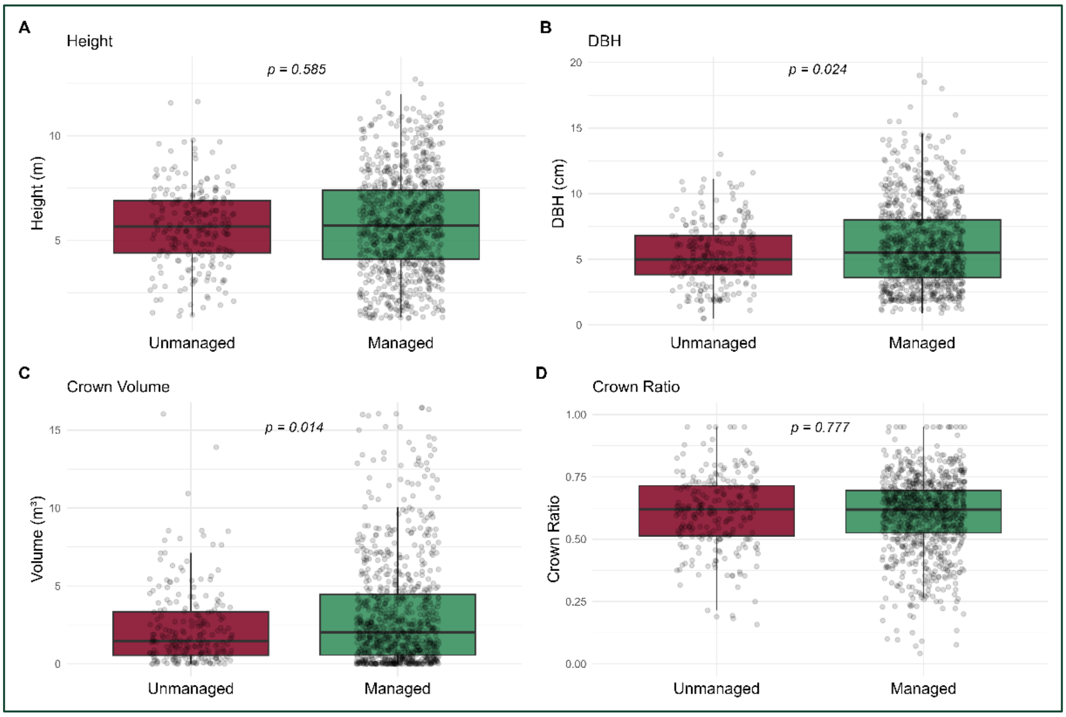

Figure 6. Boxplots of oak growth variables in managed and unmanaged stands. The figure compares individual tree height (A), diameter at breast height (DBH) (B), crown volume (C), and crown ratio (D) between oaks in managed and unmanaged plots. The median is shown as the horizontal line within each box. P-values are from Wilcoxon rank sum tests.

3.2.1 Management effects on growth – Mixed-effect models

The mixed-effect model for crown volume showed that DBH was a strong and significant positive predictor ($p < 0.001$) (Table 4). Although oaks in managed sites tended to have larger crown volumes, the effect of management was, however, not statistically significant ($p = 0.117$). Similarly, neither management nor tree age significantly affected height ($p = 0.530$ and 0.815), DBH ($p = 0.147$ and 0.358), or crown ratio ($p = 0.568$ and 0.240) in the studied stands.

The marginal and conditional R^2 values showed that the models differed in how much variation they explained. The marginal R reflects the variance explained by fixed effects (such as DBH and treatment). The conditional R includes both fixed and random effects (site and plot variation). The values below should be interpreted as a percentage.

- Crown volume: marginal $R^2 = 0.590$; conditional $R^2 = 0.681$
- Height: marginal $R^2 \approx 0.050$; conditional $R^2 = 0.497$
- DBH: marginal $R^2 = 0.046$; conditional $R^2 = 0.389$
- Crown ratio: marginal $R^2 \approx 0.050$; conditional $R^2 = 0.306$

The random effects (standard deviations) in the models accounted for variation at the site- and plot-level.

- Crown volume: SD = 1.04 (site), 0.62 (plot)
- Height: SD = 1.62 (site), 0.77 (plot)
- DBH: SD = 1.74 (site), 0.87 (plot)
- Crown ratio: SD = 0.074 (site), 0.047 (plot)

Table 4. Summary of mixed-effects model results assessing the effect of management on crown volume, tree height and DBH. Tree age was included as a covariate in the models. Significant results (p < 0.05) in bold letters.

Response Variable	Predictor	Estimate	p-value	Significant
Crown Volume	**DBH**	**0.996**	**<0.001**	**Yes**
Crown Volume	Management	-0.785	0.117	No
Height	Management	-0.453	0.530	No
Height	Tree Age	-0.072	0.815	No
DBH	Management	-1.164	0.147	No
DBH	Tree Age	-0.309	0.358	No
Crown Ratio	Management	-0.020	0.568	No
Crown Ratio	Tree Age	-0.018	0.240	No

3.3 Size of oaks Group - Spot-wise planting

According to the Wilcoxon rank sum test for planting method (group vs. spot-wise) crown ratio was significantly lower in group-planted oaks (p = 0.002), with a median crown ratio of 0.600 compared to spot-wise, 0.624. Crown volume showed a marginal trend towards larger crowns in spot-wise planted oaks (p = 0.079). No significant effect could be found for height (p = 0.216) or DBH (p = 0.614) (Figure 7).

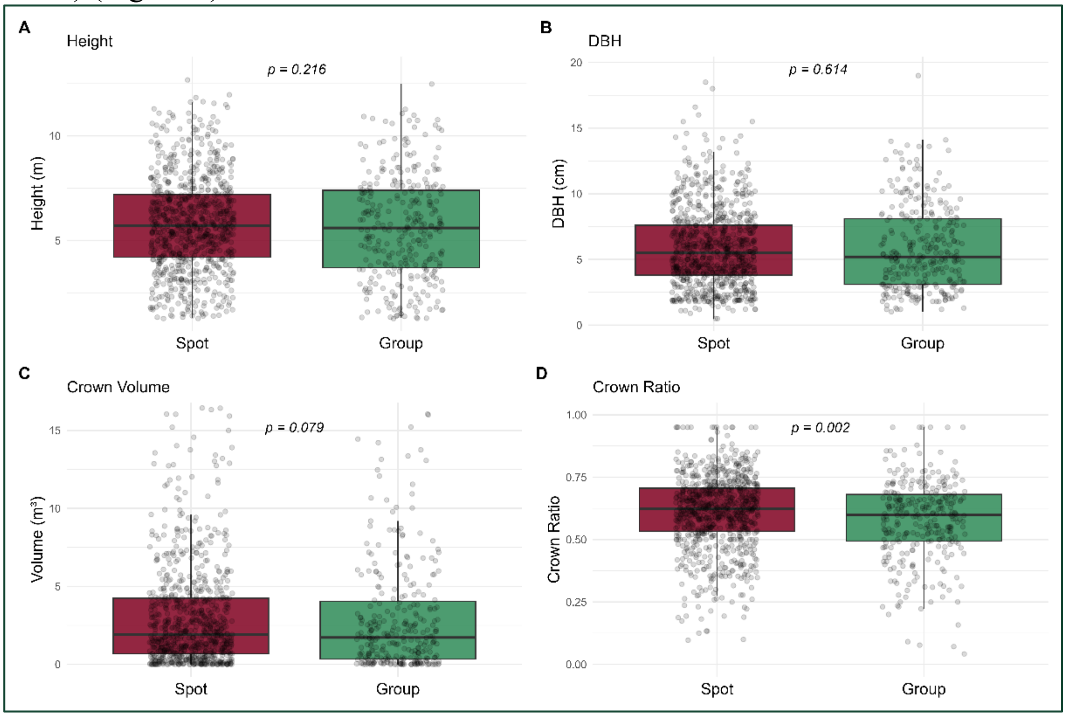

Figure 7. Boxplots of oak growth variables under different planting strategies. The figure compares individual tree height (A), diameter at breast height (DBH) (B), crown volume (C), and crown ratio (D) between group-planted and spot-wise planted oaks. The median is presented as a horizontal line in each plot. P-values are from Wilcoxon rank sum tests.

3.4 Size and browsing of oaks Fenced - Unfenced

Wilcoxon rank sum test for fencing revealed statistically significant differences in all four measured variables between fenced and unfenced oaks.

Oaks in fenced stands were significantly taller than unfenced oaks (median = 6.1 m vs. 5.4 m, $p < 0.001$). Fenced oaks also had greater DBH (5.8 cm vs. 5.1 cm, p = 0.003), larger crown volume (2.32 m^3 vs. 1.53 m^3, $p < 0.001$), and higher crown ratio (0.637 vs. 0.607, $p < 0.001$). These results suggest that fencing has a consistent positive effect on early oak development (Figure 8).

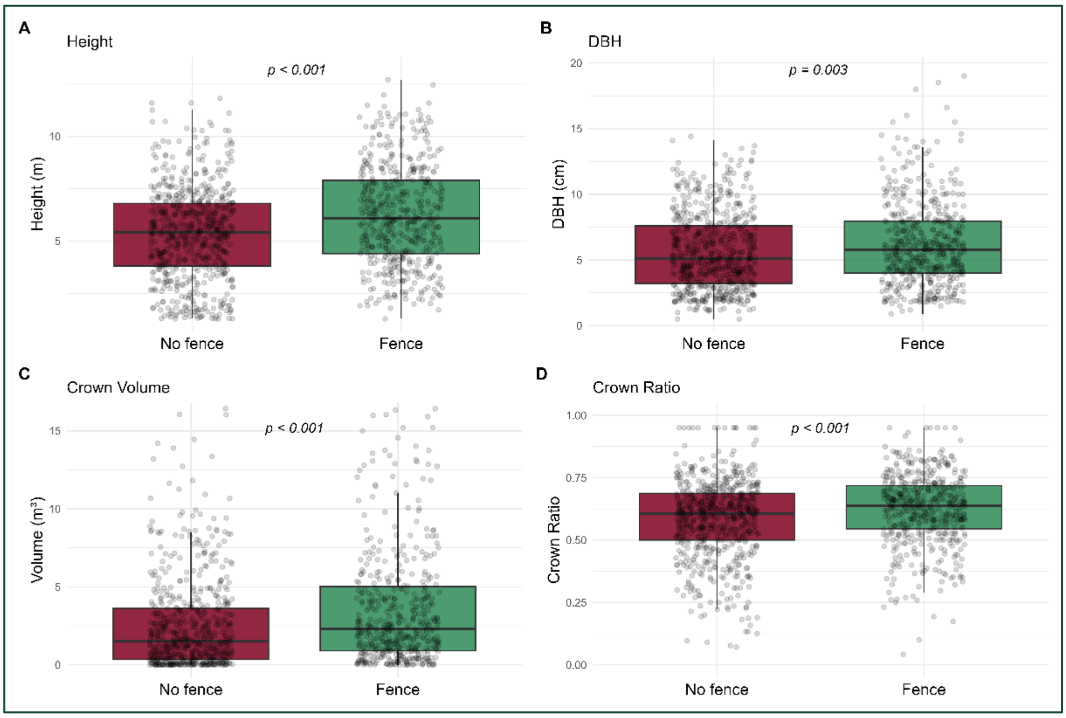

Figure 8. Boxplots of oak growth variables comparing fenced and unfenced plots: Tree height (m) (A), DBH (cm) (B), Crown volume (m^3) (C), and Crown ratio (D). Points represent individual trees. The median is presented as a horizontal line in each plot. P-values are from Wilcoxon rank sum tests.

3.4.1 Fencing effects on growth – Mixed-effect models

The mixed-effect model for crown volume showed that DBH had a strong and positive effect ($p < 0.001$), indicating that for each 1 cm increase in DBH, crown volume increased by nearly 1 m^3 (Table 5).

Fencing had a significant positive effect on crown volume ($p = 0.032$), with unfenced oaks having smaller crowns. Fencing also had a significant positive effect on height ($p = 0.017$), with fenced oaks being taller on average than unfenced ones. DBH was likewise significantly greater in fenced sites compared to unfenced sites ($p = 0.032$). For the crown ratio, fencing had a significant effect ($p = 0.014$). Tree age did not have a significant effect on either height ($p = 0.632$), DBH ($p = 0.343$) or crown ratio ($p = 0.116$).

The marginal and conditional R^2 values showed that the models differed in how much variation they explained.

- Crown volume: marginal $R^2 = 0.598$; conditional $R^2 = 0.682$
- Height: marginal $R^2 = 0.07$; conditional $R^2 = 0.497$
- DBH: marginal $R^2 = 0.046$; conditional $R^2 = 0.389$

- Crown ratio: marginal R^2 = 0.050; conditional R^2 = 0.306

The random effects in the models accounted for differences between sites and plots:

Crown volume: SD = (0.99 site), 0.62 (plot)
Height: SD = 1.46 (site), 0.77 (plot)
DBH: SD =1.66 (site), 0.87 (plot)
Crown ratio: SD = 0.065 (site), 0.047 (plot)

Table 5. Summary of mixed-effects model results assessing the effect of fencing on crown volume, tree height and DBH. Tree age was included as a covariate in the models. Significant results ($p < 0.05$) in bold letters.

Response Variable	Predictor	Estimate	p-value	Significant
Crown Volume	**DBH**	**0.998**	**<0.001**	**Yes**
Crown Volume	**Fenced/Unfenced**	**-0.922**	**0.032**	**Yes**
Height	**Fenced/Unfenced**	**-1.425**	**0.017**	**Yes**
Height	Tree Age	-0.131	0.632	No
DBH	**Fenced/Unfenced**	**-1.457**	**0.032**	**Yes**
DBH	Tree Age	-0.301	0.343	No
Crown Ratio	**Fenced/Unfenced**	**-0.071**	**0.014**	**Yes**
Crown Ratio	Tree Age	-0.021	0.116	No

3.5 Quality assessment

The most recorded defect among the surveyed oaks was Crooked Stem (39%), followed by Browsing (22.6%) and Fork <3 m (19.5%). The least frequent defect was Angled Branch (18.4%) (Figure 9).

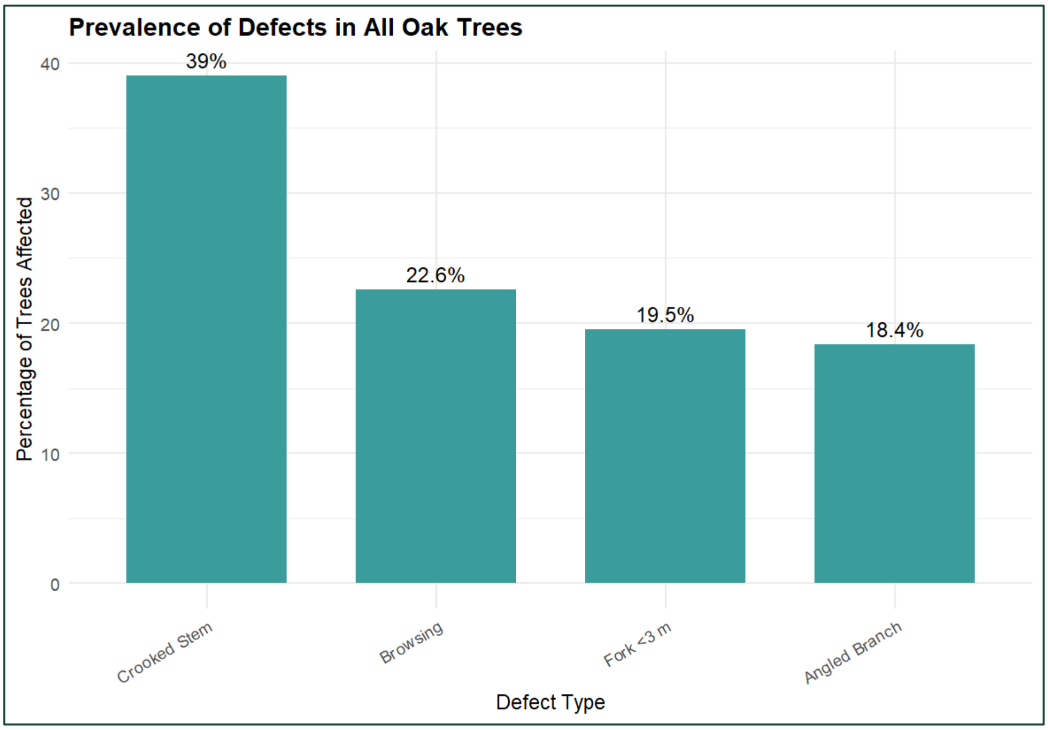

Figure 9. Percentage of oak trees affected by different types of defects across all sampled individuals (n = 1137).

A series of Chi-square tests revealed significant differences in the occurrence of all defects across the groups: management, fencing and planting method (Figure 10).

Management
All four defect types differed significantly between managed and unmanaged stands. Angled branches were more frequent in unmanaged stands ($\chi^2 = 43.2$, $p < 0.001$). Crooked stems were much more common in unmanaged stands ($\chi^2 = 74.0$, $p < 0.001$). Forks were more prevalent in unmanaged stands ($\chi^2 = 69.3$, $p < 0.001$). However, browsing showed to be higher in managed stands ($\chi^2 = 125$, $p < 0.001$).

Planting Method
Significant differences were also found for all defects between the group and spot-wise planted oaks. Angled branches were slightly more frequent in group-planted trees ($\chi^2 = 61.1$, $p < 0.001$). Browsing was more common in group

plantings ($\chi^2 = 28.1$, $p < 0.001$). Crooked stems were significantly more frequent in spot-wise planted trees ($\chi^2 = 98.6$, $p < 0.001$). Fork <3 m were more frequent in group plantings ($\chi^2 = 43.3$, $p < 0.001$).

Fencing

All defect types showed significant differences between fenced and unfenced stands, however, at varying significance levels. Angled branches were slightly more common in unfenced stands ($\chi^2 = 6.55$, $p = 0.011$). Browsing was significantly reduced in fenced plots ($\chi^2 = 32.2$, $p < 0.001$). Crooked stems were more common in unfenced plots ($\chi^2 = 16.3$, $p < 0.001$). Fork <3 m were slightly more common in unfenced stands ($\chi^2 = 4.61$, $p = 0.032$).

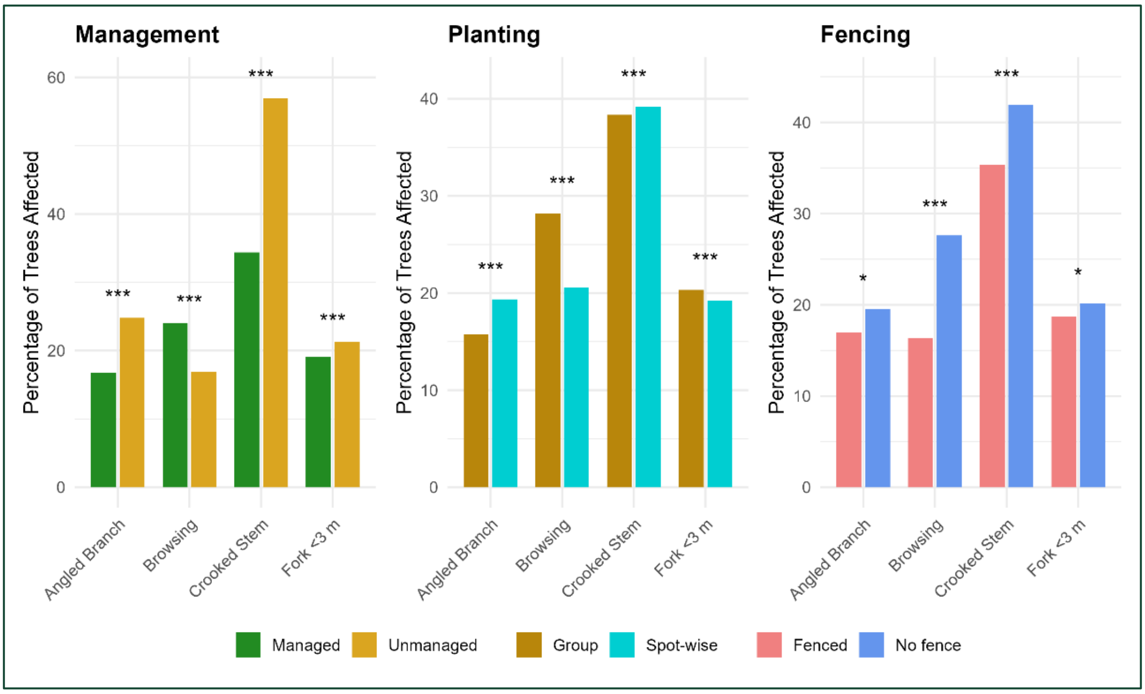

Figure 10. Percentage of oak trees affected by four types of defects: Angled Branch, Browsing, Crooked Stem and Fork <3 m, across three groups: Management, Planting and Fencing. Significant levels indicated by asterisks (= p < 0.05, ** = p < 0.01, *** = p < 0.001) based on Chi-square tests.*

4. Discussion

My study focused on investigating the development of 20-year-old oaks that were planted as part of a conversion from Norway spruce stands following the storm Gudrun. The aim was to evaluate how different silvicultural strategies (management, planting method and fencing) have influenced the performance in terms of survival, growth, browsing damage and stem quality.

My main findings were:

Fencing had the most consistent and positive impact on both oak growth and quality. Management (pre-commercial thinning) had some positive effect on DBH and crown volume, but was not significant in multilevel models. Stem density had a consistent negative effect on oak survival across all treatment models. DBH had a strong and positive relationship with crown volume across all treatments, in all models. The planting method (Group vs. Spot-wise) had a limited impact on survival and growth, but did affect crown shape and defect frequency, where group-planted oaks had lower crown ratios and overall smaller crown volume. Regarding quality defects, they were more prevalent in unfenced and unmanaged sites, and browsing and forks were more common in group settings.

4.1 Survival

The median survival in both the management and fencing groups fell below 50%, indicating a rather high level of mortality among the planted oaks and highlights the challenges of oak regeneration even when actively managed. However, such high levels of mortality of young oaks are not uncommon. A study by Jensen & Löf (2017) reported similar outcomes, with survival dropping to similar levels or lower, 8 years after planting, likely due to competition from woody vegetation that limits the availability of light. As seen in Figure 5, the oaks were clearly suppressed by other species in the overstorey, and this may be one explanation for the high mortality rate.

In line with this, the linear models in this study showed a clear and consistent pattern showing that higher total stem densities (including all species) were associated with lower oak survival, regardless of management, fencing and planting method. The R^2 values (~ 20%) are relatively high when considering the consistency across the models, and it emphasises that stem density (competition), particularly for light, is a critical driver of mortality for oaks in these stands.

Contrary to expectation, survival was not significantly higher in fenced or managed stands, suggesting that neither pre-commercial thinning nor fencing had any clear effect on the survival of the oaks within this study. The slightly higher survival observed in unmanaged sites may be explained by the fact that severely damaged individuals were likely removed during PCT, whereas damaged individuals in unmanaged sites may have persisted, leading to an apparent increase in survival. Furthermore, fences do not always manage to keep ungulate browsers outside, and this could also be a possible explanation for similar mortality rates. These results suggest that other factors beyond browsing or competition played a role in limiting the establishment of the oaks, such as the timing of interventions or climatic factors. That fenced sites did not show higher survival rates than unfenced ones is in line with results from Löf et al. (2021), where fencing also turned out to have little effect on survival and establishment.

Additionally, a higher proportion of group plantings within a site was not found to affect the survival of the oaks. However, this might be due to the limited number of sample plots and the variability within the groups, regarding size and the influence of different species compositions – why significance was not detected. These findings raise important questions, such as, how survival can be improved. As fencing has shown not to be sufficient alone, what other measurements are needed? Furthermore, although not directly investigated here, understanding the role of species composition and mixture proportion could be critical to improve survival.

4.2 Size of oaks

4.2.1 Managed versus Unmanaged

Both the non-parametric Wilcoxon tests and the linear mixed-effects models were used to evaluate the influence of PCT on oak growth. The Wilcoxon results showed that diameter at breast height as well as the crown volumes in the managed stands were significantly larger compared to the unmanaged ones, which aligns with expectations that PCT reduces competition for essential resources such as light and space, hence promoting tree growth. Interestingly, height and crown ratio did not differ between the two groups. This might indicate that when given more space, oaks prioritise allocating their resources on stem growth (DBH) and crown expansion rather than on height, which aligns with the morphological strategy of light-demanding species (Bartkowicz & Paluch 2023). Alternatively, the lack of difference in crown ratio may suggest that under high competition, crowns are first compromised in width rather than in length.

To complement the Wilcoxon tests and account for the nested data structure (trees within plots, plots within sites), mixed-effect models were applied. These confirmed that DBH was a strong and significant predictor of crown volume, with each additional centimetre in diameter associated with a nearly 1 m^3 increase in crown volume. However, in contrast to the Wilcoxon tests, the models did not detect a statistically significant effect of management on any of the growth variables once site- and plot-level variation was accounted for. This suggests that while PCT appears beneficial at the plot level, its overall effect across varied site conditions is less pronounced. Factors like environmental conditions were likely more important in determining how the young oaks developed. As pointed out by Ekö & Johansson (2022), site quality is a decisive factor, and on poor sites, the prospects of producing valuable oaks are minimal, at least within a reasonable time span.

Even though the oaks varied with a few years in age, age did not explain the variation in growth, nor in height, DBH, crown ratio or crown volume. This suggests that a slight age difference does not provide a significant growth advantage at this stage of the oaks development.

4.2.2 Group versus Spot-wise

Crown ratios were found to be significantly higher in spot-wise planted oaks, and crown volume showed a weak trend towards bigger volumes in spot-wise planted oaks. This may indicate that the oaks in group settings were subjected to more intraspecific competition, likely hindering crown development due to restricted light availability. This interpretation is consistent with findings from a study on morphological plasticity in European deciduous forests, which observed that light-demanding species like oaks develop smaller crowns under denser stand conditions due to the competition for light (Bartkowicz & Paluch 2023). No significant difference was found for height or DBH when comparing the two planting methods. This could imply that these growth variables are less sensitive to planting pattern at this juvenile stage, or that height growth is prioritised to outcompete neighbours for light. Furthermore, the absence of height and DBH differences points again to the crown architecture being more plastic and responsive than these variables, and can indicate early if the competition is balanced or too high (Bartkowicz & Paluch 2023).

Although it appears as if spot-wise planting favours crown development in oaks, there might instead be quality trade-offs of growing more freely. As some competition can improve stem form and reduce the growth of epicormics (Attochi 2015), trees growing freely may develop poorer stem form, and the natural pruning of low branches might decrease if light availability remains high. See further discussion under 4.3 *Quality of Oaks*.

4.2.3 Fenced versus Unfenced

Regarding the analysis for fenced and unfenced stands, all the measured variables – height, DBH, crown ratio and crown volume were significantly improved by a protective fence. The Wilcoxon test showed clear differences between the two groups, and the mixed-effect models confirmed that these patterns held even when accounting for nested data structure. These findings strongly agree with the notion that fencing has an important positive effect on early oak development. The results are consistent with the expected outcome, as fencing is widely recognised as essential for protecting young oaks from browsing and fraying by ungulates (Löf et al. 2021; Valkonen 2008). Nevertheless, identifying the optimal combination of fencing method and planting strategy (planting method and species composition) to reduce overall costs is crucial. As Bolibok et al. (2021) point out, more research is needed to develop effective regeneration strategies, especially for oaks under high browsing pressure.

Tree age was not a significant factor in any of the models, which again confirms that fencing effects were robust and not merely a byproduct of local site conditions or tree age. However, the mixed-effect model revealed that random site effects still played a considerable role and suggests that the choice of site is crucial even if all protective measures are taken.

4.3 Quality of oaks

Quality-wise, a large proportion of the surveyed oaks had some form of morphological defect. The most prevalent defect type in total was crooked stems, following browsing, forks below 3 m and angled branches. Stem deformation and forking are common challenges in young oak stands (Skrzyszewski & Pach 2015), and as noted by Drössler et al. (2017), achieving high-quality timber requires intensive early management. The forming of high-quality timber oaks starts early on, such as with formative pruning, leader shoot correction (removal of forks), and removal of angled branches, which are crucial to ensure high quality. Angled branches, if not removed early, become difficult for the harvester to remove cleanly (Södra 2020), and the likelihood of resulting in mechanical defects may increase, consequently leading to downgrading of the timber. Crooked stems are not always considered undesirable. In fact, in some markets – interior design, furniture, special products, etc. – irregular stems can be seen as aesthetically appealing. However, for the production of high-value timber products such as veneer logs, a straight stem is a critical quality criterion.

Browsing damage represents a more serious risk to timber quality. Not only can it cause distorted apical growth, perhaps leading to the formation of forks, but it can also introduce fungal pathogens (Marčiulynas et al. 2023) or decay organisms, lowering wood quality. While oaks have a high ability to eventually heal (overgrow) minor wounds with time, a knot will likely form, another cause of downgrading. While earlier studies have reported that oaks planted in groups reduced browsing pressure compared to traditional planting, however, the groups in the study by Bolibok et al. consisted of 18 – 27 oaks in each cluster, and therefore, it might not be completely comparable to the present study (Bolibok et al. 2021).

Forks below 3 meters are also a serious quality defect in oak timber, since it limits usable length and the typical timber quality standards require a minimum of 3 meters of branch-free, straight stem (Kährs 2025). Ultimately, oak trees with serious defects will affect the economic returns. They are either left in the forest for ecological purposes or harvested as firewood, both of which become a substantial economic loss compared to their potential.

Importantly, fencing significantly reduced the occurrence of all defect types, as indicated by Chi-square analysis. This could mean that browsing in many cases was the original cause that led to the formation of other defects, such as two top shoots (forks) and crookedness. Furthermore, angled branches, crooked stems, and forks were significantly lower in the managed stands, suggesting that PCT had positive effects on the oaks' development quality wise.

4.4 Study limitations and future directions

The sample sizes between the different groups were uneven; for example, while 23 managed stands were included, only 9 unmanaged stands were available. Such an imbalance can skew comparisons, since smaller groups are more sensitive to outlier, hence it could distort group-level summaries.

Another key limitation was the lack of records on the initial planting number with different planting methods (group and spot-wise), which limited the survival analysis between these groups. Furthermore, the variability of species mixtures, planting spacing and oak proportion per site added more complexity. These stand-level differences likely influenced both growth and quality outcomes but could not be fully controlled for in the analysis.

Due to the data structure, the Chi-square test results should not be overinterpreted as it assumes that observations are independent – a condition that was only partly met here, since trees within the same plots are influenced by the same local conditions like soil, climate and browsing pressure. Therefore, these results should rather be seen as indicative patterns.

The surveyed sites were distributed in a rather large geographic area (Götaland), spanning different vegetation zones and environmental conditions. For example, variation in temperature, precipitation, soil characteristics and browsing pressure, all of which can impact the growth and survival of the oaks. The use of the mixed-effects models did account for some of this variability; however, there may still be potential sources of noise in the data.

This master's thesis focused on early-stage growth, survival and form, but oak’s actual timber value is realised much later. A follow-up in future studies in these stands is needed to assess how the early defects, management and planting method influenced the final timber product and the economic return. Lastly, as these converted stands are a part of a broader climate adaptation strategy, and have now reached around 20 years of age, future research should shift focus toward evaluating their long-term resilience to climate-related stressors, such as storm damage, drought and possibly pest outbreaks – since one of the central motives for establishing these broadleaf mixtures was to create more robust and diverse forest systems that will better withstand such disturbances.

Conclusions

In conclusion, this study investigated early oak development in mixed broadleaf stands established following the storm Gudrun in 2005. The findings showed that high mortality of oaks can be an issue even in fenced and managed stands. However, fencing consistently benefited oak development as it reduced browsing damage and significantly improved growth in all measured aspects. PCT had a modest but positive effect on crown development and DBH, while the planting method only showed weak and varied trends. The most prevalent defects were crooked stems and forks below 3 meters, both of which are detrimental to future timber value. These defects were especially common in unmanaged and unfenced plots. Although Chi-square tests indicated significant differences in defect frequencies between groups, these should be interpreted with caution due to non-independence among trees within plots.

The results of this study, taken together, show the complexity and costs accompanying the production of high-quality oak under mixed stand conditions. To encourage more forest owners to establish oaks, cost-effective establishment strategies that provide a balance between cost and high-quality oak production in mixed species stands are an important topic to be explored. Long-term monitoring will be needed to assess whether these stands ultimately will fulfil their intended ecological and economic purposes over time, and provide a more robust climate-adapted alternative to Norway spruce.

References

Attocchi, G. (2015). Silviculture of Oak for High-Quality Wood Production. Swedish University of Agricultural Sciences. https://pub.epsilon.slu.se/12078/1/attocchi_g_150402.pdf

Bartkowicz, L. & Paluch, J. (2023). Morphological plasticity of six tree species with different light demands growing in multi-layered deciduous forests in Central Europe. European Journal of Forest Research, 142 (5), 1177–1195. https://doi.org/10.1007/s10342-023-01584-7

Bauhus, J., Forrester, D.I., Gardiner, B., Jactel, H., Vallejo, R. & Pretzsch, H. (2017). Ecological Stability of Mixed-Species Forests. I: Pretzsch, H., Forrester, D.I., & Bauhus, J. (red.) Mixed-Species Forests: Ecology and Management. Springer. 337–382. https://doi.org/10.1007/978-3-662-54553-9_7

Berg & Berg. n.d. *Om oss.* Available at: https://berg-berg.com/om-oss/ [Accessed 2025-05-18]

Blennow, K. (2008). Risk management in Swedish forestry – Policy formation and fulfilment of goals. Journal of Risk Research, 11 (1–2), 237–254. https://doi.org/10.1080/13669870801939415

Bolibok, L., Andrzejczyk, T., Szeligowski, H. & Liziniewicz, M. (2021). New methods of oak planting require modification of tending prescriptions under high browsing pressure – A case study from north-eastern Poland. Forest Ecology and Management, 497, 119449. https://doi.org/10.1016/j.foreco.2021.119449

Carbonnier, C. (1975). *Produktionen i kulturbestånd av ek i södra Sverige : Yield of oak plantations in southern Sweden*.

Dekanić, S., Vrbek, B., Matošević, D., Roth, V., Jakovljević, T., Zlatanov, T., Tomo. (2009). Crown volume in forest stands of pedunculate oak and common hornbeam. https://www.researchgate.net/publication/41194331_Crown_volume_in_forest_stands_of_pedunculate_oak_and_common_hornbeam

Dubravac, T., Dekanić, S., Vrbek, B., Matošević, D., Roth, V. & Jakovljević, T. (2009). Crown volume in forest stands of pedunculate oak and common hornbeam. *Periodicum Biologorum*, 111(4), 479–485. https://hrcak.srce.hr/47943

Drössler, L., Huth, F. & Mölder, A. (2017). NYA PERSPEKTIV PÅ EKSKOGSSKÖTSEL. https://ekframjandet.se/wp-content/uploads//2012/01/Ekbladet-32-hela-low-edit.pdf

Ekö, P.M. & Johansson, U. 2022. *Lövträd och lövskog – Skötsel för värden och miljö*. Uppsala: Skogforsk. https://www.skogforsk.se/cd_20191104171530/contentassets/d16b5f608f0a43fb9e6f54f110eaf47f/lovtrad-och-lovskog-low.pdf [Accessed 2025-05-17]

European Forest Institute (2020). Russian forests and climate change. European Forest Institute, Leskinen, P., Lindner, M., European Forest Institute, Verkerk, P.J., Nabuurs, G.-J., Van Brusselen, J., Kulikova, E., Hassegawa, M., & Lerink, B.

(red.) (European Forest Institute, Leskinen, P., Lindner, M., European Forest Institute, Verkerk, P. J., Nabuurs, G.-J., Van Brusselen, J., Kulikova, E., Hassegawa, M., & Lerink, B., red.) European Forest Institute. https://doi.org/10.36333/wsctu11

Felton, A., Lindbladh, M., Brunet, J. & Fritz, Ö. (2010). Replacing coniferous monocultures with mixed-species production stands: An assessment of the potential benefits for forest biodiversity in northern Europe. Forest Ecology and Management, 260 (6), 939–947. https://doi.org/10.1016/j.foreco.2010.06.011

Hansen, J. & Spiecker, H. (2004). Conversion of Norway Spruce (Picea abies [L.] Karst.) Forests in Europe. I: Restoration of Boreal and Temperate Forests. 2. uppl. CRC Press.

Huang, Y., Chen, Y., Castro-Izaguirre, N., Baruffol, M., Brezzi, M., Lang, A., Li, Y., Härdtle, W., von Oheimb, G., Yang, X., Liu, X., Pei, K., Both, S., Yang, B., Eichenberg, D., Assmann, T., Bauhus, J., Behrens, T., Buscot, F., … Schmid, B. (2018). *Impacts of species richness on productivity in a large-scale subtropical forest experiment*. *Science*, 362(6410), 80–83.https://doi.org/10.1126/science.aat6405

Huuskonen, S., Domisch, T., Finér, L., Hantula, J., Hynynen, J., Matala, J., Miina, J., Neuvonen, S., Nevalainen, S., Niemistö, P., Nikula, A., Piri, T., Siitonen, J., Smolander, A., Tonteri, T., Uotila, K. & Viiri, H. (2021). What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? Forest Ecology and Management, 479, 118558. https://doi.org/10.1016/j.foreco.2020.118558

Jactel, H., Gritti, E.S., Drössler, L., Forrester, D.I., Mason, W.L., Morin, X., Pretzsch, H. & Castagneyrol, B. (2018). Positive biodiversity–productivity relationships in forests: climate matters. *Biology Letters*, 14 (4), 20170747. https://doi.org/10.1098/rsbl.2017.0747

Jarnemo, A. (2023). Management of red deer and fallow deer in Sweden. Miljøstyrelsen. https://mst.dk/media/hvnhumlx/2024_management-of-red-deer-and-fallow-deer-in-sweden_2024-02-08.pdf [Accessed 2025-05-02]

Jensen, A.M. & Löf, M. (2017). Effects of interspecific competition from surrounding vegetation on mortality, growth and stem development in young oaks (Quercus robur). Forest Ecology and Management, 392, 176–183. https://doi.org/10.1016/j.foreco.2017.03.009

Jucker, T., Bouriaud, O., Avacaritei, D. & Coomes, D.A. (2014). Stabilizing effects of diversity on aboveground wood production in forest ecosystems: linking patterns and processes. Ecology Letters, 17 (12), 1560–1569. https://doi.org/10.1111/ele.12382

Karlsson, F. (1996). *Skogsbrukets bekämpningsmedel – uppkomst och förfall*. Uppsala: Sveriges lantbruksuniversitet. https://pub.epsilon.slu.se/4274/1/Karlsson_F_1996.pdf

Kährs Group (2024). *Kährs Sustainability Report 2024: A Journey of Progress – Always Moving Towards Our Goals.* Malmö: Kährs BondCo AB (publ). Available at: https://www.kahrsgroup.com/globalassets/kahrs/consumer/aboutus/environment/kahrs-sustainability-report-2024.pdf [Accessed: 2025-05-18].

Larsen, N.M. & Aagaard, A.K. (2020). Robotic processing of crooked sawlogs for use in architectural construction. *Construction Robotics*, 4 (1), 75–83. https://doi.org/10.1007/s41693-020-00028-7

Liang, J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., Schulze, E.-D., McGuire, A.D., Bozzato, F., Pretzsch, H., de-Miguel, S., Paquette, A., Hérault, B., Scherer-Lorenzen, M., Barrett, C.B., Glick, H.B., Hengeveld, G.M., Nabuurs, G.-J., Pfautsch, S., Viana, H., Vibrans, A.C., Ammer, C., Schall, P., Verbyla, D., Tchebakova, N., Fischer, M., Watson, J.V., Chen, H.Y.H., Lei, X., Schelhaas, M.-J., Lu, H., Gianelle, D., Parfenova, E.I., Salas, C., Lee, E., Lee, B., Kim, H.S., Bruelheide, H., Coomes, D.A., Piotto, D., Sunderland, T., Schmid, B., Gourlet-Fleury, S., Sonké, B., Tavani, R., Zhu, J., Brandl, S., Vayreda, J., Kitahara, F., Searle, E.B., Neldner, V.J., Ngugi, M.R., Baraloto, C., Frizzera, L., Bałazy, R., Oleksyn, J., Zawiła-Niedźwiecki, T., Bouriaud, O., Bussotti, F., Finér, L., Jaroszewicz, B., Jucker, T., Valladares, F., Jagodzinski, A.M., Peri, P.L., Gonmadje, C., Marthy, W., O'Brien, T., Martin, E.H., Marshall, A.R., Rovero, F., Bitariho, R., Niklaus, P.A., Alvarez-Loayza, P., Chamuya, N., Valencia, R., Mortier, F., Wortel, V., Engone-Obiang, N.L., Ferreira, L.V., Odeke, D.E., Vasquez, R.M., Lewis, S.L. & Reich, P.B. (2016). Positive biodiversity-productivity relationship predominant in global forests. *Science*, 354 (6309), aaf8957. https://doi.org/10.1126/science.aaf8957

Löf, M. (2006). *Halvtid för uthålligt skogsbruk i ädellövskog*. Arbetsrapport nr 30. Sveriges lantbruksuniversitet, Institutionen för sydsvensk skogsvetenskap, Alnarp. Tillgänglig: https://pub.epsilon.slu.se/33391/1/lof-m-20240423.pdf

Löf, M. & Birkedal, M. (2009). Direct seeding of Quercus robur L. for reforestation: The influence of mechanical site preparation and sowing date on early growth of seedlings. Forest Ecology and Management, 258 (5), 704–711. https://doi.org/10.1016/j.foreco.2009.05.008

Löf, M., Barrere, J., Engman, M., Petersson, L.K. & Villalobos, A. (2021). The influence of fencing on seedling establishment during reforestation of oak stands: a comparison of artificial and natural regeneration techniques including costs. *European Journal of Forest Research*, 140 (4), 807–817. https://doi.org/10.1007/s10342-021-01369-w

Löf, M., Bolte, A., Jacobs, D.F. & Jensen, A.M., (2014). *Nurse trees as a forest restoration tool for mixed plantations: effects on competing vegetation and performance in target tree species*. Restoration Ecology, 22(6), pp.758–765. https://doi.org/10.1111/rec.12136

Löf, M., Sandell Festin, E., Szydło, M. & Brunet, J. (2023). Restoring mixed forests through conversion of Norway spruce stands: effects of fencing and mechanical site preparation on performance of planted beech and natural tree regeneration.

European Journal of Forest Research, 142 (4), 763–772. https://doi.org/10.1007/s10342-023-01554-z

Marčiulynas, A., Sirgedaitė-Šėžienė, V. & Menkis, A. (2023). Fungi Inhabiting Stem Wounds of Quercus robur following Bark Stripping by Deer Animals. *Forests*, 14 (10), 2077. https://doi.org/10.3390/f14102077

Manson, R.H., Ostfeld, R.S. & Canham, C.D. (2001). Long-Term Effects of Rodent Herbivores on Tree Invasion Dynamics Along Forest–Field Edges. Ecology, 82 (12), 3320–3329. https://doi.org/10.1890/0012-9658(2001)082[3320:LTEORH]2.0.CO;2

Martin, F.M. & van der Heijden, M.G.A. (2024). The mycorrhizal symbiosis: research frontiers in genomics, ecology, and agricultural application. New Phytologist, 242 (4), 1486–1506. https://doi.org/10.1111/nph.19541

Mitchell, R.J., Bellamy, P.E., Ellis, C.J., Hewison, R.L., Hodgetts, N.G., Iason, G.R., Littlewood, N.A., Newey, S., Stockan, J.A. & Taylor, A.F.S. (2019). OakEcol: A database of Oak-associated biodiversity within the UK. *Data in Brief*, 25, 104120. https://doi.org/10.1016/j.dib.2019.104120

News Cision (2017). *Södra and Kährs Group enter new oak partnership*. News Powered by Cision. Available at: https://news.cision.com/sodra/r/sodra-and-kahrs-group-enter-new-oak-partnership,c2249377 [Accessed 2025-05-10].

Olsson, O., 2014. *Cyclone Gudrun and the future of Swedish forestry: thoughts from the Swedish Forestry Association's Annual Excursion 2014*. Stockholm Environment Institute. https://www.sei.org/perspectives/cyclone-gudrun-swedish-forestry/ [Accessed 2025-05-19].

Forest Research (n.d.). *Pedunculate oak (POK).* https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131559-pedunculate-oak-pok-2/ [Accessed 2025-05-10].

Peterson, C.J. (2007). Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns. Forest Ecology and Management, 250 (1–2), 96–108. https://doi.org/10.1016/j.foreco.2007.03.013

Reventlow, D.O.J., Nord-Larsen, T., Biber, P., Hilmers, T. & Pretzsch, H. (2021). Simulating conversion of even-aged Norway spruce into uneven-aged mixed forest: effects of different scenarios on production, economy and heterogeneity. European Journal of Forest Research, 140 (4), 1005–1027. https://doi.org/10.1007/s10342-021-01381-0

del Río, M., Pretzsch, H., Ruiz-Peinado, R., Jactel, H., Coll, L., Löf, M., Aldea, J., Ammer, C., Avdagić, A., Barbeito, I., Bielak, K., Bravo, F., Brazaitis, G., Cerný, J., Collet, C., Condés, S., Drössler, L., Fabrika, M., Heym, M., Holm, S.-O., Hylen, G., Jansons, A., Kurylyak, V., Lombardi, F., Matović, B., Metslaid, M., Motta, R., Nord-Larsen, T., Nothdurft, A., den Ouden, J., Pach, M., Pardos, M., Poeydebat, C., Ponette, Q., Pérot, T., Reventlow, D.O.J., Sitko, R., Sramek, V., Steckel, M., Svoboda, M., Verheyen, K., Vospernik, S., Wolff, B., Zlatanov, T. & Bravo-Oviedo, A. (2022). Emerging stability of forest productivity by mixing two species buffers temperature destabilizing effect. Journal of Applied Ecology, 59 (11), 2730–2741. https://doi.org/10.1111/1365-2664.14267

Schnabel, F., Schwarz, J.A., Dănescu, A., Fichtner, A., Nock, C.A., Bauhus, J. & Potvin, C. (2019). Drivers of productivity and its temporal stability in a tropical tree diversity experiment. Global Change Biology, 25 (12), 4257–4272. https://doi.org/10.1111/gcb.14792

Skiadaresis, G., Saha, S. & Bauhus, J. (2016). Oak Group Planting Produces a Higher Number of Future Crop Trees, with Better Spatial Distribution than Row Planting. Forests, 7 (11), 289. https://doi.org/10.3390/f7110289

Skogsaktuellt (2025). *Så mycket ek importerar vi från Tyskland*. Available at: https://www.skogsaktuellt.se/artikel/60755/s-mycket-ek-importerar-vi-frn-tyskland.html [Accessed 2025-05-10].

Skogskunskap (2025). *Ek (Quercus spp.)*. Available at: https://www.skogskunskap.se/skota-lovskog/om-lov/vara-lovtrad/ek-quercus-spp/ [Accessed 2025-05-10].

Skogskunskap (2025). *Föryngra lövskog*. Available at: https://www.skogskunskap.se/skota-lovskog/om-lov/varfor-lov/ [Accessed 2025-05-17].

Skogskunskap (2025). *Skötselsystem för ekskog - översikt*. Available at: https://www.skogskunskap.se/skota-skog/foryngra/planera-lovskogsbruket/skotselsystem-for-ekskog---oversikt/ [Accessed 2025-05-09].

Skogskunskap (2025). *Röjning i ek*. Available at: https://www.skogskunskap.se/skota-skog/roja/rojning-i-lovbestand/rojning-i-ek/ [Accessed 2025-05-19].

Skogsstyrelsen (2025). *20 år efter stormen Gudrun.* Available at:https://www.skogsstyrelsen.se/nyhetslista/20-ar-efter-stormen-gudrun/ [Accessed 2025-05-19].

Skogsstyrelsen (2017). Efter Gudrun: Erfarenheter av stormen och rekommendationer för framtiden. Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/bruka-skog/skogsskador/rapport-efter-gudrun.pdf [Accessed 2025-04-19]

Skogsstyrelsen. (2015). *Skötsel av ädellövskog*. Skogsskötselserien nr 10. Jönköping: Skogsstyrelsen. Available at: https://www.skogsstyrelsen.se/globalassets/mer-om-skog/skogsskotselserien/skogsskotselserien-10-skotsel-av-adellovskog-2015.pdf [Accessed 2025-05-17].

Skogssällskapet (2025). *Här är årets bidrag för dig som skogsägare*. Available at: https://www.skogssallskapet.se/pa-gang/nyheter/pressmeddelanden/2025-02-05-har-ar-arets-bidrag-for-dig-som-skogsagare.html [Accessed 2025-06-10].

Skrzyszewski, J. & and Pach, M. (2015). Crookedness of pedunculate oak (Quercus robur L.) growing under a canopy of Scots pine (Pinus sylvestris L.). Scandinavian Journal of Forest Research, 30 (8), 688–698. https://doi.org/10.1080/02827581.2015.1048713

SLU Riksskogstaxeringen (2024). *Skogsdata 2024 – Aktuella uppgifter om de svenska skogarna från SLU Riksskogstaxeringen*. Sveriges lantbruksuniversitet, Umeå.

https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2024_web.pdf.

Smith, K.M. (2005). Crown Radius and Diameter at Breast Height Relationships for Six Bottomland Hardwood Species. 59.

SMHI. (n.d). *Normalperioden 1991-2020*. Available at: https://www.smhi.se/kunskapsbanken/klimat/normaler/normalperioden-1991-2020 [Accessed 2025-05-10].

Stanturf, J.A., Palik, B.J. & Dumroese, R.K. (2014). Contemporary forest restoration: A review emphasizing function. Forest Ecology and Management, 331, 292–323. https://doi.org/10.1016/j.foreco.2014.07.029.

Sveaskog (2025). *Sveriges största skogsägare – Sveaskog utvecklar skogens alla värden*. Available at: https://www.sveaskog.se/ [Accessed 2025-05-19].

Sveaskog (2024). *Skogen efter stormen Gudrun*. Available at: https://www.sveaskog.se/skogen-pa-djupet/varierat-skogsbruk/skogen-efter-stormen-gudrun/ [Accessed 2025-05-09].

Sveaskog (2022). *Naturvärden i Ekopark Omberg*. Available at: https://www.sveaskog.se/upplev-naturen/besoksomraden/ekopark-omberg/naturvarden/ [Accessed 2025-05-11]

Sveaskog (2022). *Naturvärden i Ekopark Omberg*. Available at: https://www.sveaskog.se/upplev-naturen/besoksomraden/ekoparkomberg/naturvarden/ [Accessed 2025-05-10].

Södra (2020). *Stort behov av lövtimmer*. Available at: https://www.sodra.com/sv/se/skogmedlem/aktuellt/sodrakontakt/nyhetsartiklar/2020/nummer-3/stort-behov-av-lovtimmer/ [Accessed 2025-05-10].

Södra (2020). Gratis ekplantor när Kährs sponsrar. Available at: https://www.sodra.com/sv/se/skogmedlem/aktuellt/sodrakontakt/nyhetsartiklar/2020/nummer-3/gratis-ekplantor-nar-kahrs-sponsrar/ [Accessed 2025-05-10]

Ulmanen, J., Swartling, Å.G. & Wallgren, O. (2015). Climate Adaptation in Swedish Forestry: Exploring the Debate and Policy Process, 1990–2012. Forests, 6 (3), 708–733. https://doi.org/10.3390/f6030708

Valinger, E. & Fridman, J. (2011). Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. Forest Ecology and Management, 262 (3), 398–403. https://doi.org/10.1016/j.foreco.2011.04.004

Valinger, E., Kempe, G. & Fridman, J., (2019). Impacts on forest management and forest state in southern Sweden 10 years after the storm Gudrun. *Forestry: An International Journal of Forest Research*, 92(4), pp.481–489. https://doi.org/10.1093/forestry/cpz005https://www.researchgate.net/publication/345501317_Impacts_on_forest_management_and_forest_state_in_southern_Sweden_10_years_after_the_storm_Gudrun

Valkonen, S. (2008). Survival and growth of planted and seeded oak (Quercus robur L.) seedlings with and without shelters on field afforestation sites in Finland. Forest

Ecology and Management, 255 (3), 1085–1094. https://doi.org/10.1016/j.foreco.2007.10.038

Vergarechea, M., Astrup, R., Fischer, C., Øistad, K., Blattert, C., Hartikainen, M., Eyvindson, K., Di Fulvio, F., Forsell, N., Burgas, D., Toraño-Caicoya, A., Mönkkönen, M. & Antón-Fernández, C. (2023). Future wood demands and ecosystem services trade-offs: A policy analysis in Norway. Forest Policy and Economics, 147, 102899. https://doi.org/10.1016/j.forpol.2022.102899

Woxblom, L. & Nylinder, M. (2010). Industrial utilization of hardwood in Sweden. Ecological Bulletins, (53), 43–50

Ädellövskogslag (1984:119). Stockholm: Sveriges riksdag. Available at: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/adellovskogslag-1984119_sfs-1984-119/ [Accessed 2025-06-05].

Bättre rustade för klimatförändringar - och nästa storm

Utveckling av planterade ekar i blandskogar, 20 år efter Gudrun

Stormen Gudrun orsakade omfattade skador när hon drog in över södra Sverige 2005. Vad som stod klart var att gran – vårt mest planterade trädslag – inte står pall för starka vindar. Händelsen väckte insikter om att det svenska skogsbruket står inför utmaningar i takt med klimatförändringarna – om vi vill fortsätta driva ett hållbart och lönsamt skogsbruk krävs nya lösningar.

Sveaskogs strategi blev att återbeskoga tio procent av den stormhärjade arealen med inhemska lövträd, däribland ek – ett mer stormfast alternativ som både kan producera högkvalitativt virke och bidra till biologisk mångfald. Hur vi bäst ska balansera ekonomiska, sociala och ekologiska värden i blandskogar har vi ännu mycket kvar att utforska. Granen förblir ett av våra ekonomiskt viktigaste trädslag och kommer sannolikt spela en central roll även i framtidens skogsbruk. Men kanske inte överallt, och kanske inte ensam.

Detta mastersarbete har utförts i samarbete med Sveaskog, med deras skogsbestånd som utgångspunkt för studien. Jag har undersökt hur dessa blandskogar har utvecklats efter 20 år, med fokus på trädslaget ek. Jag har jämfört ekarna utveckling och kvalitet i olika bestånd: röjda och oröjda, olika planteringssätt (i grupp och utspritt), samt hägnade och ohägnande bestånd. Även ekarnas överlevnad samt kvalitet har undersökts.

Resultaten visade att det var relativt låg överlevnad i samtliga grupper. Hägn hade positiv effekt - ekarna var högre, grövre och hade färre kvalitetsdefekter. Ungskogsröjning gav viss positiv inverkan framförallt på kronutvecklingen, men effekten var mindre än förväntat. Planteringssättet – om ekarna växte i grupp eller utspritt visade sig ha liten påverkan på tillväxt och överlevnad. Kvalitetsdefekter som viltskador, krokighet, låga klykor och sprötkvistar noterades och förekomsten av dessa var hög – framförallt i oröjda och ohägnade bestånd.

Huruvida dessa bestånd i längden kommer att leva upp till förhoppningarna, både vad gäller lönsamhet och motståndskraft mot ett förändrat klimat och stormar återstår att se.

Appendix 1

A list of p-values from Chi-squared tests evaluating associations between oak quality defects and treatment variables (management, fencing, planting method).

Defect	Group	p-value
Angled Branch	Management	<0.001
Browsing	Management	<0.001
Crooked Stem	Management	<0.001
Fork <3 m	Management	<0.001
Fork >3 m	Management	<0.001
Angled Branch	Fencing	0.0105
Browsing	Fencing	<0.001
Crooked Stem	Fencing	<0.001
Fork <3 m	Fencing	0.0317
Fork >3 m	Fencing	0.9060
Angled Branch	Planting	<0.001
Browsing	Planting	<0.001
Crooked Stem	Planting	<0.001
Fork <3 m	Planting	<0.001
Fork >3 m	Planting	0.0241

Appendix 2

R packages used. All statistical analyses and visualisations in this thesis were conducted using R version 4.4.3. The following packages were used for data handling, modelling, and graphics:

R package	Description
tidyverse (dplyr, ggplot2, tidyr, readr, etc.)	For preparing data, generating exploratory graphics
ggpubr, patchwork, ggsignif, ggpp	For enhanced plotting and figure layout
lme4, lmerTest, performance, insight	For linear mixed models and diagnostics

Appendix 3

The three most common species at each site, in descending order.

Site number	The three most common Species
1	Birch, Oak, Rowan
2	Birch, Aspen, Oak
3	Oak, Silver birch, Larch
4	Birch, Ash, Oak
5	Rowan, Oak, Goat willow
6	Sweet cherry, Goat willow, Oak
7	Oak, Hazel, Birch
8	Silver birch, Rowan, Oak
9	Hazel, Silver birch, Oak
10	Oak, Birch, Alder
11	Oak, Birch, Aspen
12	Birch, Oak, Goat willow
13	Birch, Oak, Goat willow
14	Birch, Oak, Rowan
15	Birch, Rowan, Oak
16	Birch, Oak, Spruce
17	Birch, Oak, Rowan
18	Birch, Oak, Rowan
19	Birch, Oak, Rowan
20	Birch, Oak, Goat willow
21	Birch, Oak, Goat willow

22	Birch, Oak, Rowan
23	Oak, Birch, Goat willow
24	Birch, Oak, Aspen
25	Birch, Oak, Spruce
26	Oak, Birch
27	Oak, Larch, Birch
28	Birch, Oak, Goat willow
29	Oak, Rowan, Birch
30	Oak, Birch, Rowan
31	Birch, Oak
32	Birch, Oak
33	Birch, Oak, Pine

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