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Scandinavian Journal of Forest Research

ISSN: 0282-7581 (Print) 1651-1891 (Online) Journal homepage: https://www.tandfonline.com/loi/sfor20

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**To cite this article:** Igor Drobyshev, Maria Koch Widerberg, Mikael Andersson, Xiaoming Wang & Matts Lindbladh (2019) Thinning around old oaks in spruce production forests: current practices show no positive effect on oak growth rates and need fine tuning, Scandinavian Journal of Forest Research, 34:2, 126-132, DOI: 10.1080/02827581.2018.1557247

**To link to this article:** https://doi.org/10.1080/02827581.2018.1557247

SCANDINAVIAN JOURNAL OF FOREST RESEARCH
2019, VOL. 34, NO. 2, 126–132
https://doi.org/10.1080/02827581.2018.1557247



# Thinning around old oaks in spruce production forests: current practices show no positive effect on oak growth rates and need fine tuning

Igor Drobyshev[a,b], Maria Koch Widerberg[a], Mikael Andersson[c], Xiaoming Wang[d] and Matts Lindbladh[a]

[a]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Alnarp, Sweden; [b]Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada; [c]Asa Research Station, Swedish University of Agricultural Sciences, Lammhult, Sweden; [d]Key Laboratory for Silviculture and Conservation of Ministry of Education, Beijing Forestry University, Beijing, People's Republic of China

**ABSTRACT**

The expansion of spruce-dominated forestry in Southern Sweden during the twentieth century has led to a considerable amount of oak (*Quercus robur* L.) woodlands being converted into stands dominated by planted spruce. The thinning of spruces around oak trees is currently done in Sweden to improve local diversity of insects, oak growing conditions and eventually decrease their mortality. To evaluate the effect of these treatments, we dendrochronologically studied growth of old (100–200 years old) oaks subjected to thinning of different intensity at nine locations in southern Sweden, and compared them to oaks located in nearby pastures. The overall pattern suggests that commonly adopted thinning intensities do not significantly affect oak growth. Oak growth was positively related to oak age and negatively to the amount of dead oak crown. Analyses of correlations between oak growth and summer drought conditions, as reflected by location-specific chronologies of the Monthly Drought Code (MDC), indicated that older trees exhibited generally negative correlations, whereas the correlation remained generally positive for the younger trees, both inside and outside forest stands. We propose that removal of spruces should be primarily done around older and healthier-looking trees.

**ARTICLE HISTORY**
Received 23 January 2018
Accepted 8 November 2018

**KEYWORDS**
Oak dendrochronology; conservation management; forest biodiversity; drought conditions; tree vitality; thinning; mixed forests; European hardwoods

## Introduction

A large amount of species diversity in southern Swedish forests is associated with oak trees (*Quercus robur* and *Q. petraea*). Oaks host a variety of insect, lichen, fungi, and bird species (Nilsson 1997; Widerberg et al. 2018) and can therefore be viewed as true "biodiversity carriers", whose abundance is directly linked to habitat availability for many species. Over the last centuries, the abundance of such trees in the Swedish forests has been decreasing (Eliasson and Nilsson 1999; Lindbladh and Foster 2010), which resulted in a decline in biodiversity of many organism groups. Intensive forestry converting temperate broadleaved woodlands into monocultures of spruce was a major factor negatively affecting the oak population (Niklasson et al. 2002).

Today, in many forested areas of southern Sweden, old oaks can be found in dense spruce stands, an environment which is sharply different from open conditions which was common prior to the establishment of monoculture-dominated forestry (Lindbladh 1999). Even being a part of spruce plantations, the presence of oak trees favours biodiversity inside the stands and in the surrounding landscape (Ranius and Jansson 2000; Widerberg et al. 2012). However, there is a concern that oaks in spruce plantations experience increased mortality rates, which over the long-term may decrease the amount of habitat and threaten oak-associated species.

The rationale for developing optimized thinning (Swedish *frihuggning*) guidelines stems from the projections suggesting that forestry in southern Sweden will remain dominated by production-oriented plantations in the foreseeable future (Felton et al. 2010). A considerable number of old oaks, which were once a part of the open landscape, still exist across southern Sweden as an element embedded in the matrix of spruce-dominated plantations. For example, in the Swedish county of Östergötland, 35,000 old oaks have been identified, a large proportion of them growing inside production stands (Johannesson and Ek 2006). County administrations in southern Sweden are actively searching for land owners who are interested in joining a large-scale programme, sponsored by the Swedish government, to thin around remaining old oaks (Anonymous 2013). Thus, management of single oak trees has become an increasingly common practice in commercial forests (G. Björse, Sveaskog, personal communication), which calls for better scientific knowledge to support these treatments.

Thinning around the large oaks is believed to lower competitive interactions of oaks with neighbouring spruces and increase the amount of light available to them. However,

**CONTACT** Igor Drobyshev igor.drobyshev@slu.se Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences. PO Box 49, SE-230 53 Alnarp, Sweden; Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université, Rouyn-Noranda, QC, Canada J9X 5E4
Supplemental data for this article can be accessed at https://doi.org/10.1080/02827581.2018.1557247.

thinning may also increase trees' transpiration and affect soil water levels through soil compaction resulting from the use of machinery (Allman et al. 2015). It follows that the resulting effects on the physiology of the oak trees may be complex, affecting their sensitivity to weather variability. From a practical perspective, there is a need to better understand the relationship between the conservation value of thinning around oaks and the associated costs to the forest owner. The resources spent on both the thinning treatment and loss of future volume increment in spruce both compromise the economic return from the plantation. A recent study has shown that an average spruce stand subjected to thinning around oaks can lead to a 10–20% reduction in the total stand volume during the current rotation (Widerberg 2013). Given that the same amount of "free space" will be allocated for the same trees in the subsequent rotations, the economic effect of this treatment will increase over time. The intensity of thinning around oaks may thus have an impact on the forest stand as a habitat for biodiversity, but also on the revenues for the forest owners.

In this study, we analysed data from nine sites in southern Sweden to assess the impact of different thinning intensities on oak, using the trees' growth rate as a proxy for the treatment impact on the focal tree. Growth rates reflect mortality risk due to non-abrupt events and processes, such as competition and long-term resource availability (Dobbertin 2005; Drobyshev et al. 2007b). Quantifying growth patterns may, therefore, provide an overall assessment of oak vitality and mortality risks. We put forward three hypotheses:

(1) thinning increases oak growth rates, the increase being indicative of improved light conditions and decreased competition for soil nutrient resources with spruce trees, as suggested by common oak response to thinning (Barrio Anta and varez Gonzalez 2005; Stefancik 2012);
(2) the effect of thinning depends on the age, size and crown conditions of the focal trees;
(3) sensitivity of oaks to summer drought increases as the thinning intensity increases (Chang et al. 2016; Stojanovic et al. 2017).

Through testing these hypotheses, we provide recommendations to improve thinning protocols for oaks growing in spruce plantations.

## Material and methods

### Study area and the sites

We studied oaks in nine locations (Figure 1, SI Table 2) in the hemi-boreal vegetation zone of Sweden (Ahti et al. 1968). The climate of the region is of Atlantic type with the mean temperature in the study region between −4°C and 0°C in January and between 15°C and 16°C in July. Precipitation varies from 500 mm/year (east) to 1200 mm/year (west). Norway spruce (*Picea abies*) dominates in Southern Sweden, accounting for about 47% of the total standing timber volume (SFA 2014). Regionally, oak contributes only 4% of the timber volume (SFA 2014). The agriculture-driven clearance of the land resulted in the long-term decline of oak woodlands that was initiated in the first millennium AD (Lindbladh and Foster 2010). The protection of oak by the Swedish Kings that lasted over three centuries (1558-1823) contributed to oak conservation in the southern Swedish landscape (Eliasson 2002). However, over the last one and a half centuries, the

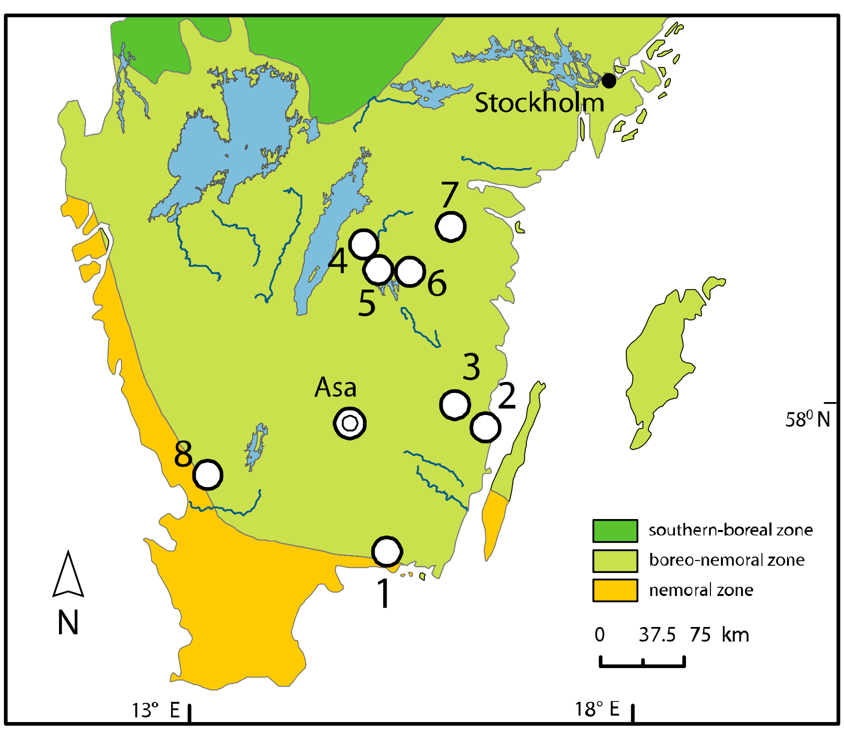


**Figure 1.** Study sites in Southern Sweden and biogeographic zones (after Ahti et al. 1968). (1) Johannishus, (2) Strömsrum, (3) Hornsö, (4) Boxholm, (5) Sandvik, (6) Malexander, (7) Adelsnäs, (8) Tönnersjö (see Table 1). Asa site is indicated with a double circle.

decline in oak abundance has intensified. The main cause of this dynamic was a gradual replacement of open and semi-open woodland and forest habitats, which are the main oak regeneration sites, by dense spruce plantations (Lindbladh et al. 2014). The studied spruce stands represented commercial even-aged plantations with a rotation period varying between 50 and 70 years. They were semi-natural pastures until the middle of the twentieth century. Each stand contained a number of oak trees that were shaded to a varying degree by spruce trees. All of the studied stands, except Strömsrum and Tönnersjö, had been subjected to pre-commercial and commercial thinning (Table 1). Initial field observations indicated there was no oak regeneration in the stands, and very sparse field layer in general (see SI Figure 1).

### Field sampling and sample preparation

Our data consisted of two sets which were treated independently in the statistical analyses. The first dataset (later referred to as *Dataset1*) was represented by the network sites over southern Sweden (Figure 1), where we inventoried oak conditions and cored the trees to obtain annual tree-ring chronologies (number of trees, $n = 71$). At each location we inventoried and cored up to eight oaks, up to six trees growing in the spruce stand (later referred to as “forest oaks”) and two in a nearby pasture (later referred to as “pasture oaks”) and commonly within 300–400 m away from the oaks growing in the spruce plantations. Oaks were cored on two randomly selected sides at the height of 0.2 m in order obtain both tree age and ring width data. The second dataset (later referred to as *Dataset2*) originated from a single site in the Swedish province of Kronoberg (site Asa, Figure 1), where a more intensive sampling of forest oaks ($n = 34$) was done, but there no pasture oaks were available. Another feature of this dataset was a dominance of hollow oaks (~65% of all trees), which precluded identification of tree age at the coring height in the majority of trees, despite multiple coring attempts. Oak tree properties (DBH, amount of dead crown, and thinning intensity) was recorded for each tree. As a proxy for the amount of dead crown we visually estimated the volume of dead branches in relation to total branch volume (Widerberg et al. 2012). The dendrochronological sampling in all locations was a part of a larger project and the detailed protocol for the selection of trees for this dataset is available in Widerberg et al. (2012).

We mounted tree cores on wooden supports, polished and cross-dated them using the visual pointer year method (Stokes and Smiley 1968). Using scanned images of dated samples, we measured the ring widths to the nearest 0.01 mm with the CooRecorder & CDendro software package ver. 7.3 (Larsson 2010) and verified dating statistically with an R package *dplR* (Bunn 2008).

### Climatic data

Since the oak growth in southern Sweden has been shown to be strongly controlled by summer drought conditions (Drobyshev et al. 2008), we used site-specific chronologies of average summer Monthly Drought Code (MDC, Girardin and Wotton 2009) to evaluate changes in oak sensitivity to drought following the thinning. MDC is the monthly version of the Drought Code, a component of the Canadian Forest Fire Weather Index, which was originally developed to capture moisture content of deep layers of the forest floor (Turner 1972). The numerical value of MDC reflects a water holding capacity of 100 mm. To generate MDC, we obtained climate data (minimum and maximum monthly temperatures and total monthly precipitation) from the CRU 3.10 dataset (Harris et al. 2014). Monthly minimum and maximum temperatures and the total of monthly precipitation, all available at 0.5° resolution, were extracted from CRU 3.10 for the grid cells encompassing our site locations. June MDC values were then calculated for each of these locations.

### Statistical analyses

Analyses were run independently for *Dataset1* and *Dataset2*. The rationale for this setup was threefold. First, we did not have data on pasture oaks in *Dataset2* and the age data from that location were largely missing since the majority of the trees were hollow. Second, by running two independent analyses we wanted to avoid a disproportionally large contribution of one of the sites to the results, due to the differences in sampling intensity at the site level. Third, we considered the proposed protocol as a way to verify the results by replicating them on an independent dataset.

**Table 1.** Properties of the sampled sites.

| Location | *n* | Coordinates | Oak Age | SD | Spruce Age | BA[a] | Thinning year |
|---|---|---|---|---|---|---|---|
| 1 Johannishus | 8 | 56.24 N 15.52 E | 149 / 95 | 40 / 2 | 43–45 | 18.4 | 1997 |
| 2 Strömsrum | 8 | 56.93 N 16.46 E | 194 / 234 | 19 / 12 | varying | 11.3 | None |
| 3 Hornsö | 8 | 57.02 N 16.23 E | 110 / 120 | 5 / 21 | 70 | 14.1 | 1999 |
| 4 Boxholm | 8 | 58.19 N 15.13 E | 150 / 127 | 12 / 33 | 53 | 10.2 | 1997 |
| 5 Sandvik | 8 | 58.12 N 15.17 E | 123 / 83 | 13 / 40 | 48 | 12.4 | 2002 |
| 6 Malexander | 8 | 58.07 N 15.36 E | 141 / 100 | 31 / 21 | 50 | 13.3 | 1999 |
| 7 Adelsnäs | 8 | 58.14 N 15.95 E | 146 / 76 | 13 / 47 | 47 | 17.3 | 2000 |
| 8 Tönnersjö | 7 | 56.70 N 13.14 E | 168 / 165 | 56 / 20 | varying | 11.1 | None |
| Asa | 34 | 57.13 N 14.75 E | 143 / - | 61 / - | 49 | 23.0 | 2008 |

Notes: Stand and tree data from the studied locations, *n* is number of oaks in the forest stand, *Age* is the mean age of the sampled oaks in each location (forest oaks/pasture oaks) determined through dendrochronological dating. BA stands for Basal Area measured in $m^2\ ha^{-1}$. The spruce data were obtained from the stands forestry plans. Site number refers to Figure 1.
[a]In $m^2\ ha^{-1}$.

To test hypothesis 1 (effect of thinning), we analysed pre- and post-thinning growth as a function of thinning treatment. For *Dataset1*, we ran a general mixed effect model, using oak type (in non-thinned patches, moderately thinned, heavily thinned, and oaks in the open), oak age, and amount of dead crown as fixed effects. Site ID (site location) was considered as the random effect. The dependent variable was growth resilience, i.e. the ratio between the mean growth during eight years prior to thinning and the eight years following it, resolved at the tree level (van der Maaten-Theunissen et al. 2015). The timeframe for the analyses (eight years) was selected as the maximum number of years between the thinning treatment and the year of sampling (2011), which was common among all sites. For the analyses of the *Dataset2*, we used the regular ANOVA model without the random effect variable and excluded tree age from the list of fixed effects.

To test hypothesis 2 (the effect of the state of oak trees on their growth) we benefited from the statistical setup used to test hypothesis 1. To test hypothesis 3 (oak sensitivity to drought) we (a) studied correlation between annual growth and June MDC chronologies along gradient of thinning intensities and (b) analysed oak growth response to the extremely dry year of 2006, when the amount of summer precipitation was between 20–50% of the long-term averages across the Southern Sweden (Persson 2015).

The MDC-growth correlations covered the period since the date of thinning, which varied among sites (Table 1) and were studied as a function of oak type, age and crown conditions, and thinning intensity in generalized linear mixed-effects models realized in the function *glmer* from R package *lmer4* (Bates et al. 2015). We normalized continuous independent variables, i.e. transformed them to variables with zero mean and the variance of one, prior to the analyses. The maximum log-likelihood (ML) was used to fit model parameters. In all analyses, we relied on the AIC score (Akaike 1974) to select the most parsimonious model from the initial pool of candidate models, including all 2-level interactive, non-interactive effects and null-model in R package *AICcmodavg* (Mazerolle 2017). We estimated marginal and conditional $R^2$ using R package *MuMIn* (Barton 2016).

## Results

The results did not support the first hypothesis: forest oaks revealed predominantly declining diameter growth rates following the thinning treatments. 61.1% trees in the Dataset1 and 61.5% of trees in the Dataset2 showed a decline (Figure 2(A,B)). Mixed effect models showed no effect of thinning treatments in any of the analyses for the *Dataset1* (Table 2, Figure 2(C,D)) and the AIC-driven selection of the most parsimonious model did not result in the inclusion of the *Oak Group* as one of the variables retained in the best model. A similar lack of significant effects of the *Oak Group* variable was observed for the *Dataset2*, where the most parsimonious model was the null model, indicating that the analysed factors had negligible predictive skill in respect to oak growth dynamics. The results did not support hypothesis 2 either, since no interactions between thinning treatments and oak

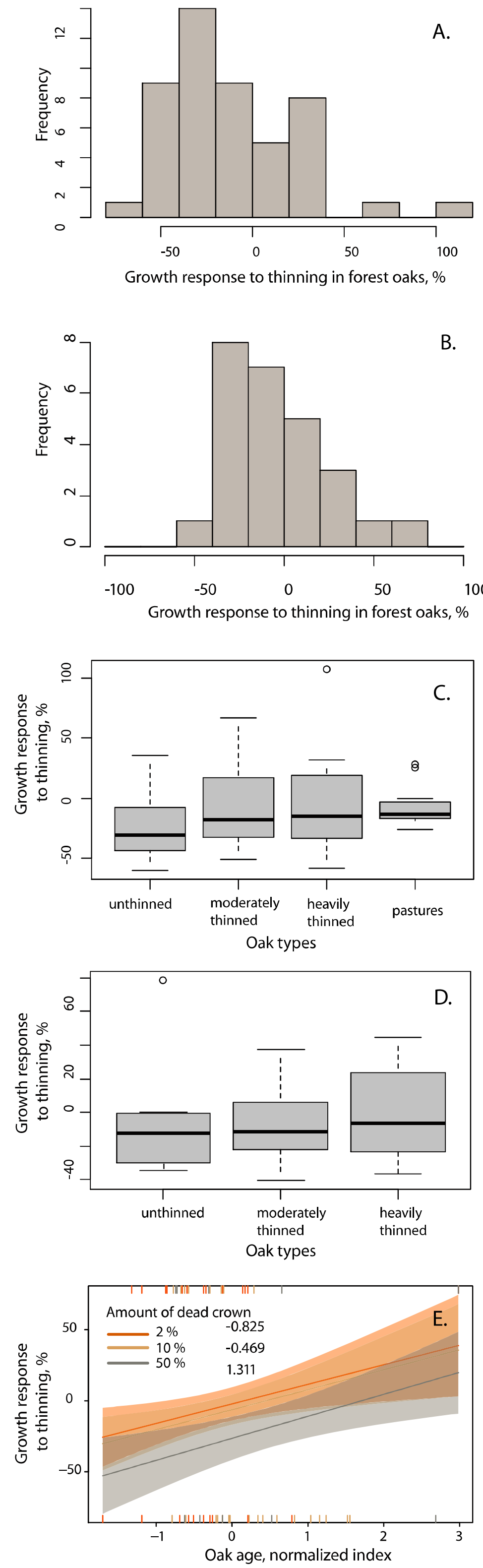


**Figure 2.** Growth responses of oaks following thinning. (A and B) Distribution of growth reactions of forest oaks, viewed as a proportion between growth prior and following the thinning treatment for the *Dataset1* (A) and *Dataset2* (B). (C and D) Lack of significant effect of thinning intensity on post-thinning growth of oaks in studied locations for *Dataset1* (C) and *Dataset2* (D). (E) Significant effects of the amount of dead crown and oak age, and non-significant effect of their interaction on the growth dynamics for the *Dataset1*. For illustrative purposes the distribution of dead crown amounts is represented by upper 0.90, 0.50, and lower 0.10 quantiles of its distribution (2%, 10%, and 50%, respectively). In figures C through E the vertical axis represents mean values for respective contrast levels. Unthinned trees are oaks which did not experience removal of neighbouring spruces and served therefore as a control.

**Table 2.** Statistical details of the ANOVA and mixed effect analyses.

| Variables | Estimate | SE | *t* value | *p* |
|---|---|---|---|---|
| *Growth resilience, see* Figure 2(C,D) | | | | |
| Intercept | −2.49 | 4.35 | −0.57 | 0. 570 |
| Oak Age | 19.80 | 5.02 | 3.95 | <0.001 |
| Dead Crown | −14.32 | 4.43 | −3.23 | 0.002 |
| Oak Age * Dead Crown | 0.811 | 2.73 | 0.30 | 0.767 |
| $n = 45$ / $R^2$ marginal 0.329, $R^2$ conditional 0.329 | | | | |
| *Reaction to summer MDC, see* Figure 3 | | | | |
| (Intercept) | 0.053 | 0.08 | 0.68 | 0.508 |
| Oaks, moderately thinned | −0.158 | 0.09 | −1.81 | 0.084 |
| Oaks, heavily thinned | 0.162 | 0.11 | 1.46 | 0.158 |
| Oaks, pastures | 0.255 | 0.11 | 2.17 | 0.040 |
| Oak Age | −0.144 | 0.07 | −2.18 | 0.051 |
| $n = 60$ / $R^2$ marginal 0.396, $R^2$ conditional 0.493 | | | | |
| *Reaction to drought year 2006* | | | | |
| Intercept | 1.02 | 0.03 | 33.78 | <0.001 |
| Oak Age | −0.05 | 0.03 | −1.80 | 0.078 |
| $n = 60$ / $R^2$ marginal 0.059, $R^2$ conditional 0.171 | | | | |

Notes: Dependent variable for each analyses are indicated on the top of each section of the table with italics. The marginal $R^2$ reflects model predictive skill associated with fixed effects, while the conditional $R^2$ reflects the skill associated with fixed and random effects together. MDC stands for Monthly Drought Code (see *Methods*). All analyses involved *Dataset1*.

tree properties significantly affected oak growth dynamics. However, the analysis of the *Dataset1* revealed significant effects of oak age and oak crown conditions on the growth. Specifically, growth was better in older trees with a lower amount of dead crown. Importantly, the interaction between these two factors was insignificant (Figure 2(E) and Table 2).

Our results did not appear to support hypothesis 3, since we found only a weak association between growth response to MDC dynamics, on one side, and oak habitat types, on the other. Specifically, oaks in pastures has a significantly more positive response to June MDC, compared to other habitat types (Table 2, *Dataset1*). The growth response of oaks also indicated that younger trees had a more positive response to warmer and dryer conditions, irrespective of the oak habitat type (*Dataset1*, Table 2, Figure 3). Specifically, older

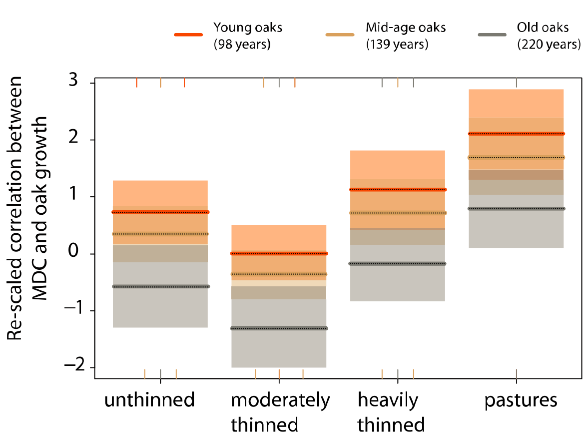


**Figure 3.** Growth sensitivity of oak to summer drought. Response of oaks to mean summer MDC across a network of studied sites (*Dataset1*), excluding Asa. Vertical axis represents mean correlation between MDC and oak diameter growth. For illustrative purposes the distribution of oak ages is represented by oaks in the upper 0.90, 0.50 and lower 0.10 quantiles of the distribution ("young", "mid-age age", and "old oaks", respectively). Unthinned trees are oaks which did not experience removal of neighbouring spruces and served therefore as a control.

trees in the forest exhibit generally negative correlations between growth and MDC, whereas the correlation remained generally positive for the younger trees, both inside and outside forest stands (Figure 3). During the drought-prone year 2006 younger trees tended to show a more positive and nearly significant ($p = 0.078$) growth response, as compared to older trees (*Dataset1*, Table 2). For the *Dataset2*, no significant effects were detected in the analysis of growth response to summer MDC nor to the drought year of 2006, the null-model exhibiting the lowest AIC value in both analyses (results not shown).

Tests for inter-correlation between the retained predictors revealed a positive correlation between *Oak Age* and the *Dead Crown* amount (r = 0.308, $p = 0.017$). This pattern, however, did not bias our results. This is because these variables, when both significant, entered into the most parsimonious model with different signs (Table 2, analysis of growth resilience). We also observed a strong positive correlation between *Oak Age* and the *Oak DBH* (0.465, $p < 0.001$) in *Dataset1*. This, however, did not appear to affect the ANOVA result, since in none of the analyses did both variables enter the most parsimonious model. The correlation between the amount of dead oak crown and DBH was not significant (0.218, $p = 0.095$).

## Discussion

Preservation of oaks retained in production Norway spruce stands is of immediate importance to maintain the biodiversity of different organism groups. Management programmes to ensure the survival of these trees are therefore urgently needed. The current study suggests, however, that the commonly adopted thinning intensities do not result in improved oak growth. In none of the datasets studied, did the thinning intensity show a significant impact on the growth dynamics, a result which did not support the first hypothesis. We propose three alternative explanations of the observed pattern. First, despite a positive effect of thinning on light conditions, the treatment might increase oak transpiration demand (though increase exposure of the tree crown to wind and solar radiation) and tree sensitivity to summer drought, therefore eliminating a positive effect of increased light availability. One-half of the studied trees were older than 139 years, which suggested increased tree maintenance costs and an associated higher sensitivity to drought. Second, the studied thinning treatments, even those done with increased intensity, might not be sufficient to generate a change in growing conditions required to provide a distinguishable signal in tree-ring chronologies. We speculate that apart from changes in light environments, underground interactions with the spruces, e.g. through the effects of tree-specific soil microbiota (e.g. De Bellis et al. 2007), may be of importance for oak trees and may still play a role in affecting tree growth in the thinned patches. Third, the tree-ring chronologies, while being a consistent proxy for overall tree vitality (Drobyshev et al. 2007a), may contain a time lag (Drobyshev et al. 2007b) which may still be present in the data stretching over 16 years. If a time lag was involved, a longer growth record would be required to correctly assess the effect of thinning treatments. We also realized that measuring diameter growth at breast height might not fully represent changes in biomass accumulation and vitality for these trees. Allocations effects, i.e. shifts in the relative distribution of assimilates between different "assimilate sinks" (e.g. fine roots, maintenance of photosynthesis machinery, production of defensive chemical compounds) might affect the predictive power of ring-width increment as a proxy of tree productivity (Andersen et al. 2000; Lopez et al. 2003).

Oak properties had an effect on growth dynamics but did not significantly interact with treatment levels. This result did not support the second hypothesis. Specifically, both older trees and trees with a low degree of crown dieback had significantly more positive growth response to thinning, as compared to younger trees and trees with larger proportion of dead crown. Earlier studies in Sweden have indicated that removal of spruce in mixed oak-spruce stands in Sweden has resulted in a positive effect on oak growth (Götmark 2007, 2009). A similar effect of removal of encroaching woody vegetation has been reported in the oak savannas of the mid-West US (Brudvig et al. 2011). At the same time, review of oak crown conditions has suggested that heavy thinning around oaks has a negative effect on oak vitality (Bergquist and Isacsson 2002). The above-mentioned Swedish studies, however, have relied on re-measurement of diameters, which make their results less precise as compared to data obtained with dendrochronological methods.

The observed effect of dead crown amount, likely indicative of lesser photosynthetic capacity of these trees, is consistent with the potentially important role of overall tree vitality in affecting its growth rates (Drobyshev et al. 2007a). A better performance of older trees might indicate their superior ability to acquire soil nutrients due to a more developed root system. We also noted that although the amount of dead crown and tree age are positively correlated, the contrasting effects of these variables on the growth (positive – in the case of oak age and negative – in the case of the amount of dead crown) were strong enough to override the potential effect of their correlation.

We did not observe a higher oak growth sensitivity to summer drought (hypothesis 3) in thinned patches during non-extreme nor extreme conditions. We speculate that the result might be affected by the short length of the analysed chronologies. The results instead suggested that younger trees responded more positively than older oaks. Together with the observations of a significantly better growth of older trees as revealed in non-climatic analyses (hypothesis 2), this result suggested that it was not drought conditions that compromised the growth of younger forest oaks and their low growth in the forest is likely related to other factors.

The independent analyses of two datasets proved useful in demonstrating the consistent lack of significant treatment effects (Figure 2(A–D)). However, other effects including trees' sensitivity to summer drought, could be best detected in the network data (*Dataset1*). A likely reason for this pattern was a wider range of conditions and tree properties, in particular oak ages and crown conditions covered by the network dataset.

### *Management implications*

The lack of sufficient empirical (experimental or observational) support hinders the development of optimal strategies for the preservation of oaks in the matrix of spruce production stands. The results of this study indicate that current management practices may be sub-optimal in balancing costs and effects associated with thinning treatments, since the heavy thinning of the spruces did not promote the growth of the oaks. However, despite several negative results presented here, our study provides insights into the ways to optimize such treatments. We propose that thinning is to be primarily applied to older and healthier-looking trees and thinning around old oaks should be of moderate intensity to avoid the potentially negative effect of summer drought on these trees. The age of an oak tree could be a difficult parameter to estimate from diameter data during field inventories (Drobyshev and Niklasson 2010). First, a dendrochronological estimate may not be always feasible to obtain, due to a larger investment of labour or a tree may be hollow. Managers should instead focus on much a less labour-intensive visual assessment of oak crown conditions, for which straightforward protocols are available (Sonesson and Anderson 2001). Prescribing thinning treatments of trees with healthier-looking crowns could be expected to maximize the growth and vitality responses. We conclude that detailed physiological measurements of oak post-thinning performance over a larger gradient of thinning intensities are warranted, in order to identify thresholds in thinning intensity for positive oak response and to optimize this silvicultural treatment.

## Acknowledgements

We would like to thank the forest managers: Magnus Roth at Johannishus Godsförvaltning AB, Rappe Family at Strömsrum, Peter Wallin at Boxholms Skogar AB, Tony Andreasson at Baroniet Adelswärd AB, Gisela Björse at Sveaskog. The field sampling in Asa has been done in cooperation with Asa Research Station, which is a part of the Swedish Infrastructure for Ecosystem Science (SITES) framework.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

ID thanks Stiftelse för skogsvetenskaplig forskning SLU and the The Swedish Institute (project CLIMECO, grant # 10066/2017) for support of this study. This research was also funded by Stiftelsen Skogssällskapet.

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