Effects of crown competition on stem growth of naturally regenerated oak

A case study from Dalby Söderskog national park

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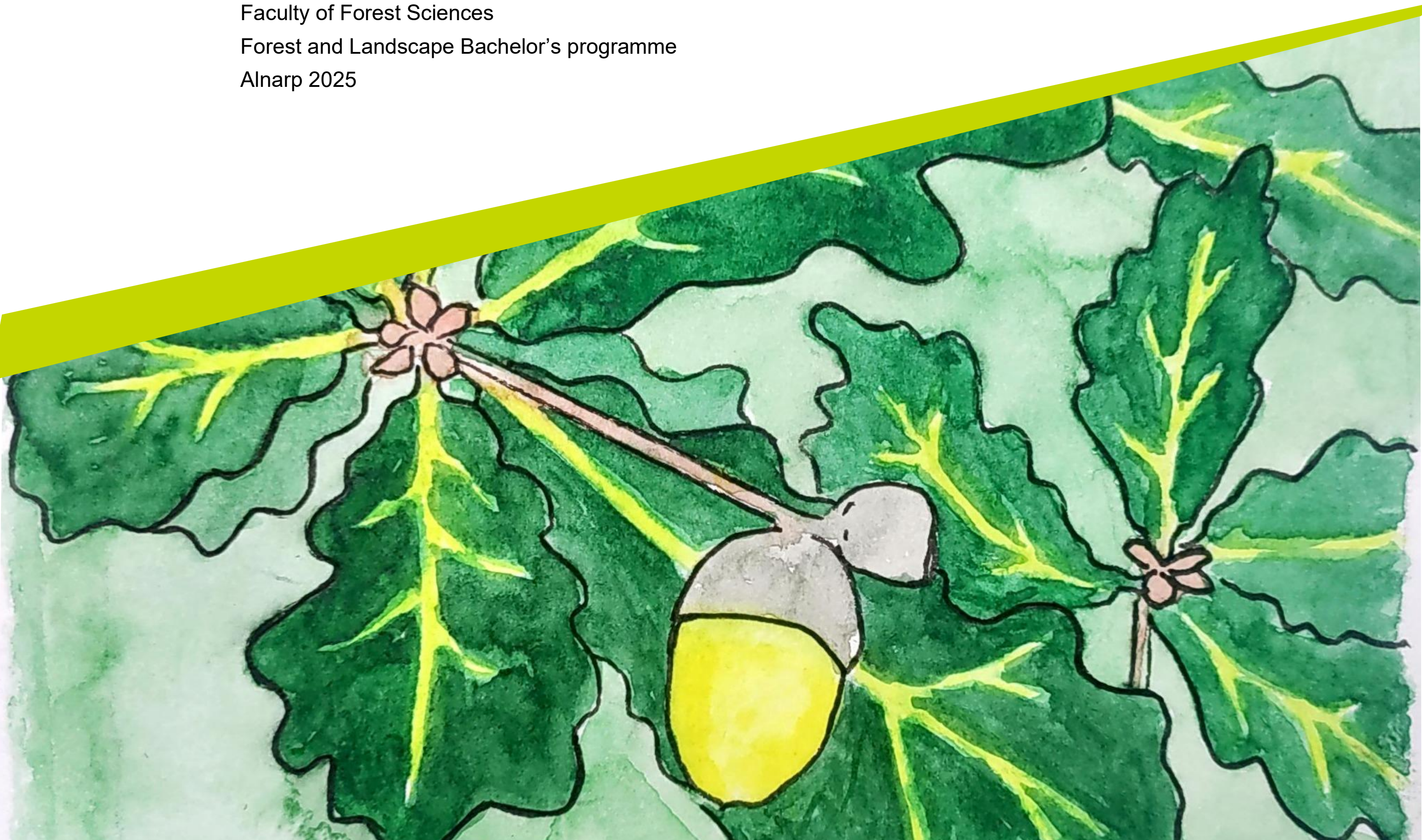

Effects of crown competition on stem growth of naturally regenerated oak – a case study from Dalby Söderskog national park

Effekter av kronkonkurrens på stamtillväxten hos naturligt föryngrad ek – en fallstudie från Dalby Söderskogs nationalpark

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Abstract

Pedunculate oak (*Quercus robur*) is a prominent tree species in European temperate forests, providing many ecosystem services and habitat for a variety of species. Intensification of forest management during the 20th century and lack of disturbance in protected areas have led to denser canopies, which negatively impact natural regeneration of oak. Oak is a light demanding species and has historically mainly been found in semi-open areas with frequent disturbance. Dalby Söderskog national park, located in southern Sweden, is a formerly oak dominated temperate forest where a new oak regeneration has established after a recent increase in light availability due to the tree diseases Dutch elm disease and ash dieback. Earlier studies have found that crown size was positively related to stem diameter in young oaks in Dalby Söderskog. The purpose of this study was to examine how crown competition influences stem diameter growth of individual oaks over time. Additionally, the difference in stem diameter growth was examined in trees for which crown competition status remained the same and in trees for which crown competition increased. This was done by statistical analyses of the stem diameter growth and the change in crown competition status of 394 young oaks between 2021 and 2025. The basic hypothesis was that stem diameter increment decreases with increasing crown competition. The results confirm the hypothesis, showing that stem growth in pedunculate oak is negatively affected by higher crown competition. The general pattern is the same for all oaks, independent on if crown competition status has been constant or increased during the four years. The young oaks in Dalby Söderskog have a very high stem growth when they have sufficient light availability, but when the crown is almost or completely overgrown the stem growth is very low. The results also showed that already one to three years of increased shading will lead to a significantly lower stem growth compared to constant competition status, demonstrating rapid negative effects of increasing crown competition and stand density.

Keywords: Forest regeneration, Pedunculate oak, *Quercus robur*, stem increment, temperate forest dynamics

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1. Introduction

1.1 Ecology of oak

Oak (*Quercus spp.*) is a prominent tree species in European temperate forests (Annighöfer et al. 2015). In Sweden sessile oak (*Quercus petraea*) and pedunculate oak (*Quercus robur*) are the native oak species, with the latter being the most common (Drößler et al. 2012; Löf et al. 2016). Oaks provide habitat for a variety of species, many of them red-listed (Götmark 2007; Löf et al. 2016; Jensen & Löf 2017). Old oak trees are especially important for biodiversity, with a range of species dependent on coarse bark, stem cavities and hollows (Ranius et al. 2009; Brunet et al. 2014). However, it can take over 150 years before characteristics like tree hollows form (Ranius et al. 2009). Oak is a light demanding species and has historically mainly been found in semi-open areas with frequent disturbance, which is required for natural regeneration of oak (Götmark 2007; Bobiec et al. 2011). Forest grazing and low intensity fires have been found to be important factors of disturbance in oak-dominated areas. Regeneration of oak is limited in dense broadleaved stands due to insufficient light levels (Götmark 2007; Brunet et al. 2014). Oak seeds can germinate in shaded conditions but for seedling survival and growth, light is a limiting factor (Annighöfer et al. 2015; Finnström 2016; Mölder et al. 2019).

As oaks grow in age and size the light requirements increase (Annighöfer et al. 2015; Jensen & Löf 2017). Slight competition can be beneficial for oak trees, with one positive aspect being that they grow taller than otherwise (Finnström 2016), with straighter stems (Jensen & Löf 2017). However, competition can also negatively affect young oak trees height- and crown size development (Attocchi & Skovsgaard 2015; Finnström 2016), and there is a close correlation between the size of the green crown and stem diameter growth (Drobyshev et al. 2007; Attocchi & Skovsgaard 2015; Finnström 2016). In more shaded conditions oak leaves photosynthesize less efficiently compared to other broadleaved species (Drobyshev et al. 2007). Therefore, crown encroachment can cause growth depression in oak seedlings, as well as cause mortality within older oak populations (Drobyshev et al. 2007; Finnström 2016; Jensen & Löf 2017). There may however be positive effects on the life span of oak trees if they are released from crown competition (Brunet et al. 2014).

While light has been found to be one of the most limiting factors for oak regeneration, another factor is browsing. Oak is a preferred food among browsing ungulates like deer (Bobiec et al. 2011; Petersson et al. 2019). Deer species mainly browse on saplings between 0.5 and 1.3 meters high (Bobiec et al. 2011; Petersson et al. 2019). Some heavily browsed oaks become “bonsai trees”, forming a more shrubby structure with several side branches replacing the top shoot, but they can still survive (Bobiec et al. 2011). If a browsed tree is left alone for some years it is able to grow past the browsing limit (1.3 meters) (Brunet & Larsson 2022). However, intense browsing pressure is a problem for natural oak regeneration, as high densities of deer populations have a negative impact on natural regeneration of their preferred tree species (Petersson et al. 2019). If there is a high browsing pressure, the oaks may stay within the browsing height (<1.3 m), unable to escape the "browsing trap" (Petersson et al. 2019).

1.2 Oak forest succession

During the 20th century there has been a large-scale shift in land-use and forest management practices in temperate forests (Brunet et al. 2014; Petersson et al. 2019). Forest canopies in production forests have become increasingly dense as modern high forest management regimes replace traditional practices like forest grazing, selective cutting methods and low intensity fires (Brunet et al. 2014; Petersson et al. 2019). This has had an impact on forest structure and natural regeneration of oak. Other oak-dominated woodlands have become forest reserves with little to no management (Götmark 2007; Brunet et al. 2014). The lack of disturbance has accommodated secondary succession of other, more shade-tolerant tree species, resulting in dense canopies. As the forests become denser the oak regeneration largely decreases, leading to large gaps in age and size distribution of the oaks, which eventually may break the continuity of old and large trees and their micro-habitats (Brunet et al. 2014).

In later decades, however, new ingrowth of oak regeneration has been found in areas that have become more open due to different tree diseases and pathogens causing mortality among other tree species (Brunet et al. 2014), and in abandoned agricultural fields left for natural succession (Bobiec et al. 2011). However, at the same time, modern forestry practices combined with changes in game management have led to an increase in herbivore populations, and subsequently an increased browsing pressure (Petersson et al. 2019). In southern Sweden the increase in browsing pressure has had a clear negative impact on natural regeneration of oak (Petersson et al. 2019).

1.3 Dalby Söderskog

The study area Dalby Söderskog is a 37 hectare forest reserve located in Skåne, southern Sweden (Länsstyrelsen Skåne n.d.). The main tree species are wych elm (*Ulmus glabra*), European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*) (Brunet et al. 2014). Dalby Söderskog is managed by the County Administrative Board of Skåne and is part of EUs Natura 2000 protected areas network (Länsstyrelsen Skåne 2024). The forest is mostly unmanaged for free development with the aim to develop a natural temperate broadleaf forest (Länsstyrelsen Skåne 2017). It is a highly fertile site, and the large amount of dead wood and old trees hosts a diverse range of species, among them saproxylic beetles, bryophytes and epiphytic lichens (Brunet et al. 2014). The old oak population in Dalby Söderskog is around 200-300 years old (Brunet & Larsson 2022). Dalby Söderskog has the characteristics of a formerly open temperate forest that has become denser and formed a more closed canopy (Brunet et al. 2014). Grazing in Dalby Söderskog decreased during the 19th century, and in 1918 it became protected as a national park. Lower disturbance rates favoured later successional species like the shade-tolerant wych elm (Brunet et al. 2014; Finnström 2016). The mortality of old oaks and absence of regeneration has led to a declining population and to a gap in the age and size distribution of oaks (Brunet et al. 2014).

More recently Dalby Söderskog has become more open again due to tree diseases (Brunet et al. 2014). Since the late 1980s, Dutch elm disease has caused the death of a large proportion of the wych elms, opening up the canopy. This has favoured regeneration of both oak and ash (Brunet et al. 2014). However, ash dieback has caused high mortality in both young and old ash trees, further creating space for the establishment of a new oak regeneration (Götmark 2007; Brunet & Larsson 2022).

During the last century, several studies have examined the tree species composition and inventoried the larger oaks (dbh >30 cm) in Dalby Söderskog (Brunet & Larsson 2022; Länsstyrelsen Skåne 2024). The status of the new oak regeneration has been investigated starting in 2012. Previous studies have shown that competition from surrounding stems negatively affects the development of the young oaks (Finnström 2016; Brunet & Larsson 2022). The browsers found in Dalby Söderskog are roe deer (*Capreolus capreolus L.)* and fallow deer (*Dama dama L.)* (Finnström 2016). Previous studies have found that some oaks have stem damage or stunted growth because of browsing, but with time most have managed to grow past browsing height (1.3 m) (Finnström 2016; Brunet & Larsson 2022). Both Finnström (2016) and Brunet & Larsson (2022) conclude that the browsing pressure is moderate and does not seem to prevent successful oak regeneration.

Pedunculate oak is an important tree species in Dalby Söderskog, and continuity of the oaks is vital for many oak-associated species. Earlier studies have examined the factors influencing the performance of the new oak regeneration in Dalby Söderskog (see chapter 2.1), so far, however, none has examined the effects of crown competition on stem growth of individual oak trees over time.

There is now the question if the young oak regeneration will manage to survive on their own or if management measures are necessary to secure successful regeneration and the continuity of oaks.

1.4 Purpose of thesis and hypothesis

The purpose of this study is to examine how crown competition influences stem diameter growth of pedunculate oak over time. Additionally, the study aims to examine differences in stem diameter growth, depending on if crown competition status has been constant or changed over time. This will be done by analysing the stem growth of 394 individual young oak trees in Dalby Söderskog between 2021 and 2025. The basic hypothesis is that stem diameter increment decreases with increasing crown competition.

2. Material and Methods

2.1 Previous studies in Dalby Söderskog

After the arrival of tree diseases in Dalby Söderskog that created openings in the canopy, a new oak regeneration has established during 1990-2010 (Brunet & Larsson 2022). The oak regeneration is mainly present in the northwestern and the southeastern part of the forest. It has been studied on three occasions, in 2012, 2015 and 2021. In 2012, oak saplings which had reached breast height (1.3 m) were inventoried for the first time (Brunet & Larsson 2022) and 455 such oaks were found. In 2015, a second complete inventory of the oak regeneration in Dalby Söderskog was made, measuring all oaks with a height ≥1.3 meters and diameter at breast height (dbh) of <20 cm (Finnström 2016). In total,784 oak saplings were measured. The results showed that an increased number of stems surrounding the oaks, and subsequent increased competition had a negative effect on the height and crown development of the young oaks. Six years later, in the winter 2020-2021, an inventory was made of all oaks >1 cm at breast height (1.3 m) (Brunet & Larsson 2022) and 770 such oaks were found. The results found that increased light availability for the crown increased stem diameter in relation to tree height. Each tree was marked, and GPS-coordinates were registered, making a re-inventory possible. This thesis examines the stem growth of the individual oaks for four years based on Brunet & Larsson's inventory 2021.

2.2 Material – data set "Oak regeneration Söderskog"

The data set "Oak regeneration Söderskog" used in this thesis consists of 394 individually marked oak trees registered during an inventory in 2021, which were re-inventoried in 2025 by Jörg Brunet. The trees are located mainly in the north-western part of Dalby Söderskog, with a smaller number in the southern part of the forest (Figure 1). For the oak inventory made by Jörg Brunet in the winter of 2021 (13 October 2020 - 15 April 2021) the following method was used (Brunet and Larsson 2022). Oaks with dbh 1-1.9 cm were counted only. Oaks with a dbh of at least 2 cm and maximum 29,9 cm were measured and marked with numbered paper ribbons, which were renewed in 2023, if deemed necessary. For these oaks the following variables were registered:

- GPS-coordinates.
- *Dbh 21*: Stem diameter at breast height 1.3 m (dbh, cm).
- *Height 21:* Height in meters (m). Measured by measuring stick up to 5 m, and by ocular estimation in one-meter classes for higher trees.
- *CC 21:* Crown competition from neighbouring young trees is specified in the following seven classes. Four main classes: 1 free-growing, no or only

singular trees/bushes that shade; 2 some trees/bushes shading but good light availability for parts of the crown; 3 trees/bushes around the oak but good light availability for upper part of the crown; 4 the crown is overgrown by other trees and bushes (visualized in figure 2). Trees in between main classes were denoted in three subclasses, 1.5, 2.5 and 3.5.

- *Fork 21:* Stem forking in three classes: 0 no forking; 1 high forking; or 2 a clearly forked tree with low starting point of forking.
- *Form 21:* Stem form in three classes: 0 straight; 1 somewhat crooked; or 2 strongly crooked.
- *Fray 21:* Occurrence of fraying damage on bark caused by roe deer, in three classes: 0 none; 1 small; 2 large.

In 2025, the oaks which had a stem diameter of at least 2 cm in 2021, and which had identifiable numbered paper ribbons, were re-inventoried by Jörg Brunet. The majority of the oaks were re-inventoried 2 January – 25 January, and the inventory was completed between 2 March and 19 March, including a total of 394 oaks. The following measurements were made:

- *Dbh 25:* Stem diameter at breast height 1.3 m (dbh, cm)
- *CC 25:* Crown competition from neighbouring young trees is specified in the same seven classes as for CC 21.

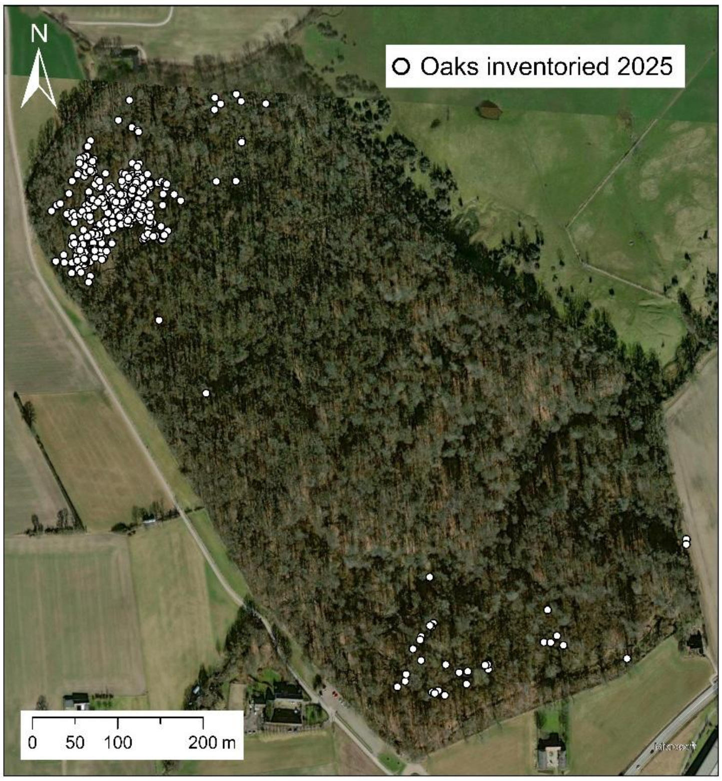

Figure 1. Distribution of the young oaks in Dalby Söderskog according to the inventory in 2025 (aerial photograph credit: Microsoft, ArcGIS).

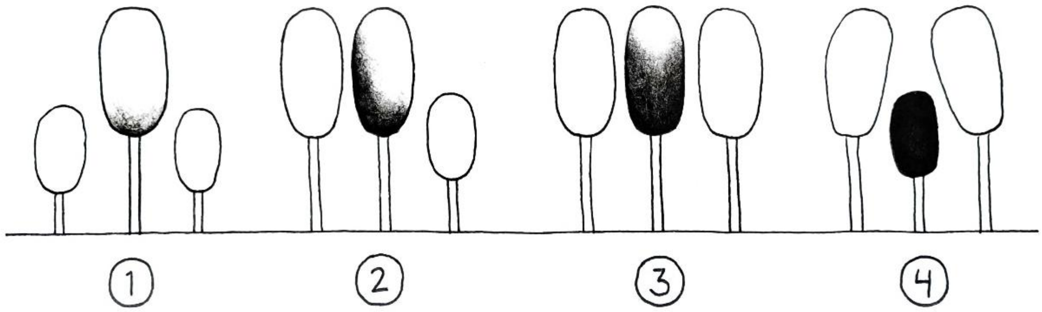

Figure 2. Visualization of the four main crown competition classes. 1) Free-growing; 2) Partly shaded; 3) Surrounded with light availability for the top of the crown; 4) Overgrown. Illustration by Nilla Björklund.

2.3 Method - data processing

Minitab and Excel were used for basic statistics, graphs and tables. ArcGIS pro was used for the map (Figure 1). RStudio was used for the Alluvial plot showing the young oaks transition of crown competition class 2021-2025 (Figure 6). The code for RStudio was generated using ChatGPT.

Minitab was used for the following analyses and tests.

- The effect of the measured explanatory variables in 2021 (dbh, height, crown competition class, forking, stem form, fraying) and 2025 (crown competition class) on stem growth (absolute growth in cm 2021-2025) was analysed with multiple regression analysis.
- A stepwise multiple regression analysis was made to find the most important factors influencing stem growth among the measured variables in 2021 and 2025.
- The effect of initial stem diameter and current crown competition class on stem growth was analysed using simple regression analysis.
- One-way ANOVA was used to analyse the difference in stem growth among trees that had no change in crown competition class, including Tukey pairwise comparison tests. The same analyses were done for trees which had seen a half-step and a one-step increase in crown competition class, respectively.
- One-way ANOVA, including Tukey tests was further used to analyse the difference in stem growth between trees with the same initial crown competition class, but with different changes in class until 2025.

3. Results

The average stem diameter (dbh) was 6.1 cm in 2021, and 9.1 cm in 2025. The average height was 5.3 m in 2021 (Appendix 1, Table 2). The distribution is relatively even between trees that had no forking, trees that where highly forked and trees that where clearly forked in 2021 (Appendix 1, Table 3). The distribution is also fairly even between trees with straight and somewhat crooked stem form in 2021, fewer trees were strongly crooked. Only a few trees had fraying damage caused by roe deer.

3.1 Variables affecting stem diameter growth

A multiple regression analysis showed that the variables included in the full model explained a high degree of the variation in stem growth between 2021 and 2025, but that only initial stem diameter and current crown competition class were statistically significant factors in the model ($R^2 = 61.61\%$, see Appendix 2, table 4). Consequently, a stepwise regression analysis revealed that the initial stem diameter and the current crown competition class alone explained almost as much of the diameter growth as all factors combined ($R^2 = 61.15\%$, Table 1). The two variables initial stem diameter (dbh 21) and current crown competition class (CC 25) are significantly but still not very closely correlated with each other (r = -0.458).

Table 1. Results of stepwise regression of stem growth 2021-2025 on explanatory variables. Retained variables include dbh in 2021 and crown competition class in 2025. R^2: 61.15%, P<0.001, n=394.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	685.16	342.582	307.69	0.000
dbh 21	1	41.04	41.040	36.86	0.000
CC 25	1	385.09	385.092	345.87	0.000
Error	391	435.33	1.113		
Lack-of-Fit	385	431.34	1.120	1.68	0.264
Pure Error	6	3.99	0.665		
Total	393	1120.50			

The initial dbh (dbh21) explains a moderate degree of the variation in stem growth 2021-205 (P=0.000, $R^2 = 29.46\%$, Figure 3). The young oaks have an increased stem growth with increased initial dbh up until around 15 cm. The current crown competition class of the young oaks explains a higher degree of the variation in stem growth ($R^2 = 57.49\%$, P=0.000, Figure 4), almost as much as all variables included in the first multiple regression analysis combined ($R^2 = 61.61\%$).

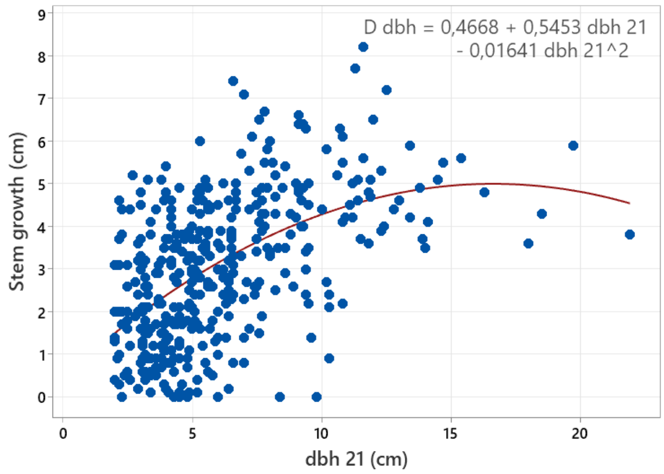

Figure 3. Stem growth 2021-2025 as response to initial dbh. R^2: 29.5%, $P<0.001$, n=394.

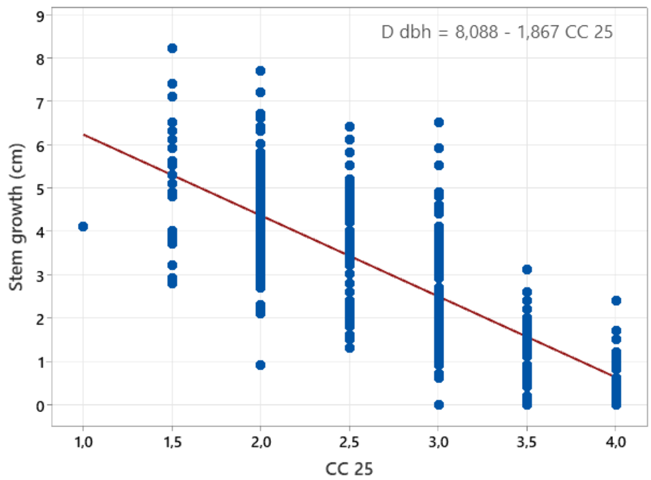

Figure 4. Stem growth 2021-2025 as response to current crown competition class. R^2: 57.49%, $P<0.001$, n=394.

3.2 Crown competition

Overall, the crown competition (CC) in Dalby Söderskog has increased during the four years (Figure 5). The number of young oaks that were free-growing or only partly shaded (CC 1-2.5) was 66% in 2021 and decreased to 49% in 2025. Correspondingly, the number of young oaks that were fully surrounded by other tree stems or overgrown (CC 3-4) was 34% in 2021 and increased to 51% in 2025. In 2021, most oaks were partly shaded (CC=2, 45%), followed by the surrounded oaks (CC=3, 26%). In 2025, most oaks are now completely surrounded (CC=3, 29%) followed the partly shaded oaks (CC=2, 24%).

Among the 394 oaks, 51.5% in total had increased crown competition between 2021 and 2025, and for 23.6% crown competition was increased by at least one class (Figure 6). Of the 394 trees, 44.9% had no change in crown competition. For a small number of the trees (3.6%) the crown competition has decreased.

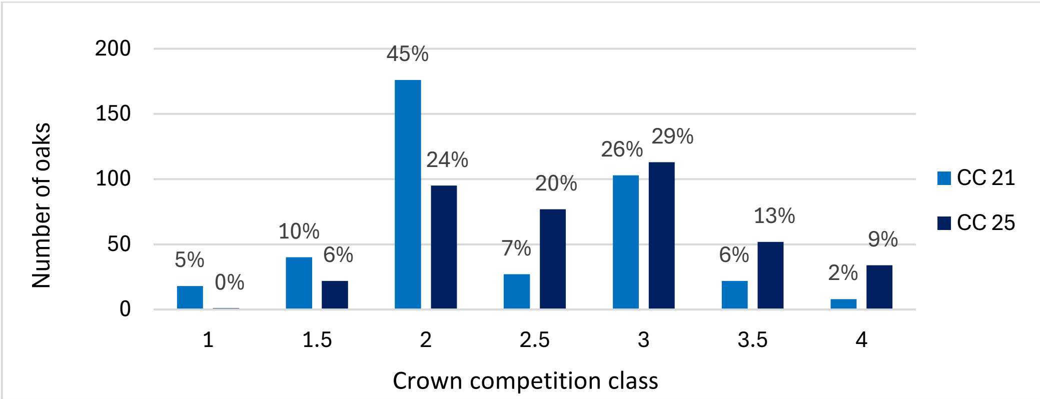

Figure 5. Number of trees in each crown competition class in 2021 (CC 21) and in 2025 (CC 25). Numbers above bars show share of trees (%) in each crown competition class for year 2021 and 2025.

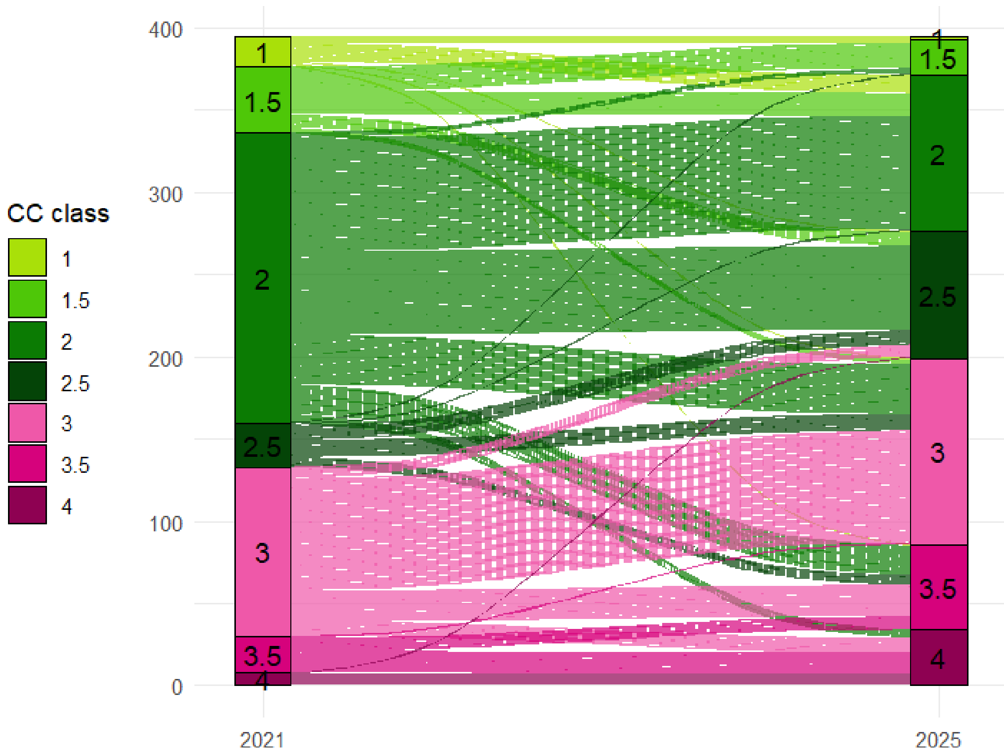

Figure 6. Alluvial plot showing the young oaks transition of crown competition classes from 2021 to 2025. The left bar shows the crown competition class in 2021, and the right bar shows the crown competition class in 2025.

To further examine the difference in effect on stem diameter growth between different crown competition classes, separate analyses were made for oaks which had the same crown competition class 2021-2025 and oaks in which crown competition class increased by 0.5 and 1 class, respectively, from 2021-2025. Due to a low sample number, further statistical analyses were not made for oaks which had a decrease in crown competition class and oaks in which crown competition class increased by more than one class.

3.2.1 Comparing effect of changes in crown competition

In the separate analyses made for oaks with different amount of change in CC class 2021-2025, it was found that the stem diameter growth was significantly different between tree groups with different initial CC class (Figure 7). A higher CC class was consistently correlated to a lower stem growth response, both in oaks which had the same CC class, in oaks for which CC class increased by 0.5 and in oaks for which CC class increased by 1.0 2021-2025. For detailed results see Appendix 3.

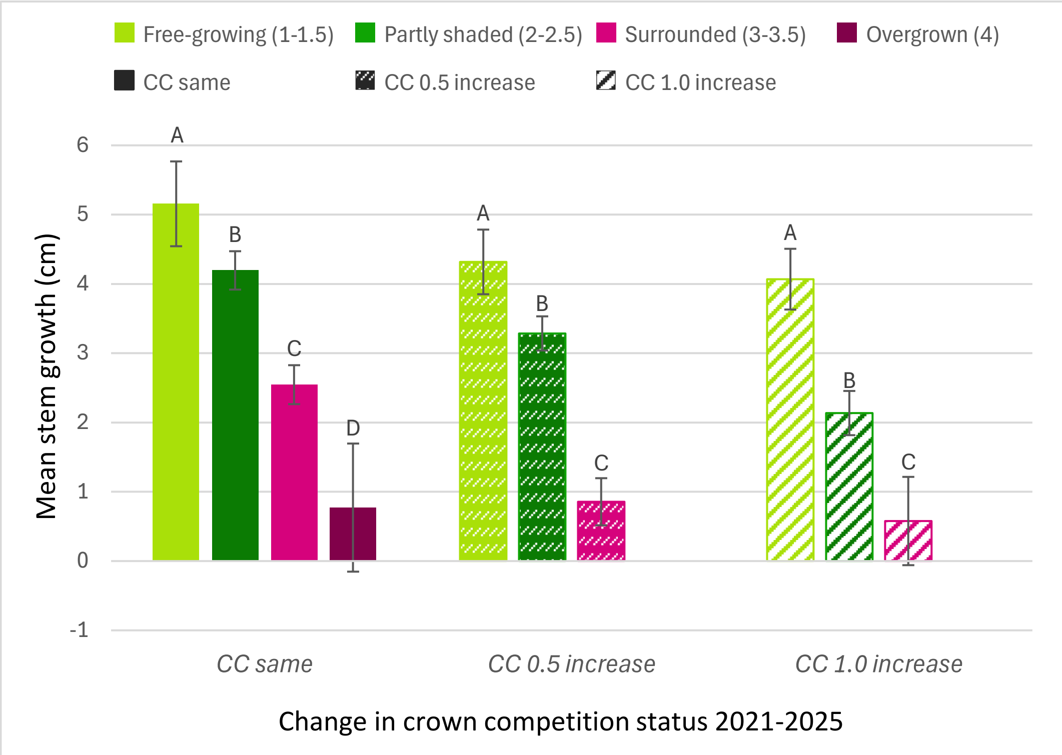

Figure 7. Difference in stem growth between tree groups that had the same change in crown competition status 2021-2025. Bars show the mean stem diameter growth, with 95% confidence intervals. Means in groups with the same change in CC status 2021-2025 that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison. CC class refers to initial CC status (CC21).

Effects of unchanged crown competition: CC same

Of the 394 trees, 177 trees had no change in CC class 2021-2025 (*CC same*, Figure 7). Among these young oaks, the grouped CC classes explain almost half of the stem growth response and there is a significant difference in stem growth between the grouped CC classes (R^2 = 43.19%, P=0.000, Appendix 3, Table 5).

Effects of slightly increased crown competition: CC 0.5 increase

Of the 394 trees, 110 had an increase in CC class by half a step 2021-2025 (*CC 0.5 increase*, Figure 7). Among these young oaks, the grouped CC classes explained a high degree of the stem growth response and there is a significant difference in stem growth response between the grouped CC classes (R^2 = 63.31%, P=0.000, Appendix 3, Table 7).

Effects of increased crown competition: CC 1.0 increase
Of the 394 trees, 64 had an increase in crown competition class by one step 2021-2025 (*CC 1.0 increase*, Figure 7). Among these young oaks the grouped CC classes explained a high degree of the stem growth response and there is a significant difference in stem growth response between the grouped CC classes (R^2 = 60.32%, P=0.000, Appendix 3: Table 9).

3.2.2 Comparing initial crown competition classes

The difference in stem growth among trees with the same initial CC class but based on if CC status remained the same or if CC status increased 2021-2025 was examined. It was found that stem growth was significantly higher for trees for which CC status remained the same (*CC same*) compared to trees for which competition increased by a whole class 2021-2025 (*CC 1.0 increase*), regardless of initial CC class (Figure 8). In trees where competition slightly increased (*CC 0.5 increase*) the effect was intermediate. For detailed results see Appendix 4.

Figure 8. Difference in stem growth 2021-2025 between tree groups with the same initial crown competition class, for which CC was unchanged, slightly increased (+0.5) and increased (+1.0). Bars show the mean stem diameter growth, with 95% confidence intervals. Means in groups with the same CC class in 2021 that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

Crown competition class in 2021: Free-growing (1-1.5)

In 2021, 52 trees were free-growing (*Free-growing (1-1.5)*, Figure 8). For these trees, the variation in stem growth response can to some degree be explained by change in CC status 2021-2025 (R^2=17.53%, P=0.009, Appendix 4, Table 11). The growth was high in all groups, regardless of change in CC status 2021-2025. The growth was highest in free-growing trees for which CC class was unchanged, average of 5.16 cm (1.29 cm/year). The trees for which competition slightly increased, the mean stem growth was 4.32 cm (1.08 cm/year), which did not significantly differ from either of the two other groups. For trees which became shaded on one side, the growth was on average 4.07 cm (1.02 cm/year), which is significantly lower compared to trees which remained free-growing.

Crown competition class in 2021: Partly shaded (2-2.5)

In 2021, 175 trees were partly shaded (*Partly shaded (2-2.5)*, Figure 8). For these trees, the variation in stem growth response can to a moderate degree be explained, by change in CC status 2021-2025. (R^2=31.92%, P=0.000, Appendix 4, Table 13). There was a significant difference in stem growth between the groups. The growth was high in trees shaded on one side for which CC class was unchanged 2021-2025, average of 4.20 cm (1.05 cm/year). The growth was lower in trees for which competition only slightly increased, average of 3.29 cm (0.82 cm/year). Trees which became completely surrounded by stems except for the top of the crown grew the least, on average of 2.14 cm (0.53 cm/year).

Crown competition class in 2021: Surrounded (3-3.5)

In 2021, 117 trees were surrounded by other stems and had light availability only for the top part of the crown (*Surrounded (3-3.5)*, Figure 8). For these trees, the variation in stem growth response can to a moderate degree be explained by change in CC status 2021-2025. (R^2=37.09%, P=0.000, Appendix 4, Table 15). The stem growth was significantly higher in trees that remained in CC class 3-3.5 compared to trees where CC status increased. The trees which were surrounded by stems but had light availability for the top of the crown during 2021-2025 (CC same 3), grew on average 2.5 cm (0.64 cm/year). The growth is very low in trees for which competition only slightly increased, on average 0.86 cm (0.21 cm/year). The growth is also very low in trees that became completely overgrown 2021-2025, on average 0.58 cm (0.14 cm/year).

4. Discussion

The purpose of this study was to increase our knowledge on the factors influencing the growth of naturally regenerated oaks in conservation forests, and specifically to examine how crown competition influences stem diameter growth of pedunculate oak over time. The results support the basic hypothesis that stem diameter growth decreases with increasing crown competition.

The results also showed that the crown competition has in general increased 2021-2025 for the young oaks in Dalby Söderskog. Brunet and Larsson (2022) write that the gaps caused by tree mortality since the 1980s have slowly been filled with regrowth. The proportion of young oaks crowded or overgrown by surrounding stems has steadily increased 2012-2021 (Brunet & Larsson 2022), and this study shows that the trend has continued to 2025.

It was found that of the measured variables, the most important factors explaining the stem growth were initial dbh and current crown competition class. The observed relation to initial dbh is to be expected, as young trees gradually reach the maximal possible growth for the site and the growth no longer increases with dbh (Johnson et al. 2019). Current crown competition class explained a much higher degree of the variation in stem growth. It is, however, likely that initial dbh and crown competition class are interacting and that part of the variation of stem growth response within current crown competition classes depends on the initial dbh.

The results confirm the importance of light availability for stem diameter growth in oak. Light is known as a limiting factor in oaks development, and low light conditions has been found to limit crown-, height- and stem growth (Annighöfer et al. 2015; Jensen & Löf 2017; Mölder et al. 2019). The result also align well with earlier studies in Dalby Söderskog that found crown encroachment to have a negative effect on crown- and height development, which was correlated to a negative effect on stem diameter (Finnström 2016; Brunet & Larsson 2022).

The difference in stem diameter growth was examined in trees for which crown competition status remained the same, for trees where it slightly increased (by half a class), and trees for which crown competition increased by a whole class 2021-2025. The general pattern is the same for all oaks, independent on if crown competition status has been constant or increased during the four years, a higher crown competition led to a decrease in stem growth. An important finding from the study was that the current crown competition is what matters for the trees stem growth. Among trees that had the same crown competition class in 2021, the stem growth was significantly lower in those trees for which crown competition increased a whole class compared to trees where crown competition remained constant 2021-2025. This was true in all grouped crown competition classes. The results show not only that higher crown competition leads to a decrease in stem diameter growth, but also that already one to three years of increased shading will lead to loss of growth and vitality. This means that it is not enough to have a head start, but the trees need to have continuous good light availability.

In 2025, oaks within the lower crown competition classes, specifically the free-growing oaks and the oaks that are only partly shaded (groups where CC25≤2.5), had a high average stem diameter growth, >1.0 cm/year. That is considerably higher than the average stem growth for free-growing production oaks in the region (Ekö & Johansson 2022), and demonstrates the good growth potential of oak on highly fertile forest soils such as in Dalby Söderskog. To note is that although the stem growth was still high in the oaks that went from free-growing (CC21=1-1.5) to partly shaded (CC25=2-2.5), it was significantly lower compared to the oaks which were constantly free-growing 2021-2025.

Among the oaks that were initially only partly shaded (CC21=2-2.5), the stem growth was significantly lower in oaks for which competition increased 2021-2025. The oaks which ended up being completely surrounded except for the top of the crown (CC25=3-3.5) grew similarly to the oaks which were completely surrounded the whole time period, an average growth of 0.53 cm/year and 0.64 cm/year, respectively. That is similar to the average growth in oak production stands in the region (Ekö & Johansson 2022). These trees can survive long-term if enough light is maintained for the upper crown, or if they get an increase of light availability due to mortality of a neighbouring tree. Some of the trees in this group, however, are in crown competition class 3.5 with little light availability left for the crown. These trees probably need a more drastic increase in light availability to be able to survive. Since Dalby Söderskog is a highly fertile site (Brunet et al. 2014) the young oaks may be less competitive compared to other species (Annighöfer et al. 2015). Studies have found that although some initial competition from other species could facilitate oaks saplings growth, long-term shading affects survival and growth negatively (Annighöfer et al. 2015; Jensen & Löf 2017; Pohl et al. 2025), and there are slight indications that competition from shade-tolerant species like beech may be worse compared to competition from other oaks (Annighöfer et al. 2015; Finnström 2016).

Of the oaks which were completely surrounded except for the top of the crown in 2021 (CC=3-3.5), the stem diameter growth was significantly higher in trees for which crown competition status remained compared to trees for which competition increased. The trees that became almost or completely overgrown by surrounding trees (CC25=3.5-4) had significantly lower growth, ≤0.21 cm/year. This is very low growth (Ekö & Johansson 2022), and these trees will probably become outcompeted and eventually die. The growth is also very low in oaks that were completely overgrown the whole time period (CC=4), average of 0.19 cm/year. These trees are losing vitality, and the low number of such overgrown trees in the survey could be because many trees in this competition class had died between the measurement in 2021 and 2025 and probably were not found (personal communication Jörg Brunet, 30-05-2025).

Earlier studies in both Dalby Söderskog (Finnström 2016; Brunet & Larsson 2022) and other areas (Götmark 2007; Götmark & Kiffer 2014) have concluded that after a large disturbance oak can naturally regenerate. The study area Dalby Söderskog is similar to other areas that have had a sudden increase in light availability, where spontaneous oak regeneration has emerged (Bobiec et al 2014, Götmark & Kiffer 2014). Götmark & Kiffer (2014) studied an area close to Gothenburg that in 1969 became open after windthrow and logging, and then was left for free development. Natural oak regeneration occurred but oak was not the predominant species to regenerate. Forty years later they found a low, but not inconsiderable, number of large oaks. Although oak is the focus of this study, it is not the predominant species to regenerate in Dalby Söderskog (Brunet et al. 2014). The oak regeneration in Dalby Söderskog that emerged during the 1990s, is now about 10 years younger than Götmark & Kiffers (2014) at their final measurement. The results of their study indicate what might happen to the oak population in Dalby Söderskog if no management measures are taken to release oaks from crown competition. There will probably be some oaks that survive, but it is unlikely that without management enough oaks will survive to maintain the current density of oak in Dalby Söderskog (c.f. scenario C, Löf et al. 2016). The results of this study showed that there is a rapid decrease in growth and survival of the oaks, and the general densification of the woody understory in Dalby Söderskog means that it will probably be too dark for oaks to have substantial future regeneration.

Decreased light availability also has a direct negative impact on species living in and on the oaks crown and stem (Ranius et al. 2009; Löf et al. 2016; Mölder et al. 2019), as many epiphytes and saproxylic insects are favoured by sun exposure (Löf et al. 2016; Mölder et al. 2019).

One of the goals in the conservation plan for Dalby Söderskog is to preserve the natural values connected to nutrient-rich oak forests (Länsstyrelsen Skåne 2024). The quick effects of crown competition and increasing stand density found in this study indicate urgency for silvicultural measurements to be made for preserving these values, and the survival of young oaks that later can become habitat trees.

To promote the new oak regeneration, management around single oak trees is necessary as they need sufficient space for their crown to develop (Drößler et al. 2012). Trees which are crowded by woody stems have smaller crowns, which limits their photosynthetic capacity and supress their growth potential (Attocchi & Skovsgaard 2015). Although crown size was not measured in this study, it can be assumed that the lower stem diameter correlated with higher crown competition is a result of smaller crown size (Attocchi & Skovsgaard 2015).

To preserve the values in Dalby Söderskog it is also necessary to secure successful future oak regeneration. Studies find that a heterogenous stand with some open parts and some more shaded parts would be best for biodiversity (Löf et al. 2016; Mölder et al. 2019), and sufficiently large gaps are needed for regeneration (Löf et al. 2016; Jensen & Löf 2017; Mölder et al. 2019). There are no definite numbers for gap size, but suggestions vary from 0.05 ha up to 2 ha (Mölder et al. 2019).

Pohl et al. (2025) found positive effects on oak recruitment with a higher canopy openness combined with less shade casting tree species which let through more light. Earlier studies suggest that there may be some difference in effect of inter- and intraspecific crown competition (Annighöfer et al. 2015; Finnström 2016). This could indicate that thinning should be focused around oaks that are competing with other more shade-tolerant and shade-casting species (Annighöfer et al. 2015; Pohl et al. 2025). However, the effect of inter- and intraspecific crown competition was not examined in this study and no specific suggestions can be made in this matter.

Browsing was not a crucial factor for the oaks in this study. The trees were all >2.5 meters, well above browsing height (1.3m). For future recruitment it might be important to consider since oak is a highly preferred species by ungulates and browsing may delay their height growth more than that of their less preferred competitors (Petersson et al. 2019; Brunet & Larsson 2022). Jensen & Löf (2017) suggest that silvicultural management of competitors could be done to protect the oaks until they are safe from browsing.

Since height was not measured in 2025, this remains to be studied. Something that could be further analysed is if the trees in competition class 3 still are taller than other trees, like found in the previous study by Finnström (2016). Future studies could also examine the effect of crown competition on crown volume (e.g. width and length) and mortality. Crown size and structure are important factors for tree growth and vitality (Dubravac et al. 2009; Attocchi & Skovsgaard 2015; Bartkowicz & Paluch 2023), and young oaks with a living crown length of less than 50% have a higher risk of mortality (Jensen & Löf 2017). This study found a loss of growth and vitality with increasing crown competition but only included oaks surviving the whole period. To better determine the effects of increased crown competition on oaks development it would be of interest to examine mortality rates as well.

5. Conclusion

This study confirms the importance of light availability for the growth of young oaks. The results show that stem growth in pedunculate oak is negatively affected by higher crown competition. The oaks in Dalby Söderskog have a very high stem growth when they have sufficient light availability, but when the crown is almost or completely overgrown the stem growth is very low. The results also showed that already one to three years of increased shading will lead to a significantly lower stem growth, demonstrating rapid negative effects of increasing crown competition and stand density.

Beyond the negative impact on oaks development, the effects of increased crown competition in Dalby Söderskog may negatively affect biodiversity. The quick effects of crown competition and densification found in this study indicate urgency for silvicultural measurements to be made for the survival of young oaks that later can become habitat trees, and to secure successful future oak regeneration in Dalby Söderskog. Comparisons to studies made in similar areas also suggest that management measures are necessary to secure successful regeneration and the continuity of oaks in Dalby Söderskog.

References

Annighöfer, P., Beckschäfer, P., Vor, T. & Ammer, C. (2015). Regeneration Patterns of European Oak Species (Quercus petraea (Matt.) Liebl., Quercus robur L.) in Dependence of Environment and Neighborhood. *PLoS ONE*, 10 (8), e0134935. https://doi.org/10.1371/journal.pone.0134935

Attocchi, G. & Skovsgaard, J.P. (2015). Crown radius of pedunculate oak (Quercus robur L.) depending on stem size, stand density and site productivity. *Scandinavian Journal of Forest Research*, 30 (4), 289–303. https://doi.org/10.1080/02827581.2014.1001782

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

Bobiec, A., Kuijper, D.P.J., Niklasson, M., Romankiewicz, A. & Solecka, K. (2011). Oak (Quercus robur L.) regeneration in early successional woodlands grazed by wild ungulates in the absence of livestock. *Forest Ecology and Management*, 262 (5), 780–790. https://doi.org/10.1016/j.foreco.2011.05.012

Brunet, J., Bukina, Y., Hedwall, P.-O., Holmström, E. & Von Oheimb, G. (2014). Pathogen induced disturbance and succession in temperate forests: Evidence from a 100-year data set in southern Sweden. *Basic and Applied Ecology*, 15 (2), 114–121. https://doi.org/10.1016/j.baae.2014.02.002

Brunet, J. & Larsson, J. (2022). *Ekens dynamik i naturvårdsskogar: ekbeståndets demografi i Dalby Söderskog 2011-2021*. Arbetsrapport nr.56. Institutionen för sydsvensk skogsvetenskap, Sveriges lantbruksuniversitet. https://res.slu.se/id/publ/116527

Drobyshev, I., Linderson, H. & Sonesson, K. (2007). Relationship Between Crown Condition and Tree Diameter Growth in Southern Swedish Oaks. *Environmental Monitoring and Assessment*, 128 (1), 61–73. https://doi.org/10.1007/s10661-006-9415-2

Drößler, L., Attocchi, G. & Jensen, A.M. (2012). Occurrence and management of oak in southern Swedish forests. *Forstarchiv*, 83 (5), 163–169. https://doi.org/10.4432/0300-4112-83-163

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

Ekö, P.-M. & Johansson, U. (2022). *Produktion och skötsel av ek*. [Fact sheet] Fakta skog. SLU, Fakulteten för skogsvetenskap. https://www.slu.se/globalassets/ew/org/andra-enh/s/forskning/fakta-skog/fakta-skog-johansson-eko-produktion-skotsel-av-ek-22-02-16-low.pdf [2025-04-25]

Finnström, O. (2016). *Regeneration dynamics of pedunculate oak in natural temperate forests: a case from southern Sweden*. (Master Thesis no. 251). Swedish University of Agricultural Sciences. MSc thesis in Biology – Jägmästarprogrammet. http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-s-5215 [2025-03-26]

Götmark, F. (2007). Careful partial harvesting in conservation stands and retention of large oaks favour oak regeneration. *Biological Conservation*, 140 (3–4), 349–358. https://doi.org/10.1016/j.biocon.2007.08.018

Götmark, F. & Kiffer, C. (2014). Regeneration of oaks (Quercus robur/Q. petraea) and three other tree species during long-term succession after catastrophic disturbance (windthrow). *Plant Ecology*, 215 (9), 1067–1080. https://doi.org/10.1007/sl 1258-014-0365-4

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

Johnson, P.S., Shifley, S.R., Rogers, R., Dey, D.C. & Kabrick, J.M. (2019). Growth and yield. In: *The ecology and silviculture of oaks*. 3. ed. CABI. 530–573. https://doi.org/10.1079/9781780647081.0530

Länsstyrelsen Skåne (2017). *Dalby Söderskog nationalparksfolder*. [Pamphlet]. Länsstyrelsen Skåne. https://www.lansstyrelsen.se/skane/om-oss/vara-tjanster/publikationer/2017/dalby-soderskog-nationalparksfolder.html [2025-04-24]

Länsstyrelsen Skåne (2024). *Bevarandeplan för Natura 2000-området Dalby Söderskog SE0430022*. Länsstyrelsen Skåne. https://www.lansstyrelsen.se/download/18.44c2e45f193902bacdb1da36/1733739549944/Dalby%20S%C3%B6derskog%20bevarandeplan%202024.pdf [2025-04-28]

Länsstyrelsen Skåne (n.d.). *Dalby Söderskog nationalpark*. https://www.lansstyrelsen.se/skane/besoksmal/nationalparker/dalby-soderskog-nationalpark.html [2025-04-24]

Löf, M., Brunet, J., Filyushkina, A., Lindbladh, M., Skovsgaard, J.P. & Felton, A. (2016). Management of oak forests: striking a balance between timber production, biodiversity and cultural services. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 12 (1–2), 59–73. https://doi.org/10.1080/21513732.2015.1120780

Mölder, A., Meyer, P. & Nagel, R.-V. (2019). Integrative management to sustain biodiversity and ecological continuity in Central European temperate oak (Quercus robur, Q. petraea) forests: An overview. *Forest Ecology and Management*, 437, 324–339. https://doi.org/10.1016/j.foreco.2019.01.006

Petersson, L.K., Milberg, P., Bergstedt, J., Dahlgren, J., Felton, A.M., Götmark, F., Salk, C. & Löf, M. (2019). Changing land use and increasing abundance of deer cause natural regeneration failure of oaks: Six decades of landscape-scale evidence.

Forest Ecology and Management, 444, 299–307. https://doi.org/10.1016/j.foreco.2019.04.037

Pohl, N.S., Hedwall, P.-O., Aldea, J., Felton, A.M., Gardiner, E.S., Muraro, L., Nordén, B. & Löf, M. (2025). Effects of stand structural attributes on oak recruitment in mixed temperate forests. *Forest Ecology and Management*, 586, 122721. https://doi.org/10.1016/j.foreco.2025.122721

Ranius, T., Niklasson, M. & Berg, N. (2009). Development of tree hollows in pedunculate oak (Quercus robur). *Forest Ecology and Management*, 257 (1), 303–310. https://doi.org/10.1016/j.foreco.2008.09.007

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Appendix 1 – General data

Table 2. Basic statistics of the data set "Oak regeneration Söderskog".

Variable	**N**	**N***	**Mean**	**SE Mean**	**StDev**	**Min**	**Q1**	**Median**	**Q3**	**Max**
dbh 21	394	0	6.066	0.162	3.214	2.000	3.700	5.250	7.700	21.900
dbh 25	394	0	9.069	0.218	4.336	2.300	5.600	8.250	11.600	25.700
height 21	394	0	5.2792	0.0673	1.3349	2.5000	4.0000	5.0000	6.0000	10.0000
CC 21	394	0	2.3236	0.0339	0.6730	1.0000	2.0000	2.0000	3.0000	4.0000
CC 25	394	0	2.7246	0.0346	0.6859	1.0000	2.0000	3.0000	3.0000	4.0000
fork 21	394	0	0.8731	0.0402	0.7970	0.0000	0.0000	1.0000	2.0000	2.0000
form 21	394	0	0.7437	0.0357	0.7082	0.0000	0.0000	1.0000	1.0000	2.0000
fray 21	394	0	0.0558	0.0121	0.2407	0.0000	0.0000	0.0000	0.0000	2.0000

Table 3. Number of trees and % of stem forking class (Fork 21), stem form class (Form 21) and occurrence of fraying damage (Fray 21) in 2021.

Class	fork 21 no trees	form 21 no trees	fray 21 no trees	fork 21 %	form 21 %	fray 21 %
0	153	162	373	38.8%	41.1%	94.7%
1	138	171	20	35.0%	43.4%	5.1%
2	103	61	1	26.1%	15.5%	0.3%
Total	394	394	394	100%	100%	100%

Appendix 2 – Multiple regression analysis

Table 4. Results of multiple regression analysis of stem growth 2021-2025 on explanatory variables. Initial stem diameter (dbh 21) and current crown competition class (CC 25) are statistically significant factors in the model (P<0.001). The other factors are non-significant (P>0.05). R^2: 61.61%, n=394.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	690.34	98.620	88.50	0.000
dbh 21	1	23.88	23.878	21.43	0.000
height 21	1	1.01	1.007	0.90	0.342
fork 21	1	2.28	2.278	2.04	0.154
form 21	1	0.44	0.443	0.40	0.529
fray 21	1	1.60	1.597	1.43	0.232
CC 21	1	0.01	0.012	0.01	0.917
CC 25	1	180.25	180.252	161.75	0.000
Error	386	430.16	1.114		
Lack-of-Fit	380	426.17	1.121	1.69	0.264
Pure Error	6	3.99	0.665		
Total	393	1120.50			

Appendix 3 – Change in crown competition.

Of the 394 trees, 177 trees had no change in crown competition class between the years 2021 and 2025. These 177 trees were grouped by initial crown competition class (CC 21) in four main classes (CC same 1-4): 1) Trees where CC 21 and CC 25 = 1-1.5; 2) Trees where CC 21 and CC 25 = 2-2.5; 3) Trees where CC 21 and CC 25 = 3-3.5; 4) Trees where CC 21 and CC 25 = 4. See results of one-way ANOVA and Tukey pair wise comparison in table 5 and 6, figure 9.

Table 5. Results of one-way ANOVA describing stem growth 2021-2025, in the young oaks for which CC class remained the same, as response to grouped CC classes (grouping CC same). R^2*: 43.19%, P<0.001, n=177.*

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
CC same	3	202.2	67.386	43.84	0.000
Error	173	265.9	1.537		
Total	176	468.1			

Table 6. Difference in mean stem growth (cm) of the young oaks between grouped crown competition classes (CC same) during 2021-2025. Means that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

CC same	**N**	**Mean**	**Grouping**			
1	16	5.156	A			
2	78	4.195		B		
3	76	2.546			C	
4	7	0.771				D

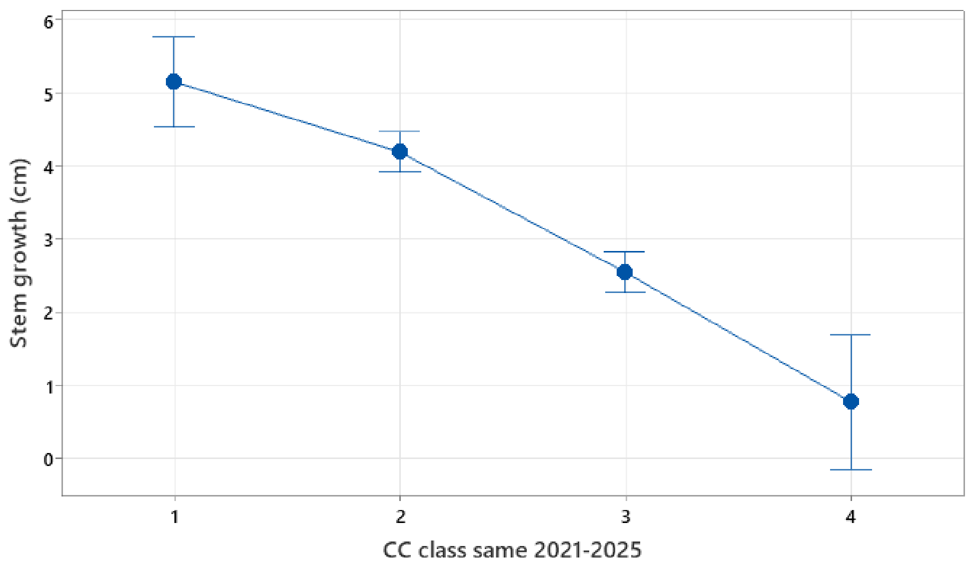

Figure 9. Stem diameter growth of young oaks for which crown competition remained the same 2021-2025 (grouping CC same). Data points are the mean stem diameter growth (cm), with 95% confidence intervals.

Of the 394 trees, 110 had an increase in crown competition class by half a step between the years 2021 and 2025. These 110 trees were grouped by initial crown competition class (CC 21) in three main classes (CC 0.5 incr 1-3): 1) Trees that went from CC 21 = 1-1.5 to CC 25 = 1.5-2; 2) Trees that went from CC 21= 2-2.5 to CC 25 = 2.5-3; 3) Trees that went from CC 21= 3-3.5 to CC 25 = 3.5-4. See results of one-way ANOVA and Tukey pair wise comparison in table 7 and 8, figure 10.

Table 7. Results of one-way ANOVA describing stem growth 2021-2025, in the young oaks for which CC class increased by 0.5 class, as response to grouped CC classes (grouping CC 0.5 incr). R2: 63.31%, P<0.001, n=110

Source	DF	Adj SS	Adj MS	F-Value	P-Value
CC 0.5 incr	2	174.0	86.9997	92.31	0.000
Error	107	100.8	0.9424		
Total	109	274.8			

Table 8. Difference in mean stem growth (cm) of the young oaks where crown competition class increased by 0.5 (Grouping CC 0.5 incr) during 2021-2025. Means that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

CC 0.5 incr	N	Mean	Grouping		
1	17	4.318	A		
2	61	3.285		B	
3	32	0.856			C

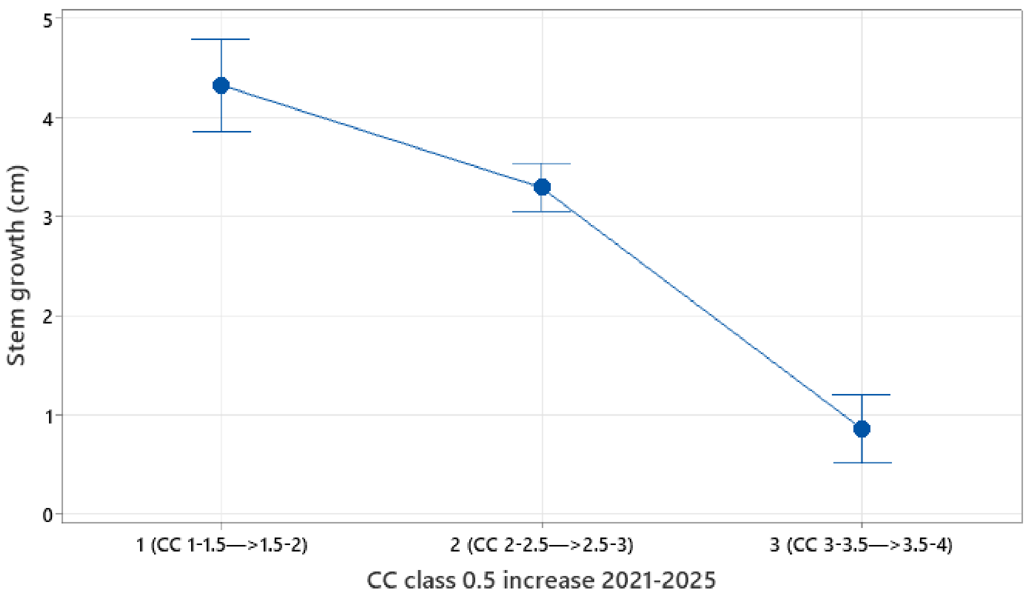

Figure 10. Stem diameter growth of young oaks for which crown competition increased with half a class 2021-2025 (grouping CC 0.5 incr). Data points are the mean stem diameter growth, with 95% confidence intervals.

Of the 394 trees, 64 had an increase in crown competition class by one step between the years 2021 and 2025. These 64 trees were grouped by initial crown competition class (CC 21) in three main classes (CC 1.0 incr 1-3): 1) Trees that went from CC 21 = 1-1.5 to CC 25 = 2-2.5; 2) Trees that went from CC 21= 2-2.5 to CC 25 = 3-3.5; 3) Trees that went from CC 21= 3 to CC 25 = 4. See results of one-way ANOVA and Tukey pair wise comparison in table 9 and 10, figure 11.

Table 9. Results of one-way ANOVA describing stem growth 2021-2025, in the young oaks for which CC class increased by one class, as response to grouped CC classes (grouping CC 1.0 incr). R^2: 60.32%, P<0.001, n=64.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
CC 1.0 incr	2	84.75	42.3774	46.36	0.000
Error	61	55.76	0.9141		
Total	63	140.51			

Table 10. Difference in mean stem growth (cm) of the young oaks where crown competition class increased by one step (grouping CC 1.0 incr) during 2021-2025. Means that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

CC 1.0 incr	N	Mean	Grouping		
1	19	4.068	A		
2	36	2.136		B	
3	9	0.5778			C

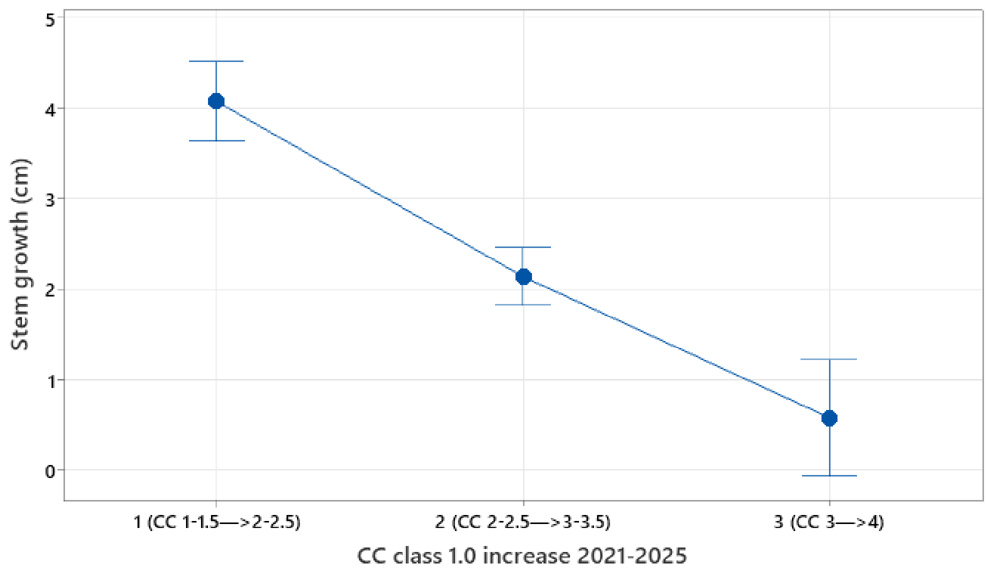

Figure 11. Stem diameter growth of young oaks for which crown competition increased with a whole class 2021-2025 (grouping CC 1.0 incr). Data points are the mean stem diameter growth, with 95% confidence intervals.

Appendix 4 – Initial crown competition class

Table 11. Results of one-way ANOVA describing stem growth 2021-2025 of young oaks with initial CC class 1-1.5 as response to change in CC class. R^2: 17.53%, $P<0.05$, $n=52$.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Comparison CC class 1-1.5	2	10.98	5.491	5.21	0.009
Error	49	51.67	1.054		
Total	51	62.65			

Table 12. Difference in mean stem growth of the young oaks where initial CC class was 1-1.5. Means that do not share a letter are significantly different ($P<0.05$) according to Tukey pairwise comparison.

Comparison CC class 1-1.5	N	Mean	Grouping	
CC same 1	16	5.156	A	
CC 0.5 incr 1	17	4.318	A	B
CC 1.0 incr 1	19	4.068		B

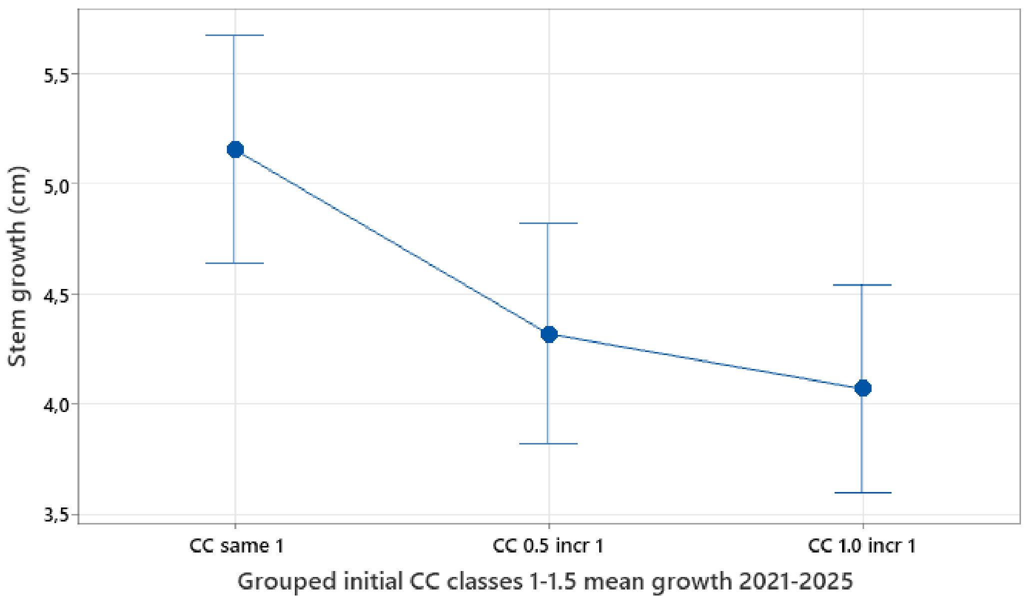

Figure 12. Stem diameter growth of the young oaks with initial crown competition class 1-1.5, grouped by change in crown competition status 2021-2025. Data points is the mean stem diameter growth, with 95% confidence intervals.

Table 13. Results of one-way ANOVA describing stem growth 2021-2025 of young oaks with initial CC class 2-2.5 as response to change in CC class. R^2: 31.92%, P<0.001, n=175.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Comparison CC class 2-2.5	2	107.1	53.538	40.32	0.000
Error	172	228.4	1.328		
Total	174	335.5			

Table 14. Difference in mean stem growth (cm) of the young oaks where initial CC class was 2-2.5. Means that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

Comparison CC class 2-2.5	**N**	**Mean**	**Grouping**		
CC same 2	78	4.195	A		
CC 0.5 incr 2	61	3.285		B	
CC 1.0 incr 2	36	2.136			C

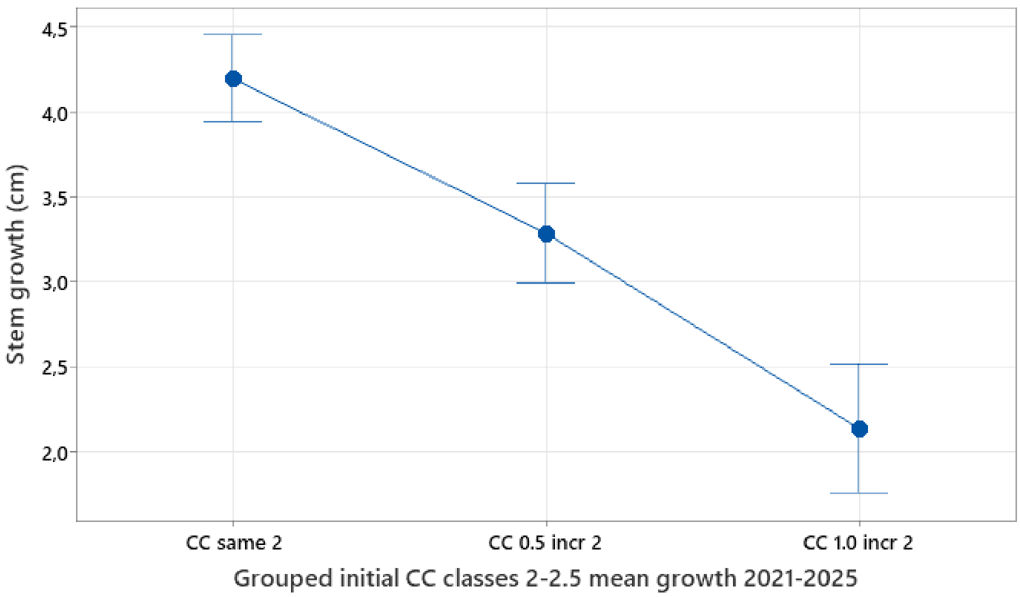

Figure 13. Stem diameter growth of the young oaks with initial crown competition class 2-2.5, grouped by change in crown competition status 2021-2025. Data points is the mean stem diameter growth, with 95% confidence intervals.

Table 15. Results of one-way ANOVA describing stem growth 2021-2025 of young oaks with initial CC class 3-3.5 as response to change in CC class. R^2: 37.09%, P<0.001, n=117.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Comparison CC class 3-3.5	2	82.19	41.097	33.61	0.000
Error	114	139.38	1.223		
Total	116	221.58			

Table 16. Difference in mean stem growth (cm) of the young oaks where initial CC class was 3-3.5. Means that do not share a letter are significantly different (P<0.05) according to Tukey pairwise comparison.

Comparison CC class 3-3.5	N	Mean	Grouping	
CC same 3	76	2.546	A	
CC 0.5 incr 3	32	0.856		B
CC 1.0 incr 3	9	0.5778		B

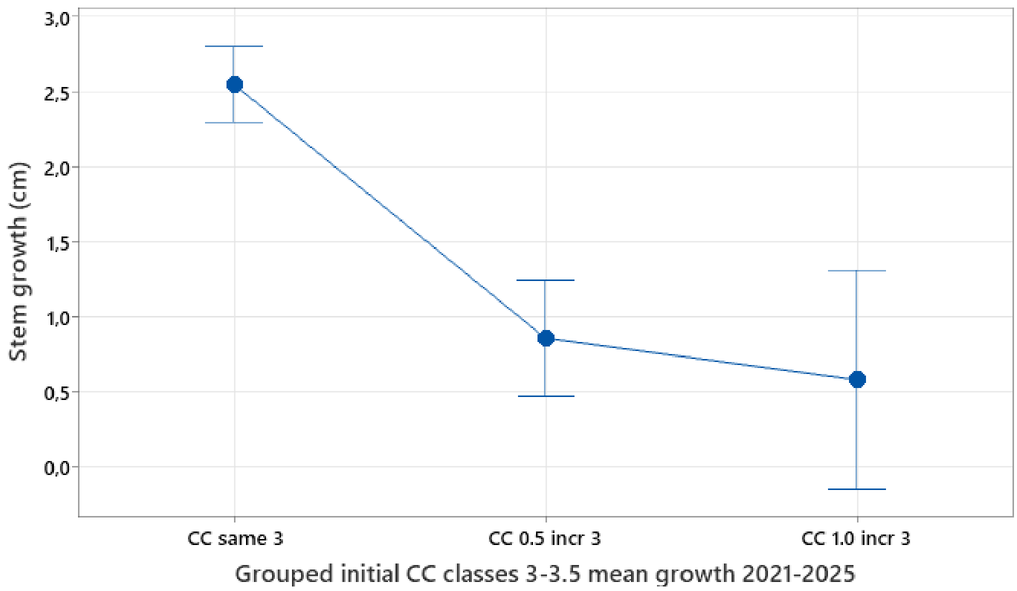

Figure 14. Stem diameter growth of the young oaks with initial crown competition class 3-3.5, grouped by change in crown competition status 2021-2025. Data points is the mean stem diameter growth, with 95% confidence intervals.

Publishing and archiving

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