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Effects of target diameter cutting on oak recruitment in a multilayered mixed conifer-broadleaved stand in southern Sweden

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ABSTRACT

Managing multi-layered forest stands is increasingly promoted as a strategic adaptation measure to climate change. Pedunculate oak (*Quercus robur* L.) and sessile oak (*Q. petraea* (Matt.) Liebl.) are ecologically and economically important species and considered important components of future forest management. However, forest management is challenged by the unsuccessful recruitment of oak, particularly under selective cutting systems, due to the species' relatively high light requirements. In this study, we investigated the long-term effects of different selective cutting treatments on oak recruitment in multi-layered mixed stands over 16 years in southern Sweden. We studied the individual tree diameter growth, height growth, and transition of oak recruits into higher canopy positions. All target diameter cutting treatments significantly promoted the individual tree diameter growth of oak recruits, compared to the control. Observed height growth was lower in target diameter cutting treatments. However, target diameter cutting treatments increased the transitions of oak recruits into higher canopy positions. The higher diameter growth and canopy class transitions into higher classes are achieved by the treatment that removed more Norway spruce trees. Therefore, to promote the advancement of oak recruits into higher canopy positions, target diameter cutting could be an appropriate management alternative if it is sufficiently strong and is focused on removing the most competitive tree species.

1. Introduction

The two predominant oak species, pedunculate oak (*Quercus robur* L.) and sessile oak (*Q. petraea* (Matt.) Liebl.), are among the most important hardwood tree species in Central and Northern Europe from both ecological and forest management perspectives (Johnson et al., 2019; Mölder et al., 2019a; Kohler et al., 2020). The two species together constitute about 10 % of the stands in Europe, making them the second most common deciduous tree species in the region after European beech (*Fagus sylvatica* L.) (FOREST EUROPE, 2020). Oak-dominated forests provide a wide variety of forest ecosystem services, including high-value timber and habitats for key biodiversity, such as lichens, fungi, insects, birds, and small mammals (Löf et al., 2016). Given their tolerance to extreme climatic events such as drought (Mette et al., 2013; Kunz et al., 2018; Perkins et al., 2018) and storng wind (Nicolescu et al., 2025), these two oak species are widely considered important components of future climate-resilient mixed-species forests in the region. The establishment of mixed broadleaved forests has been considered as a strategic adaptation measure to climate change (Bolte et al., 2009). Therefore, their proportions in forest cover are expected to increase (Bolte et al., 2009; Löf et al., 2016; Schroeder et al., 2021). Despite this potential for adaptation of forest management to climate change, there remains uncertainty about the suitable silvicultural approaches promoting natural regeneration and recruitment of oak in multi-layered, mixed-species forests for sustainable oak management.

The two oak species in Sweden are limited to the south (Fig. 1), temperate region of the country (Lindbladh et al., 2000; Lindbladh and Foster, 2010). During the past century, oak forests were not only heavily affected by conifer plantations, especially of Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.), but also by intensive land use changes for agriculture (Lindbladh et al., 2000); as a result, oak now constitutes only less than 2 % of the standing volume in Sweden (Skogsdata, 2024). Most of these remaining oak forests are currently, or have been, managed for timber production by non-industrial private forest owners under diverse management regimes. The three common management regimes in oak forest management include: (1) intensive oak timber production targeting the production of high-value timber and following the contemporary silvicultural practices, (2) combined

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management for timber production and biodiversity, and (3) biodiversity conservation without management intervention (Löf et al., 2016). With appropriate management, these forests can yield high-value timber generating substantial economic returns.

Regeneration and recruitment are the two interconnected processes from the seedling stage to the development of mature trees. Successful natural regeneration of oaks is fundamental to sustaining oak forests. However, oak forests are experiencing widespread regeneration failures (Petersson et al., 2019). The natural regeneration success depends on several biotic and abiotic factors, where heavy browsing pressure, low light availability, and competing vegetation, among others, are significant factors that negatively affect natural regeneration (Löf, 2000; Mölder et al., 2019b; Kohler et al., 2020; Löf et al., 2021). Oak recruitment, or the transition of saplings into overstory canopy layers, is another important stand development process (Camp and Oliver, 2004) in which established saplings grow to pole and sawtimber-size trees. Successful oak recruitment is achieved when the desired species can compete and grow into dominant and codominant overstory trees (Dey, 2014). Disturbances are considered necessary for successful natural regeneration and recruitment of oaks (Götmark, 2007; Götmark and Kiffer, 2014). In these regards, silvicultural approaches in oak-dominated forests are necessary for enhancing light availability and controlling competing vegetation during different development stages to foster natural regeneration and recruitment of oak into upper canopy layers.

Given the ecological and economic importance of oaks, it is challenging to balance conservation of oak-dominated forests rich in biodiversity while maintaining their economic viability (Puettmann et al., 2015; Löf et al., 2016; Stimm et al., 2022). An alternative silvicultural approach, such as continuous cover forestry (CCF), could be an option for multipurpose forest management (Peura et al., 2018; Mason et al., 2022). The CCF approach is based on ecological and biological principles, with its most prominent tenet being the abandonment of large-scale clear-cutting in favour of more environmentally friendly harvesting practices, such as selective cutting, group selection, variable density thinning, and natural regeneration methods (Pommerening and Murphy, 2004; Brunner et al., 2025). Studies suggest that canopy gaps created by selective cutting are beneficial for successful oak natural regeneration because gaps enhance light availability and selective cutting removes competing trees (Březina and Dobrovolný, 2011; Modrow et al., 2019; Kanjevac et al., 2021; Plaugher and Schuler, 2025; Pohl et al., 2025). However, there remains a limited understanding of how different forms of selective cutting favour the development of oak recruits beyond establishment, especially those that are tall enough and freed from browsing pressure.

Target diameter cutting, among different selective cutting techniques, is a forest management approach in which selected trees that reach a specified diameter at breast height (DBH) are cut, aiming to balance economic and ecological sustainability. Target diameter cutting is often used to transform even-aged forests into uneven-aged or uneven-sized structures (Sterba and Zingg, 2001; Price and Price, 2006). Target diameter cutting approaches are more flexible and practical to apply in comparison with other forms of selective cutting systems because the DBH for cutting can be adjusted to different sites with varying growth conditions and tree species (Zell et al., 2004; Roessiger et al., 2016). As such, cutting of different species and tree individuals with large diameters creates canopy gaps that are beneficial for trees in lower canopy layers, especially for more light-demanding tree species. Understanding the response of oak recruits following such cuttings, in terms of tree crown social position within the stand, and height and diameter growth, could lead to reliable canopy manipulation strategies that promote oak recruits in multi-layered mixed temperate forests.

This study aims to determine the growth and advancement of oak recruits into higher levels of tree crown social position in response to

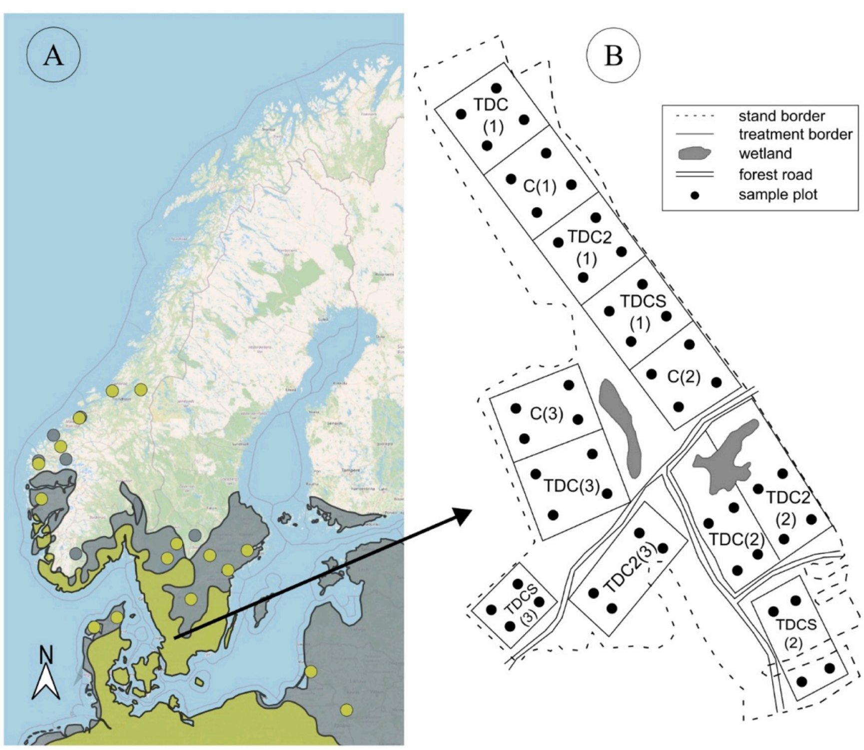

Fig. 1. Location of the experiment in southwestern Sweden (A), and the experimental design (B). Green colour in A represents distribution area of *Quercus petraea* (Matt. Liebl.), and grey colour represents distribution area of *Quercus robur* (L.) which overlap, and extends beyond, the distribution area of *Q. petraea*. TDC, TDC2, and TDCS represent different forms of target diameter cutting treatments, and C represents control without treatment. TDC stands for target diameter cutting, TDC2 is target diameter cutting with slightly modified target diameter, TDCS represent TDC and soil scarification treatment. In each treatment there were four permanent measurement plots (black filled circles). See Section 2.2 for detailed descriptions.

three different forms of selective cutting (here, different target diameter cuttings) over a period of 16 years. More specifically, we ask three research questions: (1) which stand structural and individual tree characteristics influence the diameter growth and height growth of oak recruits, (2) how does target diameter cutting influence diameter growth and height growth of oak recruits, and (3) how does target diameter cutting affect transition of oak recruits into higher tree crown/social classes?

2. Materials and methods

2.1. Study site and history

The study stand with a total area of 19 ha is located in southwest Sweden at Tönnersjöheden Experimental Forest, 20 km east of Halmstad (56°42′02″ N, 13°7′56″ E, Fig. 1). The stand is located on a productive site with site indices (dominant height at age 100) for Norway spruce and Scots pine of 32 m and 28 m, respectively (Drössler et al., 2012). The mean annual temperature is 6.7°C, and the mean annual precipitation is 1050 mm, with a vegetation period (growing season) lasting 215 days (Drössler et al., 2012). The soil type is a podzol on a sandy moraine. The forest floor is covered mainly by *Vaccinium myrtillus* L. and *Deschampsia flexuosa* L. Trin.

The study stand was established in 1912 by seeding of Scots pine with abundant natural regeneration of silver birch (*Betula pendula* Roth). Previously, the site was *Calluna* spp. heathland with some sparsely scattered trees across the landscape. Since then, many other species have established naturally over time. Currently, the stand is mainly composed of mature Scots pine and Norway spruce in the overstory. Broadleaved species, such as oak, silver birch, European beech, and European aspen (*Populus tremula* L.), are found in the under- and mid-stories. The first cutting in the stand was carried out in 1947, releasing single Scots pine trees, and thinning was then carried out several times (1947, 1953, 1958, 1974, and 1991) before the establishment of the current experiment.

2.2. Experimental design and data collection

The experiment consists of three blocks. Within each block, four treatments were randomly established, and each treatment area was 1 ha. The four treatments applied were: control without target diameter cutting (C); target diameter cutting (TDC); target diameter cutting with soil scarification (TDCS); and target diameter cutting with modified target diameters compared to the other two treatments (TDC2). DBH thresholds by tree species applied for cutting in each treatment are listed in Table 1. Target diameter thresholds applied in TDC and TDCS were chosen according to economic criteria based on timber quality and timber prices per tree species published annually by the South Swedish forest owner association for 2006 (Drössler et al., 2017). In TDC2, target diameter thresholds were slightly modified to remove more Norway spruce trees by lowering the target diameter for spruce, thereby promoting the development of broadleaved tree species. In all treatments, trees were cut when their DBH was equal to or greater than the thresholds listed in Table 1. However, retention trees were retained to increase the natural ecological value of the stand. In the TDC2 treatment, twenty retention trees per hectare were selected, while in the other two treatments, ten trees per hectare were retained. None of these retention trees were left in the sample plots. Cutting operations were carried out in the spring of 2008/2009, and soil scarification for the TDCS treatment was implemented in the autumn of 2010 using disc-trenching, which created 0.5 m wide rows with 2 m spacing. Soil scarification treatment was conducted to improve conditions for natural regeneration (see Drössler et al., 2017). The number and basal area of trees cut and the intensity of cutting (%) during target diameter cutting in each treatment within each block is shown in Table S1. Stand characteristics for each treatment are presented in Table 2 for the first inventory (pre-harvest) in 2006 and the last inventory conducted in 2021.

Table 1
Target diameter (DBH in cm) thresholds for each species and treatments during target diameter cutting in spring of 2008/2009. Class 1 and Class 2 represent the stem quality (Class 1 indicates trees with branches smaller than 6 cm in diameter, and Class 2 includes trees with low timber quality with branches thicker than 6 cm, spike-knots or forks).

Tree species	TDC/TDCS		TDC2
	Class 1	Class 2	
Scots pine	40	30	40
Norway spruce	36	26	26
Birch	30	20	30
Oaks	60	30	60
European beech	50	30	50

In each treatment within each block, four systematically distributed 10 m radius circular plots were established, resulting in a total of 48 sample plots (Fig. 1). Individual trees were numbered and repeatedly measured in 2006, 2016, and 2021. In each such circular plot, species and DBH (in millimetres) of all trees (DBH ≥ 5 cm) were recorded. DBH was measured using a caliper in two perpendicular directions, and the average value was used as tree's DBH. At each measurement, tree height was measured only for sample trees - i.e., the five largest DBH trees in each sample plot and a number of randomly selected trees of each species - using a Vertex hypsometer and transponder (Haglöf, Sweden AB). The randomly selected trees were chosen to represent all DBH classes within each sample plot. The observations of height-diameter pairs were used to estimate the height of all trees without height measurements using the height-diameter function (Eq. 1) presented by Näslund (1936). The Näslund function was used because it is the most frequently used function to describe the height-diameter relationships in northern Europe and under Scandinavian conditions (Holmström et al., 2018, Ogana et al., 2023).

$$H = 1.3 + \frac{DBH^{\gamma}}{(\alpha + \beta \times DBH)^{\gamma}} \quad (1)$$

where, H is the tree height (metre), DBH is the diameter at breast height (cm), α and β are parameters to be estimated, and γ was 3 for Norway spruce and 2 for Scots pine, birch, European beech and oak (Holmström et al. 2018, Ogana et al. 2023). The model coefficients were estimated separately for each species, treatment, and measurement occasion. However, due to limited number of sample trees for birch and European beech, the height-diameter equation for oak was applied to estimate their heights. All calipered trees without height observations were assigned predicted heights. Survival status of trees was also recorded. The oak mortality rates were 2 %, 2.1 %, 1.9 %, and 1.7 % in control, TDC, TDC2, and TDCS treatment, respectively, with average DBH of dead oak recruits being 8.6 cm.

The tallest and largest tree within each sample plot, regardless of species, was used to classify the social position of individual trees. The largest and tallest trees were mostly Norway spruce or Scots pine and did not include oak recruits or other oak trees. At each measurement the individual trees were classified into four crown classes based on their social positions: (i) dominant - trees forming the dominant canopy layer or reaching at least fifth-sixths of the dominant tree height within the plot, (ii) codominant - trees slightly lower than the dominant trees, typically reaching fourth-sixth to fifth-sixths of the dominant tree height, (iii) intermediate - trees with their heights reaching between three-sixths and four-sixths of the dominant tree height, and (iv) suppressed - trees that reach less than three-sixths of the dominant tree height, with their canopies suppressed under those of surrounding trees.

In this study, we focused primarily on oak recruitment. We did not distinguish the two oak species because both species are ecologically overlapping. A total 348 oak trees were observed in all three

Table 2
Pre-harvest (2006) and post-harvest (2021) stand characteristics of each treatment. The values (mean ± standard deviation) were calculated from four subplots in each treatment within each block (n = 12) in the experiment in Eriksköp. CV is the coefficient of deviation.

	2006				2021			
Characteristics	**C**	**TDC**	**TDCS**	**TDC2**	**C**	**TDC**	**TDCS**	**TDC2**
Total tree density (tree/ha)	1148 ± 273	1042 ± 192	1079 ± 333	846 ± 230	1157 ± 218	851 ± 248	851 ± 324	703 ± 340
Broadleaved density	334 ± 129	411 ± 257	313 ± 192	342 ± 199	324 ± 134	361 ± 255	257 ± 189	297 ± 196
Conifer density	814 ± 129	631 ± 257	767 ± 192	504 ± 199	833 ± 134	491 ± 256	594 ± 189	405 ± 196
Total basal area (m^2/ha)	35.9 ± 8.6	36.0 ± 7.9	38.9 ± 7	33.6 ± 6.1	48.6 ± 8.7	34.0 ± 8.8	34.7 ± 6.3	31.2 ± 11.2
Broadleaved BA	5.2 ± 4.5	5.7 ± 3.3	5.4 ± 2.4	7.9 ± 5.8	7.2 ± 5.6	8.1 ± 5.7	6.0 ± 3.6	8.7 ± 4.5
Conifer BA	30.7 ± 9.9	30.3 ± 9.5	33.5 ± 7.8	25.9 ± 7.9	41.4 ± 11.6	25.9 ± 11.0	28.8 ± 6.2	22.6 ± 9.4
Quadratic mean diameter (cm)	20.0 ± 1.6	21.1 ± 2.1	21.4 ± 0.9	22.6 ± 0.6	23.8 ± 1.8	23.1 ± 2.0	23.2 ± 1.1	24.1 ± 1.0
Tree height (m)	14.4 ± 0.5	13.9 ± 1.3	13.9 ± 0.6	13.6 ± 0.8	17.5 ± 0.9	16.0 ± 1.5	17.0 ± 0.6	15.5 ± 0.4
CV of DBH (%)	55.7 ± 3.2	58.9 ± 7.6	58.4 ± 1.4	57.5 ± 4.7	52.6 ± 3.8	49.2 ± 4.8	48.6 ± 1.9	54.0 ± 4.4
CV of height (%)	37.6 ± 4.2	36.9 ± 3.4	40.1 ± 1.4	44.1 ± 2.5	34.8 ± 4.4	36.9 ± 4.4	35.1 ± 1.1	41.6 ± 2.3

measurements, excluding the dead oak trees (Table S2, **and** Figure S1). Oak recruits were defined as oak trees with an initial DBH of 5–20 cm that belong to the suppressed, intermediate, or codominant initial canopy classes. These recruits have the potential to develop into the upper canopy layers, benefiting from crown release resulting from target diameter cutting. A total of 302 oak recruits were included in the analysis.

2.3. Quantification of diameter growth, height growth and strand structural attributes

Individual tree diameter growth (cm year^{-1}) and height growth (m year^{-1}) were calculated from repeated measurements. Annual growth rates for each individual recruit were calculated over the measurement intervals 2006–2016 and 2016–2021. The diameter and height growth data were annualized by dividing the observed periodic growth by the number of years between measurements. We did not remove zero diameter growth values (2.8 % of the total growth observations) because they may represent poor growth conditions. Negative height growth values were excluded, but zero growth values were included as they may also represent poor growth conditions and high neighbourhood competition. Stand structural variables such as stand density (trees ha^{-1}), basal area (m^2 ha^{-1}), coefficient of deviation of DBH (CVd), and coefficient of deviation of height (CVh) were calculated for each plot within each treatment at each measurement occasion (Table 3). Stand density and basal area were derived separately for conifers (Norway spruce and Scots pine) and broadleaved species (birch, European beech, and oak). We also calculated the total basal area of larger trees (BAL) than the individual oak recruits (Wykoff, 1990; Schröder, 1999) to account for competition affecting oak recruits. BAL, or overtopping basal area, simultaneously considers a tree's relative dominance and stand density. BAL was calculated for each sample plot within each treatment at each measurement occasion. The BAL of the smallest diameter tree approximately equals the total stand basal area. We also calculated the total number of trees (trees ha^{-1}) and total basal area (m^2 ha^{-1}) removed during target diameter cutting (Table S1).

Table 3
Summary of Generalized Linear Mixed Model for assessing the stand and individual tree characteristics influencing diameter growth and height growth of oak recruits. BAL: basal area of trees larger than individual oak recruits; CVd: coefficient of variation of DBH; CVh coefficient of variation of height; SE: standard error; AIC: Akaike's information criterion. All explanatory variables were natural log-transformed. Diameter growth rates were square-root transformed (See Table S3 for description of the models).

	Diameter growth			Height growth		
Predictors	**Estimate**	**SE**	**p-value**	**Coefficient**	**SE**	**p-value**
Intercept	-0.10	0.35	0.77	0.69	1.14	0.54
Initial DBH	0.27	0.03	< 0.001	1.73	0.22	< 0.001
Initial height	-	-	-	-2.14	0.31	< 0.001
Conifer density	-0.05	0.03	0.07	-	-	-
Broadleaved density	-	-	-	-0.20	0.08	0.01
Broadleaved BA	-0.09	0.03	< 0.001	-	-	-
BAL	-0.16	0.03	< 0.001	-	-	-
CVd	0.11	0.07	0.10	0.88	0.31	0.004
CVh	0.11	0.05	0.03	-0.97	0.28	< 0.001
Number of trees cut	-	-	-	-0.05	0.02	0.004
Variance						
Tree	0.014			0.059		
Plot	0.005			0.006		
AIC	-722.9			-445.1		

2.4. Data analysis

All data analyses were conducted in R (R Core Team, 2024). We used Generalized Linear Mixed-effects Model (GLMM) for all statistical analysis. GLMMs were performed using the "glmmTMB" package (Brooks et al., 2017). The "emmeans" package (Lenth, 2025) was used for post-hoc tests, and model evaluation, including residual diagnostics and assumption checks, was conducted with "DHARMa" package (Hartig, 2025).

To address the first research question, we examined how individual oak tree characteristics and stand structural attributes affect the individual tree diameter and height growth rates using two separate GLMM. We considered initial tree characteristics of oak recruits (DBH, height and crown class) and stand structural characteristics including conifer density (trees ha^{-1}), broadleaved density (trees ha^{-1}), conifer basal area (m^2 ha^{-1}), broadleaved basal area (m^2 ha^{-1}), BAL (m^2 ha^{-1}), CVd, and CVh as explanatory variables. In addition, the number (trees ha^{-1}) and basal area (m^2 ha^{-1}) of trees removed during target diameter cutting in 2008/2009 were also considered as explanatory variables. All these variables were included in the full GLMMs (Table S3). Variables showing high collinearity were identified using the variance inflation factor (VIF), and any variables with VIF > 5 was sequentially remove. After each removal, the models were refitted until all remaining fixed-effects variables had VIF below 5. Conifer basal area and the total basal cut during target diameter cutting were removed during this process and the remaining variables were retained in the models. The "MuMIn" package (Bartoń 2025) was then used to select the optimal models. To represent the stand conditions affecting the diameter and height growth rates, the variables derived from the first of two consecutive measurements were included in the models. A Gaussian distribution with identity link function was used in the diameter model. Diameter growth values were square-root transformed to ensure that model residuals met the assumptions of a Gaussian distribution. The height growth model included a Tweedie distribution to handle continuous height growth values, including zero. We considered individual trees nested within plots as random effects in both diameter and height growth models.

To address the second research question, which investigates how target diameter cutting influence diameter and height growth of oak recruits, we compared growth rates across treatments using GLMM. The descriptions of the models are provided in Table S3. Annual growth rates were compared among treatments by including the interaction between treatment and measurement year as fixed effects. Individual trees nested within plots were included as random effects (Table S3). A gaussian distribution with identity link function was used in the diameter model. The height growth model included a Tweedie distribution to handle continuous height growth values, including zero.

Further, we examined how target diameter cutting affects the transition of oak recruits to the higher crown classes. We defined trees that moved to higher canopy classes as 1 and, and those that remained in the same class as in the previous measurement as 0, regardless of the specific transition class (e.g., from suppressed to intermediate and intermediate to codominant). The interactions between treatments and measurement years were considered as fixed effects in GLMM. In addition, we also assessed the factors influencing the transition of oak recruits into higher canopy classes. We included individual tree variables, stand structural variables, and the number and basal area of trees cut as fixed effects, and the plots was included as random effects (Table S3). A binomial distribution with a logit link function was used in all models analysing tree crown transitions. The variable and optimal model selections were performed following the procedure as described above.

3. Results

3.1. *Stand structural and individual tree characteristics affecting the diameter and height growth of oak recruits*

Initial tree diameter showed a strong positive effect ($p < 0.001$) on the individual tree diameter growth of oak recruits (Table 3). A negative effect of broadleaved basal area ($p < 0.001$) and the total basal area of trees larger than individual oak recruits ($p < 0.001$) was observed. The coefficient of variation of height was found to have a positive effect ($p = 0.03$) on diameter growth.

Initial oak diameter showed a significant positive effect ($p < 0.001$), while initial tree height exhibited a negative effect ($p = 0.001$) on individual tree height growth (Table 3). Further, negative effects on height growth of oak recruits were observed for broadleaved density ($p = 0.002$), the coefficient of variation of tree height ($p < 0.001$), and the number of trees removed during target diameter cutting ($p = 0.004$). In contrast, the coefficient of variation of DBH ($p = 0.004$) had positive effects on height growth.

3.2. *The effect of target diameter cutting on the diameter and height growth of oak recruits*

The results indicate a significant positive influence of target diameter cutting on the diameter growth of oak recruits. Regardless of treatment types, the diameter growth rates in treatment plots were significantly higher than those in the control plots (Fig. 2**a**). The mean DBH growth rates (cm year^{-1}) in each treatment were 0.11, 0.24, 0.26, and 0.21 for control, TDC, TDC2, and TDCS, respectively. There were no significant differences ($p > 0.05$) among the three different selective cutting treatments (Fig. 2a). Eight years following selective cutting, in 2016, the diameter growth rate in TDC ($p < 0.001$) and TDC2 ($p < 0.001$) treatments was statistically higher than in C (Fig. 2b). TDCS showed no significant difference from the other two treatments or control. Sixteen years following selective cutting, in 2021, the growth rate of oak recruits was significantly higher in all selective cutting treatments compared to the control (Fig. 2b). Again, no significant differences among the selective cutting treatments were observed. In 2021, the growth rate was slightly decreased across all treatments, and the control plot showed the significantly lowest growth rate.

We found that height growth rates in TDC and TDCS treatments were significantly lower than the control without cutting (Fig. 3a). The average height growth rates (m year^{-1}) of oak recruits were 0.23, 0.17, 0.19, and 0.16 for control, TDC, TDC2, and TDCS respectively. There were no significant differences in height growth rates among the three different selective cutting treatments. Eight years after target diameter cutting, height growth rates in TDC treatment were significantly lower than in control and TDC2 treatment (Fig. 3b). However, sixteen years after cutting, height growth rates in TDCS treatment were lowest among all treatments including control, and were significantly lower than those in TDC and control.

3.3. *Effects of target diameter cutting on the transition of oak recruits into higher canopy classes*

Only 18 recruits in codominant positions were observed, and none of these recruits were transitioned into dominant canopy positions. We combined these 18 trees with intermediate canopy class, which did not significantly affect the results. The TDC2 treatment showed the highest transition rate of oak recruits into higher canopy classes Fig. 4a). Significant higher transition rate in TDC2 treatment (31 %) was observed than in the TDC (13 %) and TDCS (13 %) treatments, although the difference was not statistically significant compared to the control (17 %). Eight years after target diameter cutting (in 2016), no significant differences in the probability of canopy transition were observed across all

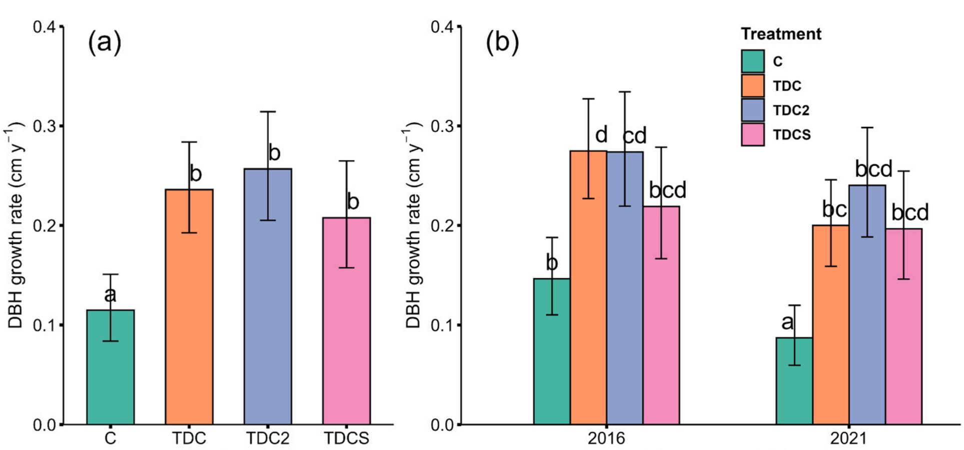

Fig. 2. Diameter growth rates of individual oak recruits in different treatments from 2006 to 2021 (a), in different measurement years (b). Measurement year 2016 in (b) represents the diameter growth between 2006 and 2016, and 2021 represents diameter growth between 2016 and 2021. Error bars indicate the ± standard error for the mean diameter growth rate. Letters in common show no significant differences ($p > 0.05$).

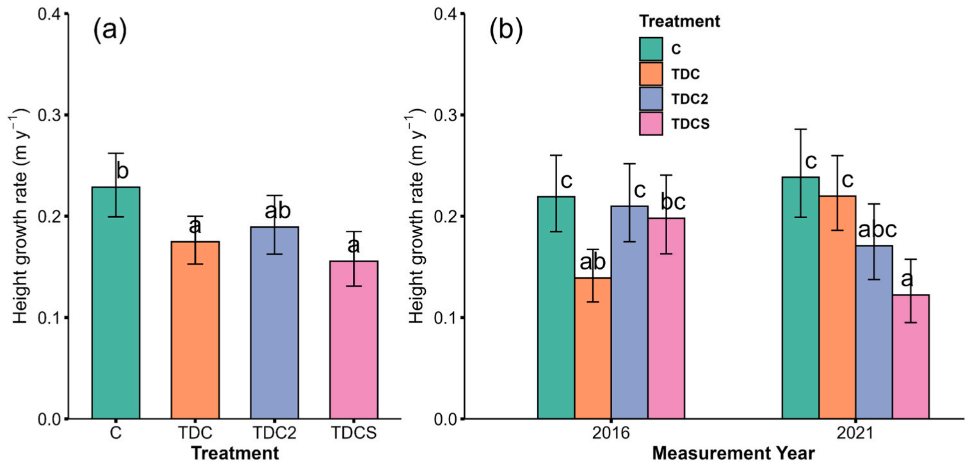

Fig. 3. Height growth of individual oak recruits in different treatments from 2006 to 2021 (a), in different measurement years (b). Measurement year 2016 in (b) represents the height growth between 2006 and 2016, and 2021 represents height growth between 2016 and 2021. Error bars indicate the ± standard error for the mean height growth rate. Letters in common show no significant differences ($p > 0.05$).

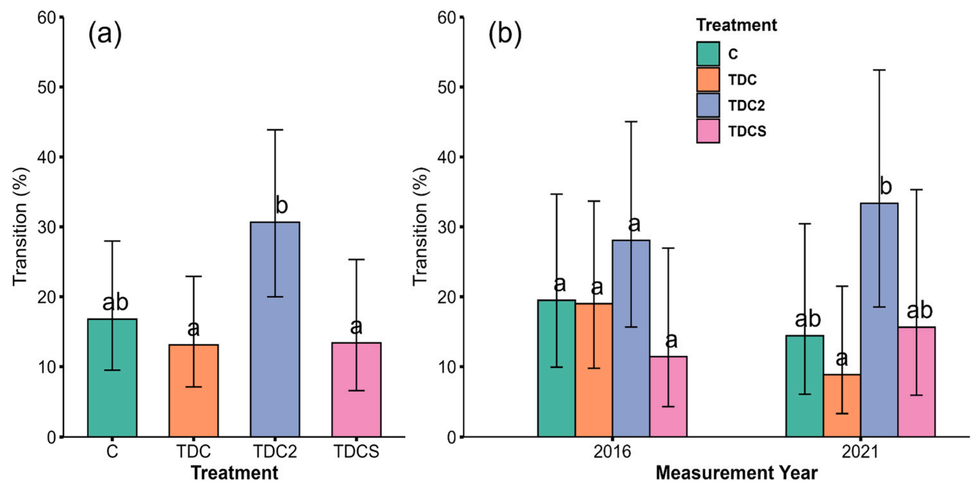

Fig. 4. The observed probability of oak recruits moving to higher canopy classes in different treatments from 2006 to 2021 (a), and in different measurement years (b). Measurement year 2016 includes all transitions between 2006 and 2016, and 2021 includes transitions between 2016 and 2021. This included all transitions, i.e., from suppressed into intermediate, intermediate into codominant. Error bars indicate the ± standard error for the mean probability of canopy class transition. Letters in common indicate no significant differences ($p > 0.05$).

treatments (Fig. 4b). Following the third measurement, conducted in 2021, the overall probability of transition to higher canopy classes was significantly higher in the TDC2 (33 %) compared to the TDC (8 %) treatment. No significant differences were observed compared to the TDCS (16 %) treatment and the control (14 %).

The probability of transition of oak recruits into higher canopy classes is dependent on initial tree characteristics and stand structure. The results indicate that oak recruits with larger DBH ($p < 0.001$) have a higher chance of advancing into higher canopy classes (Table 4). Trees already in intermediate canopy class have lower probability of transitioning into higher canopy classes compared to suppressed trees ($p < 0.001$). A higher coefficient of variation of height ($p = 0.008$) within a stand promote the probability of transition of oak recruits into higher canopy classes.

Table 4
Summary of GLMM showing the factors affecting the probability of transition of oak recruits into higher canopy classes. CVh: coefficient of variation of height. All explanatory variables were natural log-transformed. Crown class variables are categorial variables with two categories: suppressed and intermediate.

Predictors	Estimate	Standard error	p-value
Intercept	-17.53	4.35	< 0.001
Initial DBH	0.47	0.08	< 0.001
Initial height	0.18	0.11	0.09
Initial crown class (Intermediate)	-3.26	0.49	< 0.001
Broadleaved BA	-0.57	0.35	0.10
CVh	2.85	1.07	0.008
Variance			
Treatment:plot	0.63		
AIC	383.7		

4. Discussion

4.1. Stand structural and individual tree characteristics affecting the diameter and height growth of oak recruits

The diameter and height growth of oak recruits was influenced by initial tree DBH, with larger recruits exhibiting a higher diameter and height growth. A higher basal area of larger trees (BAL) than the individual oak recruits reduced diameter growth. This suggests that an increased number of trees larger than the individual oak recruits in the area reduces the diameter growth of those recruits. BAL accounts simultaneously for a target tree's social ranking and the density of the stand (Wykoff, 1990; Schröder, 1999), and similar negative effects on the diameter growth of oak were observed in previous studies (Rohner et al., 2017; Schelhaas et al., 2018). In our study, Norway spruce and Scots pine constitute over 70 % of the stem density, and their combined stem density and basal area of broadleaved species (birch, European beech and oak) further negatively affected the diameter growth of oak recruits. This finding aligns with earlier studies that have reported negative effects of density on oak growth (Adame et al., 2008; Noguchi and Yoshida, 2009; Rohner et al., 2017; Pohl et al., 2025).

Although height growth is generally expected to decline with increasing DBH (Johnson et al., 2019), a positive effect of DBH on height growth was observed. This is likely because our study focused on relatively small recruits. In line with previous studies (Sumida et al., 1997; Trouve et al., 2015), the results indicate that height growth decreases as tree height increases. The stand structural variables of broadleaved density showed negative effects on the height growth. In dense stands with more broadleaved trees, light becomes a major limiting factor negatively affecting the growth of oak recruits. Managing stand density is thus very important to favour the oak recruit's growth. Compared to several other tree species, oaks need more light for sustainable height growth (Modrow et al., 2019; Petersson et al., 2020). For example, while beech needs about 10 % of above-canopy light, oak requires twice as much to reach an optimum growth (Ligot et al., 2013).

Managing stand density through target diameter cutting also alters tree size variation. The negative effect of CVh on height growth of oak recruits suggests that structurally heterogeneous stands, where taller individuals strongly dominate and height variation is large, intensify asymmetric competition and suppress height growth smaller recruits. Our results contrast with those of a previous study (e.g., Stimm et al., 2021), who reported positive effects of stand density and vertical stand structure on height growth of oak. However, their study focused on relatively large oaks with a mean DBH ranging from 35.6 to 47.8 cm and mean height ranging from 22.5 to 27.9 m in different forest types with different species mixture. The positive effects of CVd on height growth indicate that stand structure complexity may facilitate height growth of oak recruits. Higher variation in tree DBH creates a more irregular forest structure with spatially heterogeneous light conditions that could promote height growth of light-demanding oak recruits. In addition, we observed a negative relationship between height growth and the number of trees removed during target diameter cutting. High-intensity selective cutting may not benefit the height growth of oak recruits, even after competition is reduced and light availability is improved. A previous study by Vallet and Perot (2016) also reported a lower growth rate of oak as light availability increased.

4.2. The effects of target diameter cutting on diameter and height growth of oak recruits

Our results indicate that target diameter cutting promoted the diameter growth of oak recruits. Target diameter cutting reduced competition for resources such as soil water, nutrients, growing space, and light availability by decreasing the stand density and basal area (Yoshida and Kamitani, 1998; Götmark, 2009; Gorrod et al., 2024), which in turn positively affected the diameter growth of oaks. Although a slight decrease in the annual growth rate was observed across all treatments over time, the positive effects of selective cutting on oak diameter growth persisted for at least 16 years post-selective cutting. This long-term response is consistent with a 25-year post-thinning study carried out in planted oak (*Q. robur*) forests in Southern Sweden (Barbeito et al., 2024). They reported that the initial benefits of thinning on oak growth tend to diminish over time. Similar long-term positive effects of thinning but diminishing effects on the growth of different oak species have also been reported in previous studies in coppice stands (Cabon et al., 2018; Đodan et al., 2024).

Target diameter cuttings did not promote the height growth of oak recruits. In contrast to diameter growth, our results indicate a significant negative effect of target dimeter cutting on the height growth of oak recruits. Therefore, it seems that the different forms of target diameter cutting promoted the diameter growth of oak recruits rather than height growth. Under partial shade, oaks are less responsive in height growth (Johnson et al., 2019). These results are further supported by several other studies (Miller, 2000; Đodan et al., 2024). For example, Miller (2000) found that crop tree release treatment promoted the diameter growth, but the total height growth was reduced by heavy release. However, released crop trees tend to maintain their initial crown class better than unreleased trees (Miller, 2000). Furthermore, a study in a thinning experiment in oak (*Q. petraea*)-hornbeam coppice stands (Fedorová et al., 2016) revealed that thinning promotes primarily diameter growth rather than height increment. Further, Cañellas et al., (2004) reported that in a *Q. pyrenaica* (Willd.) coppice stand subjected to thinning treatments of varying intensities, there were no significant differences in height increment among the treatments. In addition, regardless of light conditions, the growth of other broadleaved species, such as European beech, may grow faster than oaks (Ligot et al., 2013).

4.3. The effect of target diameter cutting on the transition into higher canopy classes

Without release from competition, small oaks, especially sapling and pole-size trees, in the lower canopy layers are more likely to die (Miller, 2000; Ward, 2009). Therefore, the effect of target diameter cutting on canopy class transition may be more important to examine than its effect on height growth. Oaks that are suppressed beneath the canopy at a younger age are likely to remain suppressed as they grow older; therefore, silvicultural interventions are necessary to prevent oak recruits from eventually becoming permanently overtopped and unable to recover (Zenner et al., 2012). After silvicultural interventions, such as target diameter cutting, remaining trees experience not only reduced competition from the surrounding trees but also a potential shift in social position since trees are removed from the stand. We found that the transitions of a recruit's social positions into higher canopy classes were higher in the TDC2 treatment 16 years following selective cutting treatments. The TDC2 treatment was designed to favour the growth of broadleaved species by removing dominant species, such as Norway spruce, by lowering the target diameter thresholds for cutting compared to the other two treatments, TDC and TDCS. By cutting more Norway spruce trees, the resulting lower stem density and stand basal area are likely to promote the development of suppressed recruits into upper canopy positions. A study on the effect of release cutting on the development of red oak (*Q. rubra* L.) in North America also reported that only a few intermediate (<10 %) and suppressed (<1 %) oaks were able to recruit into the higher canopy layers without thinning (Ward, 2009). Since the recruits in our study is relatively small, active management is essential to promote the growth and to ensure that successfully established oak recruits develops to larger individuals that can advance into the upper canopy layers, as competitive pressure can undermine the recruitment process into the overstory (Zenner et al., 2012; Dey, 2014).

While target diameter cutting reduces stand density and alters tree size distribution by removing trees of specified sizes, it may not fundamentally alter the underlying mechanisms of how trees compete and transition into higher social positions. We observed that larger recruits, in terms of DBH and height, have a higher chance of transitioning into higher canopy classes when canopy openings are created by silvicultural interventions. Trees that are already in the intermediate positions are less likely to advance into higher canopy classes compared to suppressed trees. Suppressed trees, which are half or less of the total height as defined in this study, are more likely to advance to intermediate canopy position when canopy openings occur due to selective cutting. It is likely that the higher probability of the advancement of suppressed trees into the intermediate canopy class was due to shift in social position following selective cutting of larger competing trees. Intermediate trees, on the other hand, are less limited by light availability than suppressed trees, although they still experience lateral competition for light. Selective cutting could benefit crown development (Attocchi, 2015) of recruits in intermediate and codominant canopy classes. Our results are consistent with those of (Willis et al., 2018), who reported that the recruitment of large trees did not accelerate 14 years after thinning. In our study, following 16 years post-target diameter harvesting, the pattern of transitions into higher canopy classes is likely increasing gradually. Studies (O'Hara, 1986; Zenner et al., 2012) have reported the latent dominance capacity of oaks, in which they can persist in suppressed positions for decades and gradually transition into higher canopy positions. However, thinning or selective cutting are necessary to ensure oak survival and growth as competitive dynamics in the overstory positions during the recruitment process may increase oak mortality (Ward and Stephens, 1994; Dey, 2014). Greater tree height variation may enhance upward transitions in canopy positions. This is also primarily because selective removal of larger and taller individuals alters canopy stratification, allowing previously suppressed individuals to gain space even if their height growth remains limited.

The success of oak forest management depends on sustaining oak recruitment. This study provides an important piece of information for the management of oak forests. Selective cutting can help ensure the sustainable management of oak forests. In our experiments, target diameter cutting intensity reached an average of up to nearly 40 % across all treatments. Our results highlighted that selective cutting of larger individuals promote diameter growth but reduce height growth of oak recruits. Repeated but lower intensity selective cutting could maintain enhanced height growth while still releasing oak recruits for higher diameter growth. To maintain a dynamic light environment, selective cutting may need to retain scattered large trees, as CVd positively affected height growth. Therefore, selective cutting should focus on competitors directly above young oaks to promote height growth. In addition, retaining mixed size classes (higher CVd) while keeping overall stand density moderate produces beneficial light environments (Pohl et al., 2025) that could promote oak recruitments. However, it should also be noted that target diameter cutting, which remove the most vigorous trees, can compromise future forest health and long-term sustainability (Curtze et al., 2022). Therefore, selective cutting should be implemented to retain mixed size classes, preserving trees with high-quality phenotypes, creating canopy openings to promote light availability and reduced competition. This approach could promote oak recruitment while maintaining stand productivity and genetic diversity.

5. Conclusion

This study examined the effects of different forms of target diameter cutting on the growth and advancement of oak recruits into higher social positions over a period of 16 years. Our results indicate that all three different forms of target diameter cutting primarily promoted the diameter growth of recruits, and that this growth persisted 16 years following cutting. Height growth was not likely to be promoted by selective cutting, as oak recruits invested more in diameter growth. Target diameter cutting was likely to promote the transition of oak into the higher canopy positions, and this could be due to a combination of removal of other trees, even if height growth of the oak recruits remains limited. Basal area of larger trees negatively affected diameter growth of oak recruits. The recruitment process into higher canopy positions is a long-term process and a period of 16 years, as in this study, may not be sufficient to monitor this process. Therefore, longer-term studies are needed with repeated selective cutting. The findings highlight the critical role of silvicultural practices in supporting oak growth and recruitment process. This study suggests that target diameter cutting could be an alternative forest management approach to facilitate the growth and recruitment of oak and to ensure the sustainability of oak-dominated forests.

CRediT authorship contribution statement

Nora Sophie Pohl: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Kyaw Thu Moe:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Magnus Löf:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jorge Aldea:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2026.123519.

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