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Tree-level differences in Norway spruce and Scots pine growth after extreme thinning treatments

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ABSTRACT

We studied tree-level dynamics (stem slenderness and growth) in spruce- and pine-dominated stands after intermediate commercial thinning of different type (low, crown normal, and crown strict) and intensity (standard and extreme), for two 5-years growth periods. Thinning treatments were included in modeling as numerical variables based on how they changed the stand- and tree-level conditions (in terms of mean diameter of remaining trees and basal area of larger trees removed). Stem slenderness significantly decreased with time for both species and all types only in the extreme intensity (excluding low thinning for pine). Regarding basal area growth, for both species it was slightly higher in low than crown thinning, and much higher in extreme intensity for all thinning types. Pine had a lower basal area growth in the second period after thinning compared with the first one. Height growth differences were not found across treatments. Concluding, extreme thinning increased individual tree basal area growth and decreased stem slenderness for both species compared with thinning carried out according to the standard guidelines. Across types, there were only small differences, hence crown thinning seems a viable option to the widely used low thinning in Fennoscandia.

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intensive thinning; low thinning; crown thinning; Fennoscandia

Introduction

Thinning removes a portion of the standing trees, providing extra growing space for the remaining ones. Thinning activities can be carried out for many different reasons, not necessarily exclusive to each other, such as improving the quality of the remaining stems, removing unwanted species, diversifying the forest structure for ecological purposes, providing an economic return, and for increasing the vitality of the remaining trees.

In a "low thinning" (also called "thinning from below") the mean size of the removed trees is lower than the mean size of the remaining one, as trees removed are mainly suppressed and co-dominants, while the contrary in a "crown thinning" (also called "thinning from above"), as trees are removed primarily from the upper canopy (Eriksson 2006; Kerr and Haufe 2011). Low thinning has been the prevailing type in Fennoscandia (Wallentin 2007). However, in the Finnish silvicultural guidelines, crown thinning has been recently introduced to be a suitable intervention for well-managed Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* (L.) Karst) stands in intermediate thinnings (i.e. after the first commercial thinning and before final felling) (Rantala 2011).

Thinnings may also have harmful effects on stand development and vitality. Very heavy thinnings may considerably reduce total stemwood yield during rotation (Mäkinen and Isomäki 2004a; Eriksson 2006; Del Río et al. 2017). Biotic and abiotic damage risks can also increase during the first years after thinning (Jactel et al. 2009). Trees may be more exposed to wind and snow damage before they have adapted to wider spacing by strengthening their crown, stem and root system (e.g. Del Río et al. 2017). Thus, in practice, heavy thinnings are not recommended in the Finnish silvicultural guidelines although they are allowed (Rantala 2011; Äijälä et al. 2019). Heavy thinnings could be selected by forest managers, amongst other possible reasons, when they want to increase the cutting revenues especially in the short term or to transform an even-aged stand to continuous cover forestry management. For example, economic optimization in forest growth simulations suggested that for both species the last thinning should be heavier than officially recommended (Hyytiäinen and Tahvonen 2002).

Thinning studies traditionally compared different treatments either considering responses at stand or at tree level. For the latter, they usually addressed parameters such as stem form, crown length, and diameter and/or height growth. Mäkinen and Isomäki (2004b, 2004c), in thinning experiments with three different intensities, found that for both spruce and pine heavy thinning resulted in a clearly faster tree-level diameter increment, but the difference between light and moderate thinning was smaller. The basal area removed in each intensity class was not specifically provided, but heavily thinned plots were considered having on average 60% basal area of the control (unthinned) plots. Similar findings were observed also in pine, where higher tree growth was observed in heavier thinning (up to the removal of 60% of original basal area) (Mehtätalo et al.

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2014). Nilsson et al. (2010) also addressed heavy thinning (removing 60–70% of original basal area) for both pine and spruce stands, noting a tendency towards larger diameters in the remaining trees after cutting compared with lighter thinnings. They also compared low thinning and crown thinning, finding no significant difference in the stand-level production. Similarly, Mäkinen et al. (2006) did not find differences across treatments comparing tree-level diameter growth in an experiment including low and systematic thinnings (in the latter trees were removed only according to their location), with a maximum 33% of basal area removed. Related to stem form parameters, slenderness (calculated as the height/diameter ratio) was found lower after heavy than moderate or light thinning both for pine and spruce Mäkinen and Isomäki (2004b, 2004c). Other authors found slenderness lower in less dense stands in spruce plantations (aged less than 50 years), although not many treatments were compared (Brüchert et al. 2000; Slodicak and Novak 2006).

We could retrieve only few studies with high-intensity thinnings, or when they were included it was so with only few replicates. This was especially true for crown thinning. This is due to the changes in practical forest operations. Those thinnings that were classified decades ago as heavy thinnings refers to our current common practices of moderate thinnings, and it was reflected in the experimental design. Thus, there is an urgent need for empirical results of the effects of extremely heavy thinnings with different tree selection methods.

To cover this gap, we carried out a study involving experimental stands subjected to different thinning types (i. low thinning, crown thinning with ii. normal and iii. strict strategy) and intensities (i. moderate, according to the guidelines, and ii. heavy, extremely stronger than the guidelines recommendations), for a total of six different treatments. Our hypothesis was that the various treatments would have significantly different effects on the tree-level parameters after thinning (namely, crown stem slenderness and basal-area growth). We considered the moderate thinning as the business-as-usual practice against which the extreme thinning was compared under different types of intervention.

Methodology

Study sites

The study material consisted of a thinning trial comprising six stands established during years 2005–2008 by Finnish Forest Research Institute (Metla) in Southern and Middle Finland, currently maintained by Natural Resources Institute Finland (Luke). Three stands were dominated by pine and three by spruce. For each species, the stands were chosen as similar as possible in terms of age, structure, growth potential and past management: this was the reason for the relatively small number of sites. At the experiment establishment, the stands were at the stage of second and third commercial thinning, respectively, for pine and spruce. Pine stands had on average age 42 ± 6 years and dominant height (calculated as the average height of the thickest 100 trees per hectare) of 17 ± 2 m, while spruce stands 59 ± 2 years and dominant height 20 ± 2 m. All pine stands and one spruce stand were classified as *Myrtillus* forest site type or fresh heath, while two spruce stands were growing on higher fertility *Oxalis-Myrtillus* forest site type or grove-like heath (Cajander 1949; Tonteri et al. 1990). The stands were almost pure: in pine-dominated stands, after thinning on average only 2% of the total basal area was represented by other species, while it was 10% in the spruce-dominated ones. They were located between 61.2–62.9 north and 24.3–25.6 east (decimal degrees in WGS84), and the temperature sum (the sum of degree-days above 5°C) was quite similar in all stands, ranging from 1192 to 1256, according to the mean for the years 1980–2010.

Treatments

Rectangular plots were established in each stand. Plot size varied from 1000 to 1200 m^2. Each plot was surrounded by a 5–10 m wide buffer zone, which was treated similarly as within the plot. We tested a total of six thinning treatments, in a matrix of three thinning types (i. low thinning, crown thinning with ii. normal and iii. strict strategy) × two thinning intensities (i. moderate, and ii. heavy). Each treatment was applied in one or two plots in each stand according to a randomized block design. The absence of untreated control plots was due to both the difficulty to find extra-large stands for the study and to the rationale of considering the moderate intensity as the baseline for the comparison.

For the thinning types, in the low thinning and crown thinning with normal strategy (or “crown/normal”), small suppressed trees, unsound and damaged trees (crooked, forked, etc.), were first removed. Thereafter, in low thinning, suppressed and co-dominant trees were removed. In crown thinning, mostly dominant trees were removed, but aiming to maintain regular spatial distribution of the trees throughout the plots. In crown thinning with strict strategy (or “crown/strict”), only dominant trees were removed. Small suppressed trees were let to grow and regularity of spatial distribution of remaining trees was not emphasized as much as in other thinning types. However, large openings (i.e. removing groups of several trees) were avoided. Unless otherwise specified, “crown thinning” refers to both the normal and the strict type. Two levels of thinning intensity were studied: moderate thinning intensity based on prevailing thinning guidelines applied in Finland, which usually applies around 35% of removals (Rantala 2011), and heavy thinning corresponding to 50% lower remaining stand basal area than in the plots of moderate thinning intensity. The experiment was carried out after the first commercial thinning in pine stands and after the second commercial thinning in spruce stands, so that the heavy thinning had the objective of an early high monetary income before the final cut. In Table 1, plot-level values pre- and post-thinning are shown.

Data collection

At the establishment of the experiments, plots were measured and treatments were carried out. A second measurement was carried out after five- or six-year period and a third one 10 years after the establishment. Tree species, diameter at breast height (1.3 m from ground) in two rectangular directions and any damage were recorded for each tree on the plot. During the tally, every nth tree was selected as a sample tree aiming that in each plot around 34 samples were selected before thinning treatments. On average, 22 trees were left growing in every plot after thinning. The size distribution of the sample tree well represented the full population (results not shown). Sample trees were measured for tree height. In Table 1, tree-level values are shown.

Data analysis

We estimated the height of trees using Näslund's height curve (Näslund 1936) fitted for each plot with the help of the sample trees measurements, using Luke's KPL software (Heinonen 1994). We then carried out all data analyses with R Statistical Software (R Core Team 2021). We investigated only pine and spruce trees growing in the stands dominated by the same species, to exclude possible confounding effects due inter-species dynamics which were not the aim of the present study. However, we included all trees when calculating stand-level variables.

We defined slenderness as the ratio between height (in dm) and diameter (in cm). We investigated the differences between the six treatments and the two periods, considering only the live sample trees of the dominant tree species. We used a Tukey's HSD (honestly significant difference) test with the package *agricolae* (de Mendiburu 2020) separately for each species.

We considered basal area growth as the difference between two consecutive measurements and scaled to 5 years (cm^2 year^{-5}), only for live trees of the dominant tree species. We use a descriptive modeling approach to understand what factors were involved in the response after thinning. For competition we tested as symmetric index the total basal area of all trees in the plot (*batot*, m^2 ha^{-1}), and for asymmetric index the basal area sum of trees larger than the subject tree across the whole plot (*bal*, m^2 ha^{-1}). As an indicator of stand development, we tested the stand dominant height (*hdom*, m), calculated as the mean height of the 100 largest trees per hectare in terms of diameter. Explicit thinning variables were the ratio between the mean diameter (basal-area weighted) after and before the intervention (dm_{thin}) (calculated at plot level), the basal area sum of trees larger than the subject tree and removed during thinning (bal_{thin}, m^2 ha^{-1}); and *heavy*, a dummy variable indicating heavy thinning treatments. A variance inflation factor analysis (VIF) showed the absence of auto-correlation between these predictors. We then fitted species-specific non-linear mixed models with the package *nlme* (Pinheiro et al. 2020) according to the following form, modified from (Stadelmann et al. 2019):

$$[1]\,\Delta ba = \exp\left(X + u_p + u_{p.t}\right) + \varepsilon_{a.p.t.m}$$

$$\begin{aligned}[2]X = {} & b_0 + b_1{*}(1 - \exp(b_2{*}d^{b_3})) + b_4{*}\ln(batot) \\ & + b_5{*}\frac{bal}{\sqrt{d+1}} + b_6{*}hdom + b_{7a}{*}dm_{thin}{*}m_1 \\ & + b_{7b}{*}dm_{thin}{*}m_2 + b_{8a}{*}bal_{thin}{*}m_1 + b_{8b}{*}bal_{thin}{*}m_2 \\ & + b9{*}heavy\end{aligned}$$

where *Δba* was the individual tree basal-area growth; b_i coefficients to be estimated during model fitting for each of the explanatory variables (previously described); m_1 and m_2 dummy variables with the value of 1, respectively, for the first and second growth period after thinning; u_p and $u_{p.t}$ random nested effects, respectively, for each plot to account for the spatial correlation of trees in the same areas (preliminary analysis showed a random effect at stand level to not be significant), and for each tree to account for the longitudinal experimental design structure (i.e. the repeated measurements on the same trees); and $\varepsilon_{a.p.t.m}$ the error for each measurement. We used a power variance function to account for heteroscedasticity (Pinheiro and Bates 2006) according to the following form:

$$[3]\,var(e_i) = \sigma^2 \exp(u_i^{2\alpha})$$

where u_i is the fitted growth value from the fixed effects of the models and α is estimated during model fitting. The final structure of the models was selected according to

Table 1. Description of study material. Values are given as mean and standard deviation. Pre- and post-thinning consider the plot-level values immediately before and after the thinning. Growth measurement was assessed for all tallied trees. Sampled trees were measured also for the height of the crown base and total height.

Type	Intensity	Plots	Basal-area total (m^2 ha^{-1})		Mean diameter (cm), basal-area weighted		Tallied trees	Sampled trees	Basal-area growth, tree level (cm^2 year^{-5})	
			Pre-thinning	*Post-thinning*	*Pre-thinning*	*Post-thinning*			*First period*	*Second period*
Pine-dominated stands										
Low	Moderate	3	26.5 ± 4.9	18.1 ± 1.4	17.5 ± 1.9	18.7 ± 2.4	238	103	74.2 ± 30.0	45.9 ± 19.0
Low	Heavy	3	26.5 ± 3.6	8.7 ± 0.6	18.0 ± 1.9	20.4 ± 2.7	95	84	123.4 ± 40.0	85.4 ± 31.1
Crown/n	Moderate	4	27.3 ± 2.0	18.2 ± 1.4	17.3 ± 1.6	16.9 ± 1.9	410	130	55.4 ± 30.1	33.9 ± 20.7
Crown/n	Heavy	4	23.9 ± 2.7	8.7 ± 0.5	17.6 ± 1.2	16.5 ± 2.5	195	120	75.3 ± 31.5	57.2 ± 26.6
Crown/s	Moderate	6	25.4 ± 2.5	17.9 ± 1.3	17.1 ± 1.6	16.1 ± 1.7	618	206	46.2 ± 27.1	33.5 ± 21.2
Crown/s	Heavy	5	26.0 ± 3.9	8.6 ± 0.7	18.0 ± 3.4	15.7 ± 3.0	261	159	77.8 ± 33.6	61.8 ± 26.4
Spruce-dominated stands										
Low	Moderate	5	26.3 ± 3.3	20 ± 2.1	20.3 ± 2.9	21.4 ± 3.6	308	119	50.9 ± 22.4	56.1 ± 26.1
Low	Heavy	6	26.0 ± 2.4	10.0 ± 1.6	20.8 ± 3.1	23.3 ± 3.6	137	111	93.9 ± 36.9	136 ± 56.3
Crown/n	Moderate	4	27.4 ± 3.8	20.0 ± 2.4	20.8 ± 2.3	20.3 ± 3.0	287	100	45.8 ± 24.1	58.7 ± 30.6
Crown/n	Heavy	3	25.6 ± 4.0	9.3 ± 0.6	21.3 ± 4.0	18.8 ± 4.6	139	68	70.3 ± 34.6	101.6 ± 49.8
Crown/s	moderate	6	28.1 ± 2.7	19.7 ± 2.7	22 ± 2.7	21.1 ± 3.2	387	149	47.9 ± 24.7	59.7 ± 35.3
Crown/s	heavy	6	27.6 ± 4.5	10.3 ± 1.7	20.8 ± 3.4	18.3 ± 4.3	298	140	47.9 ± 28.4	74.3 ± 44.6

reduced Akaike Information Criteria (AIC), parsimony of predictors, residual distribution and biological validity. The transformation of *batot* and *bal* shown in the formula was found to reduce AIC compared with the base terms. Both temperature sum and dummy variables related to the vegetation type (MT or OMT) did not fulfill the criteria to enter the model, suggesting low differences in growth potential across sites.

After selecting the model, to observe the cumulative effect of all predictors, we simulated growth as a function only of diameter, which we let to vary from the minimum to the maximum observed in every treatment and period. We kept all other selected variables at the mean observed for every treatment and period. In the case of *bal* and bal_{thin} (as they were selected, see later in results), they changed not only with treatments but also with diameter, so we simulated those changes with simple species-specific linear models based on diameter classes and fitted for each treatment and period. For both species and thinning types, the diameter-growth relationship was clearly higher in the heavy thinning, with a difference that increased with tree size more in spruce than in pine (see Figure 5).

We considered height growth (*hgr*) as the difference between two consecutive height measurements and scaled to 5 years (m year^{-5}), only for sampled live trees of the dominant tree species. We tried to fit models for height growth similarly as for basal-area growth. Preliminary results showed that they were very difficult to converge with a meaningful form. We decided to use simple linear mixed models using the same variables and random effects as above.

Results

Description of thinning treatments

After low thinning the average level of the ratio between post- and pre-thinning mean diameter basal-area weighted (dm_{thin}) was above one, as expected since many small trees were removed resulting in a higher post-mean diameter (Figure 1). The opposite was true after the crown thinnings. The difference was stronger in the heavy thinnings. In pine-dominated stands, the crown/strict type had a slightly lower ratio than the crown/normal type, while in spruce stands no clear difference was found.

Regarding the basal area of larger trees removed for each target tree (bal_{thin}), for trees of the same social position (tree diameter divided the plot mean diameter basal area weighted), it was on average lower in the low thinning: the differences were stronger in the mid-sized trees compared with very small and very big trees, and in the heavy thinning compared with the moderate thinnings (Figure 2). Hence, there was a similar pattern in the symmetric competition

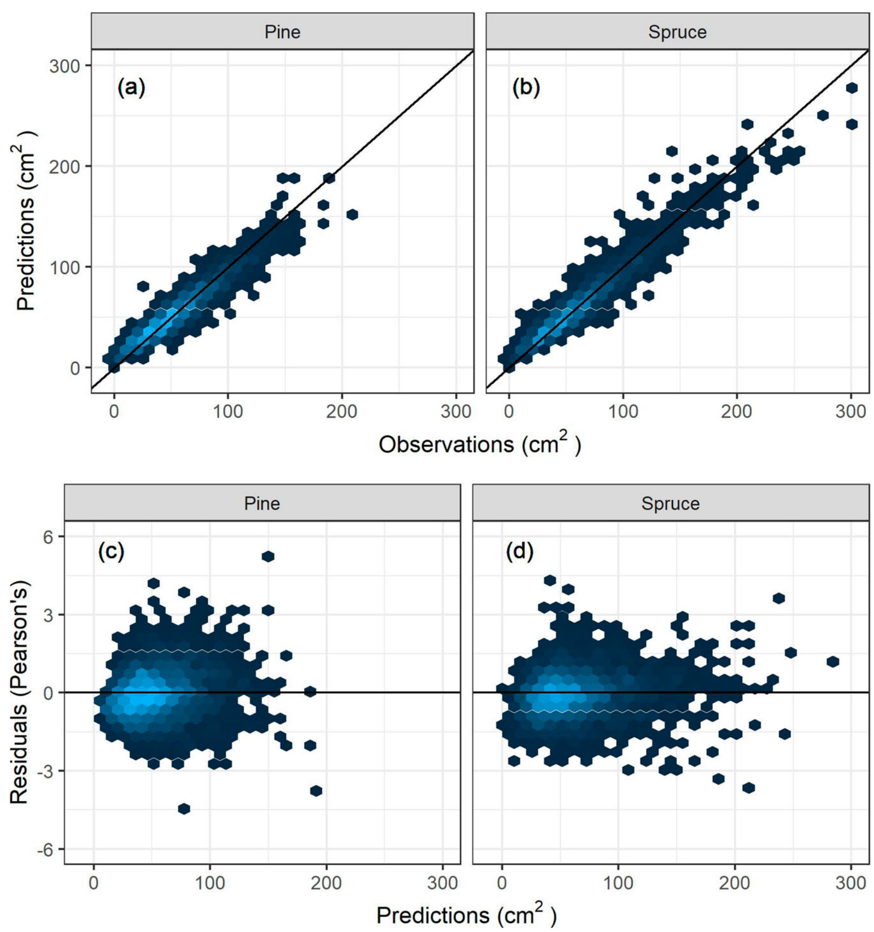

Figure 5. Results of the non-linear mixed models for individual basal-area growth. Plots a & b, predictions versus observations. Plots c & d, standardized residuals versus predictions. Brighter colors indicate higher density of points. The black line is the identity line.

bal: for trees of the same social position, it was higher in the low thinning and in the heavy intensity (data not shown).

After intervention, there were large windthrown events due to storms in two spruce stands, one immediately after and one in the following year. All treatments were affected, with a loss of volume ranging around 3–34 m^3 ha^{-1}. No significant differences were found across treatments. Following those events, natural mortality ranged for pine between 0 and 1.3 m^3 ha^{-1} and for spruce 0.1–2.0 m^3 ha^{-1}. Within species, no significant differences were found across treatments and growing periods, but for a slightly higher mortality in the crown/systematic thinning for pine in the first period only (results not shown).

Thinning effects on slenderness

Only in the heavy thinning, trees of both species started reducing their slenderness (lower *hdr*) immediately 5 years after the intervention (Figure 3), in all types but the low thinning for pine. Eventually, slenderness became statistically significantly lower in heavy than in moderate thinning of the same type for both species. The only exception was for spruce with crown/strict thinning, where the stands after heavy thinning had on average more slender trees than for the moderate. Comparing thinning types, *hdr* was lower in low thinning than in the crown thinnings (all cases but for spruce with moderate intensity).

Growth analysis

The selected non-linear mixed models for individual basal-area growth (cm^2 $year^{-5}$) used for the most part continuous variables to indicate the effect of the thinning types (see Table 2). The positive sign of dm_{thin} indicated higher growth for trees left in low thinning stands compared with crown thinnings. On the contrary, the positive sign of bal_{thin} indicated higher growth for the trees in the stands crown thinned, especially for the mid-size classes. The models revealed similar species-specific responses to the thinning regarding the timing. The aforementioned coefficients were in both species higher in the second growth period, indicating an increasing delayed response. The other co-variates behaved as expected. There was a strong and positive non-linear relationship between growth and diameter for both species. The competition indices (*batot*, *bal*) and stand development (*hdom*) all expressed reduced growth potential for the trees, having negative coefficients. Species-specific differences showed that spruce was affected only by symmetric competition while pine also by asymmetric competition. The negative effect of both competition indices indicated higher growth in heavy thinning, where those variables were lower. However, only for pine, the negative effect of the dummy variable *heavy* was needed to counterbalance that positive effect to values more fitting the data.

To observe the cumulative effect of all predictors and investigate better the differences across treatments, we used the results of the sensitivity analysis (Figure 4). For both species, the higher growth in the heavy thinning was evident. Regarding differences across types, they were present only for pine, where growth was slightly higher in low thinning than in crown thinning, albeit only in the first period with heavy intensity. Regarding the timing, for pine growth was slightly lower in the second period in all cases, while for spruce it stayed at the same level. In all cases, the model predictions well fitted the observed data points.

The fitted values were strongly correlated to the observations (Figure 5, plot a and b), and scatterplots of residuals versus the fitted values did not show heteroscedasticity (Figure 5, plot c and d).

For height growth, the models we could fit explained a very small part of the variance and were not worth being presented extensively here. To summarize, we found that for

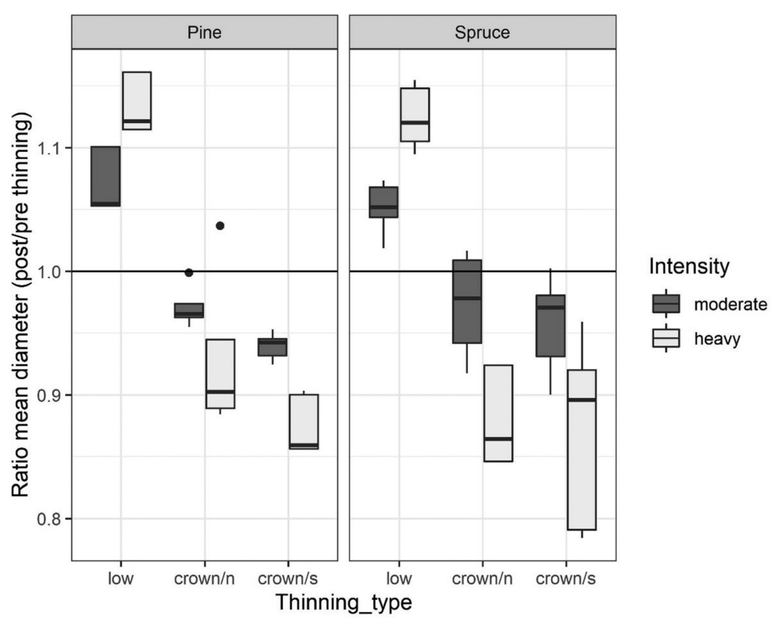

Figure 1. Average values of the ratio between the mean diameter (basal-area weighted) after and before the thinning, for both species-dominated stands and each thinning treatment.

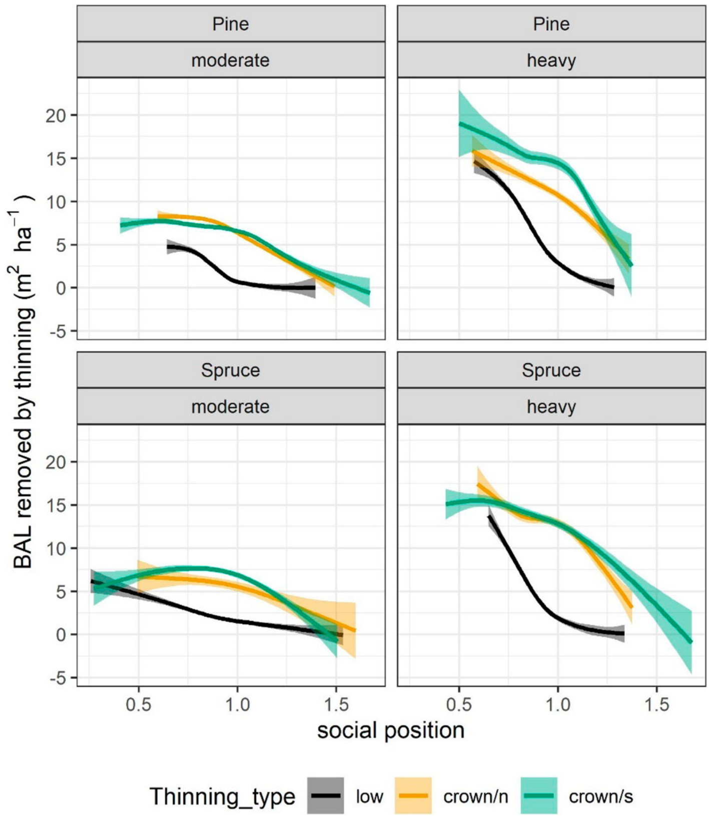

Figure 2. Average basal area of trees larger than the target tree (BAL) removed during thinning as function of the social position pre-thinning (considered as diameter divided the mean diameter basal-area weighted) of the target tree, for all treatments and species. The lines are interpolation of the values for all trees in the database with generalized additive models and enveloped by 0.95 confidence interval.

both species, trees of the same size grew significantly higher in the second period after thinning (positive effect of *m*2, $p < 0.05$), and with a higher release of asymmetrical competition (positive effect of bal_{thin}, $p < 0.05$). However, both effects were negligible and no significant differences were found across treatments (either thinning type or intensity).

Discussion

This study provides experimental data on thinning of extreme intensity, aiming at covering such a lack in literature for Fennoscandia. We considered moderate thinnings, carried out according to existing guidelines in Finland, as the reference scenario (i.e. control) against which to compare the less frequently reported extreme thinning.We observed some differences across treatments for tree slenderness. After the intervention, more slender trees were left in crown thinnings than in low thinning as a result of the methodology applied. Then, slenderness decreased with time only in the heavy thinning for most types, i.e. trees grew relatively more in diameter than in height in line with previous studies (Mäkinen and Isomäki 2004b, 2004c), generally ending up less slender than in the corresponding moderate thinning. For spruce in young stands repeatedly thinned (first around 50% of stems removed, then two for 25% stems removed every 5 years), Slodicak and Novak (2006) reported that the slenderness remained more or less stable. Only if more thinnings were carried out later, slenderness decreased. Dušek et al. (2021) reported similar mean slenderness values for spruce stands thinned with different timing but all ending up with around the same number of trees. Generally, slenderness values higher than 100 imply low stability of stands, although some studies set the critical value as low to 90 (Slodicak and Novak 2006). However, Wallentin and Nilsson (2014) show that stand stability is more complicated than a simple value. They studied three treatments, namely, unthinned (standing stock 30–35 m^2 ha^{-1}), low thinning with moderate and heavy (respectively, with ~25 and 12–15 m^2 ha^{-1}) intensity. After the area was hit by a storm and heavy snow 3 growing periods after the thinning, there was a clear negative relationship between damage and standing basal area, even if the remaining trees in the heavily thinned plots had already decreased their slenderness from around 96 to around 88. Given the similarity of slenderness and standing stock values of the low thinning with heavy intensity in our study, and the even higher slenderness values in the crown thinning, we must assume a similar high risk of storm and snow damage at least straight after thinning. Regarding pine stands, they are usually found much less likely to be damaged by a storm than spruce stands both in Finland and Sweden (Valinger and Fridman 2011; Suvanto et al. 2016; Gardiner 2021). For both species, the probability of damage generally increases straight after a thinning before trees are acclimatized (Gardiner 2021), while in the long term, the risk is higher in unthinned stands (Cremer et al. 1982; Cameron 2002; Suvanto et al. 2016). These trends are sometimes contradicted by different studies, since very different thinning regimes may be used (Schütz et al. 2006).

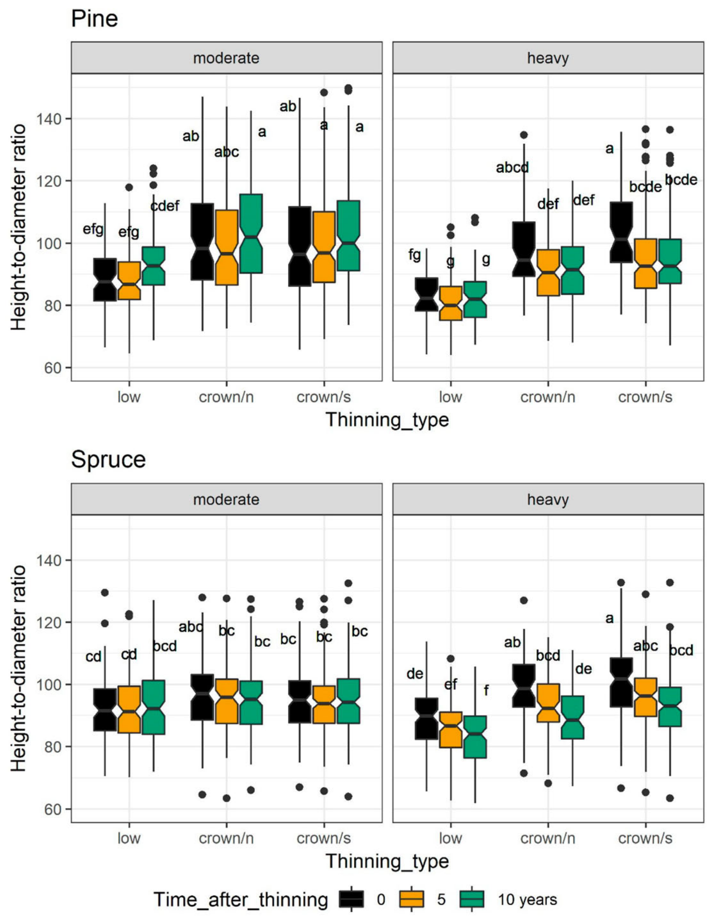

Figure 3. Summary of slenderness for sample trees across species, thinning treatments and periods after thinning (0: measurement at the time of the thinning, then 5 years and 10 years later). The letters correspond to the groups of a Tukey "honestly significant difference" test.

The analysis of the tree basal-area growth with a non-linear explanatory model approach showed that it is possible to include the effect of different thinning types using numerical variables both at stand and tree level. Only for pine a dummy variable indicating the heavier treatments was still needed to better fit the model. The tree-level diameter-growth relationship for both species increased from moderate to heavy intensity in all thinning types, as expected from the increase of resources availability (e.g. Nilsson et al. 2010; Mehtätalo et al. 2014). The overall effects of all variables showed almost no differences between thinning types in the diameter-growth relationship, similar to Mäkinen et al. (2006).

Table 2. Details for the non-linear mixed models of individual trees basal-area growth (cm^2 $years^{-5}$). For each fixed effect parameter, it is listed to which predictor is linked: d, diameter (cm); batot, stand total basal area (m^2 ha^{-1}); bal, sum of the basal area of trees larger than the target tree (m^2 ha^{-1}); hdom, dominant height (m); dm_{thin}, ratio post/pre mean diameter (basal-area weighted); bal_{thin}, sum of the basal area of trees larger than the target tree removed during the thinning (m^2 ha^{-1}); m_1 and m_2, dummy variables, respectively, for the first and second 5-year period; heavy, dummy variable for heavy thinning treatments. Please refer to the methodology section for the model formula.

		Pine			Spruce		
Fixed effects							
Predictor	Parameter	Value	Std. error	*p* Value	Value	Std. error	*p* Value
d	b1	8.6497	0.7598	<.0001	8.1613	0.4255	<.0001
d	b2	−0.3654	0.0683	<.0001	−0.1972	0.0195	<.0001
d	b3	0.7869	0.088	<.0001	0.6388	0.0455	<.0001
batot	b4	−1.2260	0.0954	<.0001	−0.5921	0.0589	<.0001
bal	b5	−0.1345	0.0134	<.0001	NA	NA	NA
hdom	b6	−0.1587	0.0152	<.0001	−0.0459	0.0102	<.0001
dm_{thin}, m_1	b7a	2.1788	0.6416	0.0007	0.5719	0.2426	0.0185
dm_{thin}, m_2	b7b	2.5823	0.6474	0.0001	0.7747	0.247	0.0017
bal_{thin}, m_1	b8a	NA	NA	NA	0.0137	0.0044	0.0019
bal_{thin}, m_2	b8b	0.0147	0.0013	<.0001	0.0249	0.0043	<.0001
heavy	b9	−0.6203	0.1251	<.0001	NA	NA	NA
Random effects		std. Dev			std. Dev		
Plot	u_p	0.2670			0.0845		
Tree in plot	$u_{p.t}$	0.1881			0.2250		
RMSE		9.8467			10.7029		

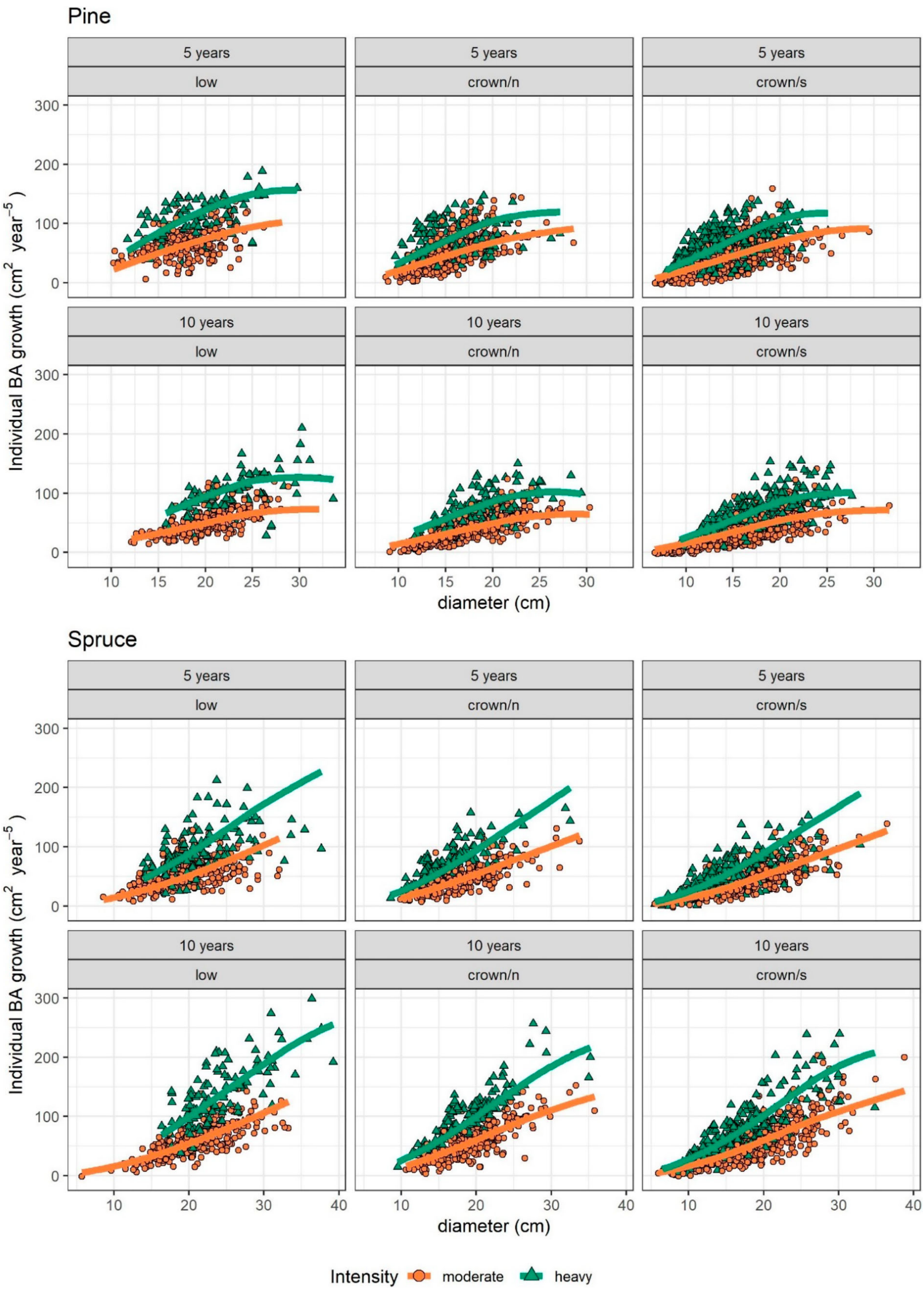

Figure 4. Sensitivity analysis of the models for individual basal-area growth as a function of diameter (diameter-growth relationship): points represent observed values, lines represent simulated values from fitted models.

Only in pine-dominated stands with heavy thinning, growth was lower in crown thinnings than low thinning in the first 5-year period. Likely the pine trees left after intensive crown thinnings were more suppressed and needed more time to adjust to the new environment. In the second period, individual pine diameter-growth relationship slightly decreased compared with the first one: likely the thinning boost was already counteracted by the increase of competition. Contrarily for spruce, the end result of all factors was to have a similar diameter-growth relationship for all treatments and periods.

We found only negligible effects of thinning on height growth for both species, in line with the available literature (Mäkinen et al. 2006). Hynynen (1995) did not find height growth affected by thinning for pine in moderate and heavy thinning (respectively, less and more than 50% of original basal area removed), similar to Valinger and Fridman (2011) (where thinning intensity was 40%). In Mäkinen and Isomäki (2004d) dominant height increment decreased only slightly with increasing thinning intensity. Contrarily for spruce, in Mäkinen and Isomäki (2004a) dominant height increment was not affected by thinning. Mäkinen et al. (2006) in systematic thinning found only a negligible effect of thinning on height growth for both species.

Conclusions

Our study provides useful insights in tree-level dynamics in pine- and spruce-dominated stands after thinning of different intensity: moderate, according to current silvicultural prescriptions, and heavy, much higher than those prescriptions. Especially we included two types of crown thinning that are not often shown in literature with heavy intensity. Overall, we observed few and small tree-level differences across different thinning types. Low thinning is a well-known and safe option in Fennoscandia, and crown thinning seems a viable option regarding tree-level dynamics, albeit growth was slightly lower for trees of the same size. More significantly, there were differences across thinning intensities in stem slenderness and basal-area growth: the former was lower and the latter higher in heavily thinned stands of both species and all thinning types. In forest management, one of the main reasons for thinnings is to improve the diameter growth of growing stock and thus increase the timber yield production. Our results showed that heavy thinnings had a significant and positive effect on the basal-area growth of single trees, possibly also shortening rotation time. However, even with the less slender trees resulting with the heavy intensity, storm and snow damage can still pose a huge risk. Considering the timing of the response, spruce was maintaining a growth boost for a longer time than pine. This analysis at the tree level will have to be complemented with an in-depth analysis of the stand-level variables, including an economic assessment, before providing detailed silvicultural suggestions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Äijälä O, Koistinen A, Sved J, Vanhatalo K, Väisänen P. 2019. Metsänhoidon suositukset [best practices for forest management]. Helsinki: Tapion julkaisuja.

Brüchert F, Becker G, Speck T. 2000. The mechanics of Norway spruce [Picea abies (L.) Karst]: mechanical properties of standing trees from different thinning regimes. For Ecol Manag. 135:45–62.

Cajander AK. 1949. Forest types and their significance. Helsinki: Suomalaisen Kirjallisuuden Seuran Kirjapainon Oy.

Cameron AD. 2002. Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. Forestry. 75:25–35.

Cremer KW, Borough CJ, McKINNELL FH. 1982. Effects on stocking and thinning on wind damage in plantations. N Z J For Sci. 12:624–668.

Del Río M, Bravo-Oviedo A, Pretzsch H, Löf M, Ruiz-Peinado R. 2017. A review of thinning effects on Scots pine stands: from growth and yield to new challenges under global change. Forest Syst. 26:eR03S.

de Mendiburu F. 2020. Agricolae: statistical procedures for agricultural research. https://CRAN.R-project.org/package=agricolae

Dušek D, Novák J, Kacálek D, Slodičák M. 2021. Norway spruce production and static stability in IUFRO thinning experiments in the Czech republic. J For Sci. 67:185–194.

Eriksson E. 2006. Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. Biomass Bioenergy. 30:848–854.

Gardiner B. 2021. Wind damage to forests and trees: a review with an emphasis on planted and managed forests. J For Res. 26:248–266.

Heinonen J. 1994. KPL–a computer programme package for computing stand and single tree characteristics from sample measurements. Finnish Forest Research Institute Research Papers 504, 80.

Hynynen J. 1995. Predicting the growth response to thinning for Scots pine stands using individual-tree growth models. Silva Fenn. 29:225–246.

Hyytiäinen K, Tahvonen O. 2002. Economics of forest thinnings and rotation periods for Finnish conifer cultures. null. 17:274–288.

Jactel H, Nicoll BC, Branco M, Gonzalez-Olabarria JR, Grodzki W, Långström B, Moreira F, Netherer S, Orazio C, Piou D, et al. 2009. The influences of forest stand management on biotic and abiotic risks of damage. Ann For Sci. 66:701–701.

Kerr G, Haufe J. 2011. Thinning practice – a silvicultural guide. Forestry Commission, UK.

Mäkinen H, Isomäki A. 2004a. Thinning intensity and growth of Norway spruce stands in Finland. Forestry. 77:349–364.

Mäkinen H, Isomäki A. 2004b. Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. For Ecol Manag. 201:295–309.

Mäkinen H, Isomäki A. 2004c. Thinning intensity and long-term changes in increment and stem form of Scots pine trees. For Ecol Manag. 203:21–34.

Mäkinen H, Isomäki A. 2004d. Thinning intensity and growth of Scots pine stands in Finland. For Ecol Manag. 201:311–325.

Mäkinen H, Isomäki A, Hongisto T. 2006. Effect of half-systematic and systematic thinning on the increment of Scots pine and Norway spruce in Finland. For: Int J For Res. 79:103–121.

Mehtätalo L, Peltola H, Kilpeläinen A, Ikonen V-P. 2014. The response of basal area growth of Scots pine to thinning: a longitudinal analysis of tree-specific series using a Nonlinear mixed-effects model. For Sci. 60:636–644.

Näslund M. 1936. Skogsforsoksasstaltens gallringsforsokitallskong. Meddelanden fran Statens Skogsforsoksanstal. 29:1–169.

Nilsson U, Agestam E, Ekö PM, Elfving B, Fahlvik N, Johansson U, Karlsson K, Lundmark T, Wallentin C. 2010. Thinning of Scots pine and Norway spruce monocultures in Sweden effects of different thinning programmes on standlevel gross- and net stem volume production. Fakulteten för skogsvetenskap, SLU, Umeå.

Pinheiro J, Bates D. 2006. Mixed-effects models in S and S-PLUS. New York: Springer Science & Business Media.

Pinheiro J, Bates D, DebRoy S, Sarkar D, Core Team R. 2020. nlme: linear and nonlinear mixed effects models. https://CRAN.R-project.org/package=nlme

Rantala S. 2011. Finnish forestry: practice and management. Metsäkustannus Oy.

R Core Team. 2021. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Schütz J-P, Götz M, Schmid W, Mandallaz D. 2006. Vulnerability of spruce (Picea abies) and beech (fagus sylvatica) forest stands to storms and consequences for silviculture. Eur J Forest Res. 125:291–302.

Slodicak M, Novak J. 2006. Silvicultural measures to increase the mechanical stability of pure secondary Norway spruce stands before conversion. For Ecol Manag. 224:252–257.

Stadelmann G, Temperli C, Rohner B, Didion M, Herold A, Rösler E, Thürig E. 2019. Presenting MASSIMO: a management scenario simulation model to project growth, harvests and carbon dynamics of Swiss forests. Forests. 10:94.

Suvanto S, Henttonen HM, Nöjd P, Mäkinen H. 2016. Forest susceptibility to storm damage is affected by similar factors regardless of storm type: comparison of thunder storms and autumn extra-tropical cyclones in Finland. For Ecol Manag. 381:17–28.

Tonteri T, Hotanen J-P, Kuusipalo J. 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio. 87:85–98.

Valinger E, Fridman J. 2011. Factors affecting the probability of windthrow at stand level as a result of gudrun winter storm in southern Sweden. For Ecol Manag. 262:398–403.

Wallentin C. 2007. Thinning of Norway spruce, Acta Universitatis agriculturae Sueciae. Southern Swedish Forest Research Centre, SLU.

Wallentin C, Nilsson U. 2014. Storm and snow damage in a Norway spruce thinning experiment in southern Sweden. Forestry. 87:229–238.