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Exploring the interplay between within-stand variation and thinning practices in southern Sweden

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ABSTRACT

The state of within-stand variation (WSV) in boreal, coniferous production forests and how it is dealt with in thinning operations is a scarcely researched topic. In the autumn of 2018, we surveyed a series of Norway spruce (*Picea abies* (L.) Karst) or Scots pine (*Pinus sylvestris* L.) dominated production stands scheduled for first commercial thinning from below. Here, we evaluate the potential causes of WSV in basal area, how WSV was addressed in the thinning operations, and finally how the stands and subsequent thinning practice conformed with the basal area target specified in the thinning guidelines. WSV in the yield attributes was defined as the dispersion in a stand attribute within a stand and quantified using the Q_n scale estimator (a robust measure of dispersion). First, WSV in basal area at the time of first thinning was evaluated as a function of WSV in stem number and WSV in site index. Next, yield attributes before and after thinning were compared using paired *t*-tests, and the future development of WSV in basal area was evaluated using linear mixed-effects models. Finally, the thinning practice was evaluated before and after thinning by modelling the compliance with the basal area target as a function of stem number and dominant height, also using linear mixed-effects models. WSV in basal area appeared to be influenced by WSV in site index and WSV in stem number for Norway spruce, but not for Scots pine. Thinning reduced the WSV in basal area, standing volume, and stem number, while dominant height, quadratic mean diameter and basal area weighted mean height remained unaffected. At first thinning, compliance with the thinning guideline increased with increasing stem density and dominant height. However, moderate to high compliance with the basal area target in the thinning guidelines was only reached for plots with elevated dominant height (>15 m) in combination with high stem number (>2250 N ha^{-1}). Thus, the recommended range in dominant height (12–14 m) for first thinning was generally exceeded, which may be attributed to the generally low stem number at the time of thinning. This study suggests that sub-optimal regeneration efforts and management of young forests can lead to WSV across a wide range of stand attributes, and likely also reductions in yield. Thinning decreased WSV in basal area, standing volume and stem number, however, the plots were heavily thinned to such a degree that it could potentially cause production losses.

1. Introduction

Silviculture has historically revolved around the stand concept, where the central idea is that there is greater variation in stand attributes between stands than within stands. This motivates site-specific silvicultural regimes for individual stands, including the definition of specific treatments (pre-commercial thinning, commercial thinning and final felling etc.) at different times. By relying on the stand concept, it is also assumed that the implementation of a predefined forest management objective into silviculture, such as thinning intensity (proportion of removed basal area), is practically feasible and desirable across the whole stand. Conceptually, increasing within-stand variation (WSV), defined as the dispersion in a stand attribute within a given stand, challenges the stand concept as the difference between stands diminishes (O'Hara and Nagel, 2013).

In southern Sweden, reforestation is normally carried out by planting 1800 – 2500 seedlings ha^{-1} of the target tree species, mainly Norway spruce (*Picea abies* (L.) Karst) or Scots pine (*Pinus sylvestris*), preceded by soil scarification and pre-commercial thinning to homogenise the site and improve the growing conditions (Nilsson et al., 2010). The main

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factors causing mortality during the establishment phase include pine weevil (*Hylobius abietis*) attack (Wallertz et al., 2018), browsing (Bergqvist et al., 2003; Bergström & Bergqvist, 2008), environmental stresses (Nilsson et al., 2010), and/or competition induced by the lack of pre-commercial thinning. The intensity of reforestation treatments (soil preparation and planting) typically increases forest production and reduces reliance on natural regeneration, which in turn reduces uncertainty in forest management (Jonsson et al., 2022). Overall, reductions in stand density – as a result of mortality – may prevent optimal use of the site productivity, resulting in lower-than-expected yields, unless compensated by natural regeneration.

In practical forestry, considerable WSV in seedling survival (seedlings ha^{-1}) is common in homogeneously regenerated Norway spruce sites in southern Sweden, attributed to poor micro-site planting, spot selection and variable soil moisture conditions (Holmström et al., 2019). Thus, abiotic and biotic factors cause mortality followed by sizeable WSV in basal area growth (m^2 ha^{-1} y^{-1}) early in the rotation. Little is known about how slight within-site variation in growing conditions and stem number (N ha^{-1}) after the establishment affect WSV in general. Of particular interest is whether WSV in stem number and inherent WSV in site productivity increase WSV in standing volume (m^3 ha^{-1}), and how thinning affects WSV in basal area (m^2 ha^{-1}) after thinning and its development. This motivates an investigation of how WSV affects stand production and how it is managed in thinning operations today.

Stand density management diagrams are commonly used in the management of planted forests to support decision-making regarding pre-commercial thinning and commercial thinning. Usually, stand density is represented by mean tree size (tree volume or quadratic mean diameter) and stem number (Newton, 2021). In Sweden, these translate into thinning guidelines which include curvi-linear trajectories representing an appropriate basal area at a given dominant height (m) when thinning can be conducted (hereafter called upper target). The thinning guidelines also include trajectories illustrating a minimum recommended basal area after thinning (hereafter called lower target) which is consistently above the line determining the lowest allowable volume after a thinning (§10, the Swedish forest act). The trajectories are adapted to different species, site fertility and climatic regions (Fig. 1). The thinning guidelines assume that a certain minimum stand density can be reached in normal production forests for each site index within the interval recommended for first thinning (12–14 m in dominant height). Deviation from the upper target in the thinning guideline at first thinning should reflect the regeneration survival densities, density

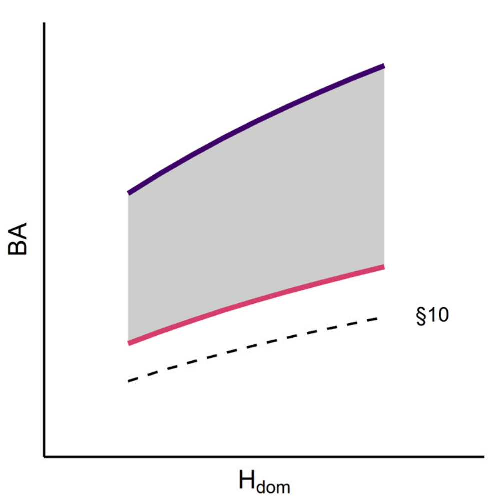

Fig. 1. Thinning guideline with basal area (BA) on the y-axis and dominant height (H_{dom}) on the x-axis, along with an upper target line (deep purple) and a lower target line (crimson red) representing the range in basal area. The dashed line represents the minimum allowable basal area (translated from standing volume) after thinning (§10, Swedish forest act).

management in young stands and the ability of the remaining trees to account for the available resources. Of particular interest is to evaluate if damaged stands or plots, reach the upper basal area target later, i.e. at a greater dominant height, and to identify the consequences for thinning.

Thinning from below reduces the dispersion in tree size in plots and stands as small trees are harvested. Besides the forced, minimum harvest of strip roads across the stands, thinning can additionally influence each of the stand attributes by varying the thinning intensity and/or the thinning form across the stand to homogenise it further, but the extent to which this is actually done in practice is unknown.

In this study, we explore how stand attributes and thinning practice affect WSV using planted conifer stands (Norway spruce, Scots pine) at first commercial thinning in southern Sweden as an example: Firstly, we examine whether WSV in standing volume correlated with attributes of stand productivity and regeneration survival densities and young stand tending (using site index from height and stem number as indicators). Secondly, we investigate whether thinning influenced the WSV in all stand attributes and how WSV in basal area was projected to develop after harvest to examine the long-term effects of the thinning practice. We hypothesise that:

1. WSV in stem number and dominant height is positively related with WSV in basal area at thinning.
2. Thinning decreases the WSV in all targeted stand attributes: dominant height, mean height (Lorey's mean height, m), mean diameter (quadratic mean diameter, cm), standing volume, stem number and basal area.

Finally, we evaluate thinning practice compliance by mapping the relative compliance with the established thinning guidelines before and after thinning. Again, stem number before thinning indicates regeneration success and young stand tending.

2. Material and methods

2.1. The survey

The data originate from a field survey, established in planted conifer-dominated stand in southern Sweden in 2018 (Fig. 2), using a random selection of stands from the government-owned forest company Sveaskog (Persson et al., 2022). The stands represent normal production stands at the time of first thinning and were planned to be thinned at the time of the inventory. In total, there were 20 stands of which 10 were dominated by Scots pine and the other 10 by Norway spruce. In each stand, ten plots were arranged in a rectangular grid. The plots were circular with a 10 m radius and at the time of inventory and tree measurements were recorded. One of the Scots pine stands proved to be a mixed forest after the inventory was finished and was removed from the analysis.

The stands were thinned from below in the fall of 2018 and spring of 2019 by different forest workers, and the field inventory was carried out shortly after the thinning operations were finished. Two plots were randomly assigned not to be thinned in 13 of the 19 stands. The thinning operations were carried out by harvester and forwarder teams (named forest workers onwards) contracted by Sveaskog. The harvester and forwarder created strip roads that were 3.5 m in width. The thinning treatments were not controlled for in any way, and the location of the eight plots remained unknown to the driver of the harvester. The procedure of procuring the stands, the sampling method and initial measurements is further described in detail in Persson et al. (2022). In summary, all trees in the plots were calipered at breast height (DBH, diameter at 1.3 m height), sample trees were randomly drawn from a diameter distribution according to the methodology outlined in Karlsson et al. (2012). The height of the sample trees (H) was measured using a Haglöfs Vertex Laser Geo.

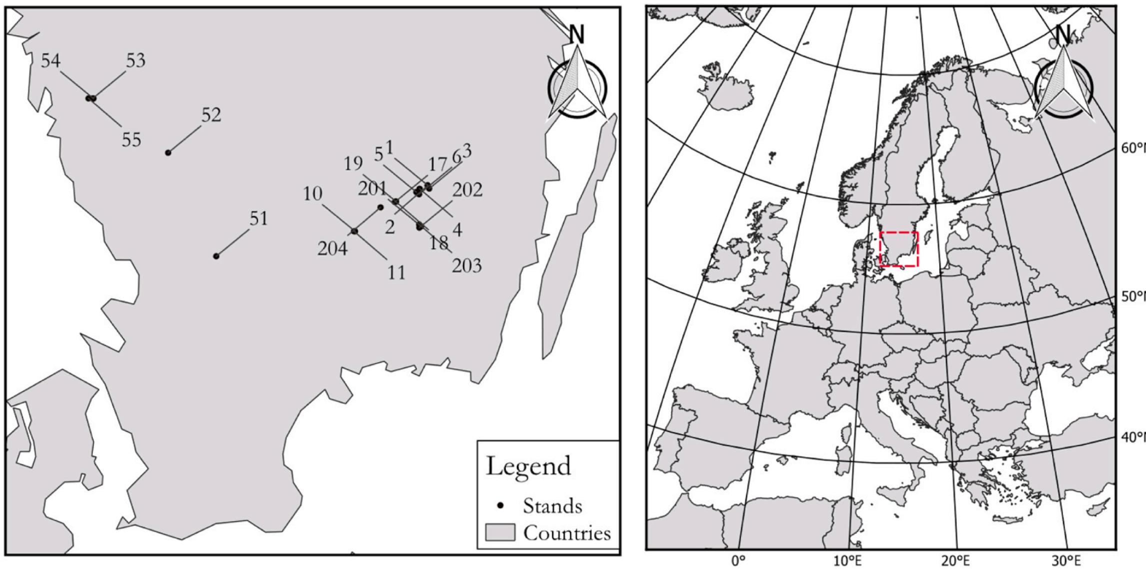

Fig. 2. The geographic location of the 20 stands within the study area (left), location in a European context (right). © EuroGeographics for the administrative boundaries.

2.1.1. Calculations

First, height-diameter models were created based on sample-tree measurements. Tree height was modelled as a function of diameter at breast height (DBH, 1.3 m above the ground, cm) using non-linear mixed effects regression (Näslund, 1936). Separate models were fitted for each stand, and species group: Scots pine, Norway spruce and broadleaves.

$$H = \frac{DBH^p}{(a + b * DBH)^p} + 1.3$$

where $p = 2$ for Norway spruce and $p = 3$ for Scots pine and broadleaves. The parameters a and b were fitted as random factors for each stand ID.

The harvested trees were recreated by modelling DBH as a function of stump diameter and tree species (Persson et al., 2022). Later, height was estimated on each tree (remaining/calipered tree or harvested) using the height-diameter models described above. Tree volume (V, m^3) was estimated on the sample trees using species-specific volume functions from Brandel (1990). Tree volume was predicted for each tree (remaining/calipered tree or harvested) through a simple linear regression model utilising the linear relationships between the natural logarithm of stem volume and the natural logarithm of DBH of the sample trees.

Dominant height was calculated as the mean height of the two dominant trees in each plot. Basal area weighted mean height (hereafter denoted mean height, m) was expressed using Lorey's mean height. Quadratic mean diameter (hereafter called mean diameter, cm) was also calculated. Standing volume, basal area and stem number calculated by summarising tree volume, tree basal area and number of trees in each plot, respectively, and dividing by the plot area (0.0314 ha). The listed plot attributes describing yield and standing stock were calculated before and after thinning by including and excluding the harvested trees in the calculation. Site index (SIH) based on height development curves (H100) at a predetermined age (e.g., 100 years) was calculated at the plot level (Hägglund, 1973, 1974). Note, from here onwards, the standard deviation is provided within parentheses after the value for each stand attributes when appropriate.

The thinning quotient is defined as the relative size of the harvested mean diameter to the retained mean diameter. Thinning intensity (BA_{int}) was calculated at the stand level and defined as the proportion of harvested basal area (BA_{harv}) to the basal area of the stand before thinning (BA_{bt}) given as a percentage.

$$BA_{int} = \frac{BA_{harv}}{BA_{bt}} \times 100$$

In this study we describe and measure WSV at the stand level using the Q_n scale estimator for the previously listed yield attributes. The Q_n scale estimator is a scale insensitive, robust measure of dispersion, meaning that it can efficiently estimate scale regardless of the underlying distribution of the data. Q_n has a high Gaussian efficiency (82%) meaning that fewer observations are needed for an efficient estimate compared to other scale estimators, such as the standard deviation and Median Absolute Deviation, also it has a breakdown point of 50%, which means it can resist up to half of the data being outliers (Rousseeuw and Croux, 1993).

$$Q_n = C_n \bullet \{|x_i - x_j|; i < j\}_{(k)}$$

where C_n is a constant, $\{|x_i - x_j|; i < j\}$ is the set of pairwise absolute differences of the observation points x_i and x_j and k is the index of the order statistic. The R package *robustbase* was used to calculate the Q_n (Maechler et al., 2023). See Appendix 1 for a full description.

The stand simulator Heureka StandWise was used to project basal area at the plot level (Wikström et al., 2011). StandWise contains functions for growth, mortality, bucking and silvicultural response based on National Forest Inventory-data (hereafter called NFI-data) and field experiments (Elfving, 2010). Tree lists containing the remaining trees after thinning were imported into StandWise and each plot represented a treatment unit, and the growth was forecasted 20 years into the future. The Q_n scale estimator in basal area, representing WSV, was calculated at each time step (0, 10 and 20 years).

Compliance with the upper and lower target in the thinning templates was expressed as the relative difference (%) in basal area compared to the basal area demanded. The relative difference to the upper and lower basal area target was calculated for each plot. The latest version of the thinning guideline, developed by the Swedish Forest Research Institute (Skogforsk), was used. The trajectories differ slightly from the first guideline published in 1984 by the Swedish Forest Agency (Skogsstyrelsen, 1984).

2.1.2. Thinning procedure

At the time of thinning for the Scots pine stands, the average basal area was 26 (2.8) m^2 ha^{-1} and the mean height was 13.6 (0.9) m.

Similarly, for the Norway spruce stands the average basal area was 27.6 (4.2) m^2 ha^{-1} and the mean height was 13.4 (1.1) m. For Scots pine the average thinning intensity at the stand level was 34.1 (2.4)% and the average thinning quotient was 0.86 (0.08) and for Norway spruce the average thinning intensity at the stand level was 38 (3.9)% and the average thinning quotient was 0.94 (0.07). See Table 1 for a detailed stand summary.

Forest workers contracted by Sveaskog have access to near real-time estimates of stand attributes post-thinning, thinning intensity and thinning quotient through the software hprGallring (Möller et al., 2015; Möller et al., 2021). This is a standard tool implemented in Sveaskog's harvesters today, however, at the time of thinning in 2018 it was not thoroughly implemented.

2.2. Data analysis

During the data analysis a range of statistical models were built to evaluate each hypothesis and objective. All data analyses were carried out in R (R Core Team, 2023) using linear regression and linear mixed (-effects) models (LMM) (R package *nlme*; Pinheiro et al. (2013)). Model assumptions of variance homogeneity and normality were evaluated using graphical model validation tools, e.g. plots of the standardised residuals vs fitted values and against explanatory variables to assess the variance criterion as well as quantile–quantile plots to check deviations from normality. Throughout the analysis, the significance (p <.05) of the fixed terms was evaluated using a backwards-selection approach based on likelihood-ratio tests (L) using the R-command *drop1*, as suggested by Zuur et al. (2009). When needed, Pseudo-R^2 is provided as a goodness-of-fit for the LMM models (R package *piecewiseSEM)* based on the Nagelkerke-method.

WSV in basal area was modelled as a function of WSV in site index and WSV in stem number. Separate models were fitted for Scots pine (n = 9) and Norway spruce (n = 10). Age-dependent effects were accounted for by evaluating stand age as a continuous predictor. Variance heterogeneity was detected for Norway spruce and was modelled using the *varPower* variance structure (R package *nlme*) using the fitted values as a variance covariate. WSV in basal area was used instead of standing volume as there were no independent estimates of standing volume on each plot since the height-diameter functions were parameterised at the stand level. Each tree was calipered (except the harvested trees) and independent estimates of basal area could be calculated assuming independence.

Subsequently, one-sided paired t-tests (p <.05) were used to test if the variation within the stands was reduced (lower Q_n) after thinning for dominant height, mean height, QMD, standing volume, stem number, basal area. Tests were made for each attribute and separately for Scots pine (n = 9) and Norway spruce (n = 10). Histograms and Shapiro-tests were used to check the model assumptions of normality in the difference metric of each attribute. The area-dependent attributes expressed in per hectare units (standing volume, stem number, basal area) were most likely influenced by the strip roads (SR). The original plot estimate (Plot) was compared with an adjusted estimate (SR adjusted) of the WSV in standing volume, basal area and stem number which removed the strip road effect. The strip road-adjusted attribute was calculated by adding the product of the strip road proportion and the plot attribute value of standing volume, basal area and stem number to the original plot value, respectively. Accordingly, the Q_n-value was calculated on stand level for both attributes. The same test was used as above: a two-sided paired t-tests (p <.05) hypothesising there was no difference.

The Q_n in basal area was modelled as a function of time of assessment (before thinning, after thinning, 10 years after thinning and 20 years after thinning) and dominant tree species (Scots pine or Norway spruce) using LMM (n = 76, 19 stands and 4 times of assessment). Stand identity was used as a random factor to account for the repeated measures at each time of assessment. Variance heterogeneity was detected and modelled using the *varPower* variance structure (R package *nlme*) using the fitted values as a variance covariate. Multiple comparisons were used to evaluate contrasts for factors and their factor levels (R package *multcomp*; Hothorn et al. (2008); R package *emmeans*; Lenth et al. (2022)). The resulting p-values were multiplicity-adjusted using the false discovery rate approach (Benjamini and Hochberg, 1995).

Compliance with the thinning guidelines at (before) thinning was expressed using the relative difference in basal area of a plot compared to the upper basal area target in the thinning guideline. The compliance was modelled as a function of dominant height and stem number using LMMs. Stand identity was used as a random factor to account for the nesting of plots with stands. Separate models were fitted for Scots pine (n = 90, 9 stands) and Norway spruce (n = 100, 10 stands). A similar approach was used to evaluate the compliance with the lower target in the thinning guidelines, however, the compliance was modelled as a function of dominant height and stem number after thinning. Again, separate models were fitted for Scots pine (n = 78, 9 stands) and Norway spruce (n = 90, 10 stands) and this time without the non-thinned plots. No variance heterogeneity or gross deviations from normality were found in the residual plots for either model.

Table 1
Summary of the stand attributes. SP = Scots pine, NS = Norway spruce.

Stand	Species	Stand age (y)	SI (m)	BA (m^2 ha^{-1})	Stem number (N ha^{-1})	QMD (cm)	Mean height (m)	Dominant height (m)	Volume (m ha^{-1})
1	SP*	32	28 ± 0.3	29 ± 7	1615 ± 567	17 ± 1.9	15 ± 0.5	17 ± 0.3	198 ± 46
5	SP	28	28 ± 0.4	27 ± 4	1793 ± 315	16 ± 1.4	13 ± 0.5	15 ± 0.4	185 ± 28
6	SP	29	27 ± 0.5	22 ± 4	1522 ± 365	15 ± 1.2	13 ± 0.4	14 ± 0.4	145 ± 25
17	SP	26	27 ± 0.7	22 ± 4	1567 ± 304	15 ± 2.1	12 ± 0.6	13 ± 0.7	147 ± 35
18	SP	33	27 ± 0.5	23 ± 6	1589 ± 823	17 ± 2.5	14 ± 0.9	16 ± 0.4	159 ± 46
19	SP	33	27 ± 0.2	27 ± 4	1682 ± 285	17 ± 0.8	14 ± 0.3	16 ± 0.3	181 ± 25
201	SP	26	28 ± 0.5	27 ± 4	1790 ± 403	16 ± 1.5	13 ± 0.5	15 ± 0.4	183 ± 30
202	SP	31	28 ± 0.3	29 ± 5	1866 ± 242	16 ± 0.8	15 ± 0.3	17 ± 0.3	198 ± 38
203	SP	33	26 ± 0.3	27 ± 3	1860 ± 246	15 ± 1.2	13 ± 0.4	15 ± 0.3	178 ± 24
2	NS	23	34 ± 0.6	21 ± 4	1580 ± 233	15 ± 1.5	13 ± 0.6	15 ± 0.7	137 ± 28
3	NS	25	33 ± 0.6	26 ± 8	2217 ± 508	14 ± 1.7	12 ± 0.7	15 ± 0.7	164 ± 56
4	NS	23	35 ± 0.4	24 ± 2	1822 ± 221	14 ± 0.6	13 ± 0.3	16 ± 0.4	153 ± 17
11	NS	26	35 ± 0.9	27 ± 5	2051 ± 320	15 ± 1.2	14 ± 0.7	17 ± 1.1	177 ± 37
51	NS	28	33 ± 0.8	28 ± 4	1873 ± 462	16 ± 1.6	14 ± 0.7	16 ± 1	189 ± 28
52	NS	27	35 ± 0.8	36 ± 7	2099 ± 420	17 ± 1.7	15 ± 0.8	18 ± 1	251 ± 53
53	NS	23	34 ± 0.4	28 ± 6	1981 ± 228	15 ± 1	13 ± 0.4	14 ± 0.5	182 ± 46
54	NS	22	33 ± 0.7	25 ± 7	2347 ± 302	13 ± 1.2	12 ± 0.6	13 ± 0.8	152 ± 50
55	NS	31	33 ± 0.3	32 ± 4	1745 ± 158	17 ± 1.1	15 ± 0.4	18 ± 0.4	224 ± 35
204	NS	29	33 ± 1.2	28 ± 8	2003 ± 461	16 ± 2.2	14 ± 1	17 ± 1.5	188 ± 64

3. Results

3.1. Within-stand variation in production

WSV (Q_n) in basal area was evaluated as function of WSV in stem number and WSV in site index for Scots pine and Norway spruce individually. For Scots pine, WSV in site index was not a significant predictor, but WSV in stem number alone was almost significant ($p = .066$). For Norway spruce, Q_n in basal area was positively related to WSV in stem number ($p = .004^{**}$) and WSV in site index ($p = .006^{**}$; Fig. 3) with a Pseudo-R^2 of 41%.

3.2. Within-stand variation after thinning

We hypothesised that the thinning operations would decrease WSV for all studied stand attributes. The thinning operations did not decrease the WSV in dominant height, mean height or mean diameter. However, the thinning operations reduced WSV in standing volume, stem number, basal area for both Scots pine and Norway spruce (Fig. 4).

Adjusting for the strip roads only led to significant differences for WSV in standing volume (both species) and basal area for Norway spruce (Fig. 5).

The model estimating WSV basal area included time of assessment as a significant predictor ($L = 20.7$, $df = 2$, $p < .001^{***}$). The *post hoc* test showed that the WSV in basal area decreased after thinning. After 10 years WSV was not significantly different from directly after thinning, although for both species there appears to be a tendency for increased WSV. However, 20 years into the simulations the WSV significantly surpassed the levels directly after thinning (Fig. 6).

3.3. Thinning guideline compliance

At thinning, the basal area of most plots was below the upper target recommended in the thinning guideline regardless of tree species. Most plots were thinned well below the recommended basal area after thinning (Fig. 7). The compliance with the upper target in the official thinning guideline before thinning increased with stem number and dominant height for both Scots pine and Norway spruce (Fig. 7;

Table 2 Similarly, the compliance with the lower target after thinning in the thinning guideline was positively related to stem number and dominant height for both Scots pine and Norway spruce.

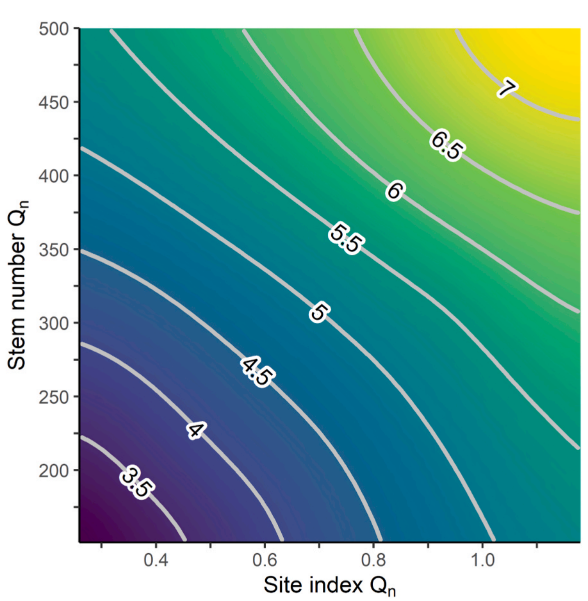

Fig. 3. Illustration of how the predicted Q_n in basal area (blue-yellow colour gradient) increases with Q_n in stem number (y-axis) and Q_n in site index (x-axis) for Norway spruce. Q_n is the robust scale estimator used to express WSV.

4. Discussion

We quantified WSV in planted Scots pine and Norway spruce forests in southern Sweden before and after the first commercial thinning to explore potential implications for thinning operations, especially with regard to officially recommended basal area targets.

4.1. Within-stand variation

4.1.1. Effects on stand production

We hypothesised that WSV in stem number and WSV in site index would be positively related with WSV in basal area before thinning. However, the presupposed effect of WSV in stem number and site index on WSV in basal area was only supported for Norway spruce and not Scots pine. WSV in site index within stands may cause differences in volume production as there is a strong correlation between height growth and volume production (Eichhorn, 1902). This is a likely explanation why WSV in site index was statistically significant for WSV in basal area for Norway spruce. WSV in stem number was also positively related to WSV in basal area for Norway spruce which may be explained by dispersion in basal area production within the stands due to variation in regeneration survival densities and insufficient young stand tending.

The non-significant results for Scots pine could be explained by the fact that the WSV in dominant height was rather low for most of the stands, which may be at least partly related to a greater environmental stress tolerance of Scots pine compared to Norway spruce (Zang et al., 2012). Thus, a larger sample size may have been required to detect trends and find statistically significant effects. Future research on this topic will therefore benefit from a larger sample size, covering a wider range of stand conditions from very homogenous to very heterogeneous. For the same reasons, it is difficult to generalise the results in the case of Norway spruce.

Managing Norway spruce stands that promote high WSV in site index (stands with large gradients in microclimate and site factors) and high WSV in stem number is likely to result in high WSV in terms of basal area yield at the time of first thinning. Consequently, the stand average may be an unreliable estimate for implementing the prescribed stand-level treatment, given that the WSV in site index and stem number is sufficiently high. This motivates adapting the silvicultural treatments to the specific sub-stand situation.

4.1.2. Precision Forestry aspects

Modern, open-source forest resource maps derived from remote sensing data sets can be used to visualise WSV for a wide range of forest attributes (Appiah Mensah et al., 2023; Kangas et al., 2018; Maltamo et al., 2021; Nilsson et al., 2017). Together with optimisation algorithms, operational and tactical decision-making is possible at the sub-stand level (Holmgren and Thuresson, 1997; Wilhelmsson et al., 2021), or even at the tree level (Fransson et al., 2019; Pukkala et al., 2015). As a result, these Precision Forestry methodologies can facilitate the implementation of forest management objectives to actively reduce or increase WSV in any relevant stand attribute.

The underlying assumption and rationale for Precision Forestry methodologies is that an increased level of spatial detail in forest management decision-making and implementation will add value, i.e. increase production, reduce harvesting costs, reduce residual damage or improve forest structures important for biodiversity, as compared to decision-making based on stand level averages. The positive outcomes of this theorem should improve with increasing WSV (or other measures of stand heterogeneity). As described in the previous section, the increasing WSV in stem number and site index was related to higher WSV in basal area and this motivates an adapted thinning practice. However, in terms of stand economy and volume production, there is no

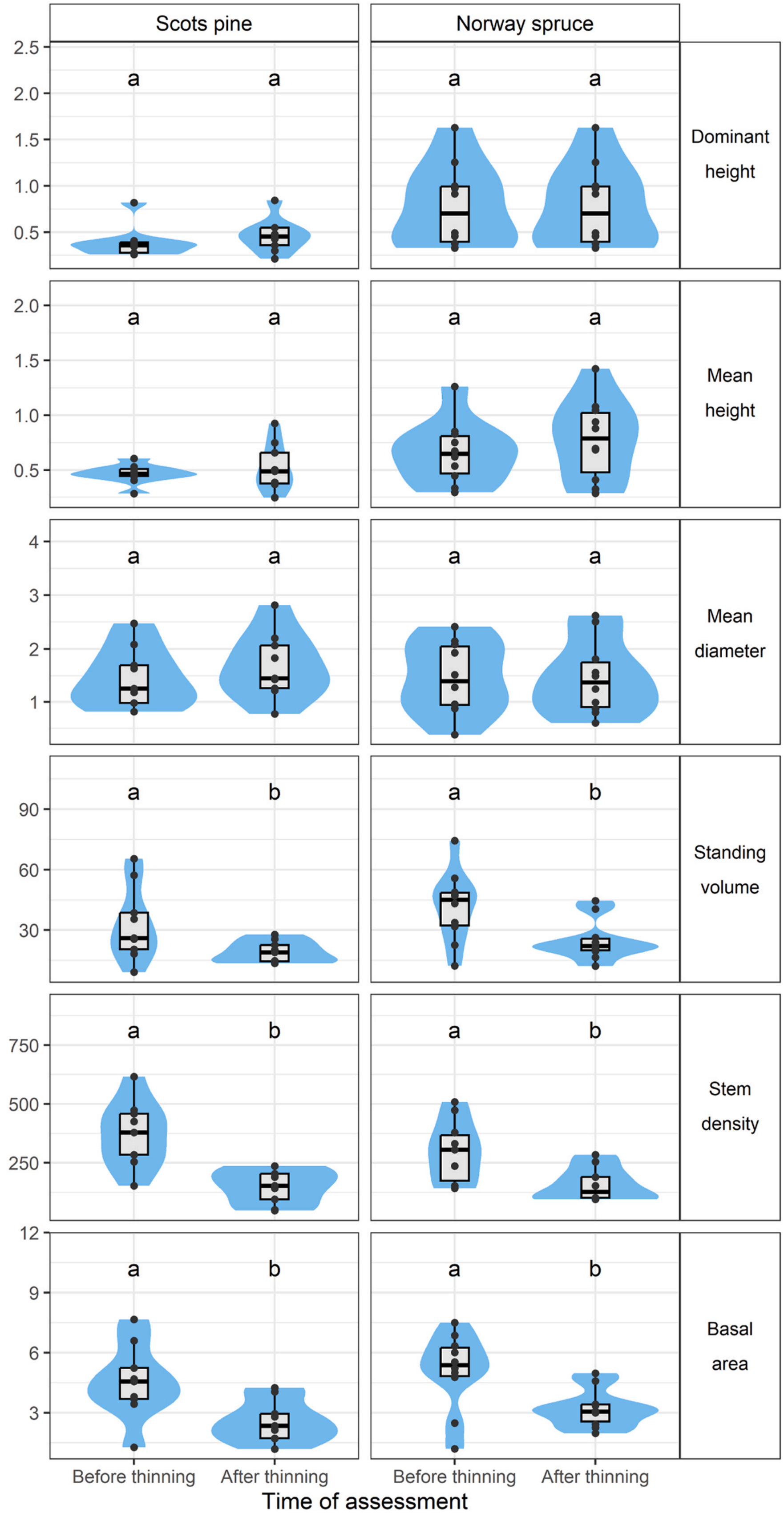

Fig. 4. Within-stand variation before and after thinning for Scots pine (left) and Norway spruce (right). Light blue violins indicate the frequency distribution of Q_n for each attribute. Different lower-case letters indicate statistically significant differences ($\alpha = 0.05$, paired t-test).

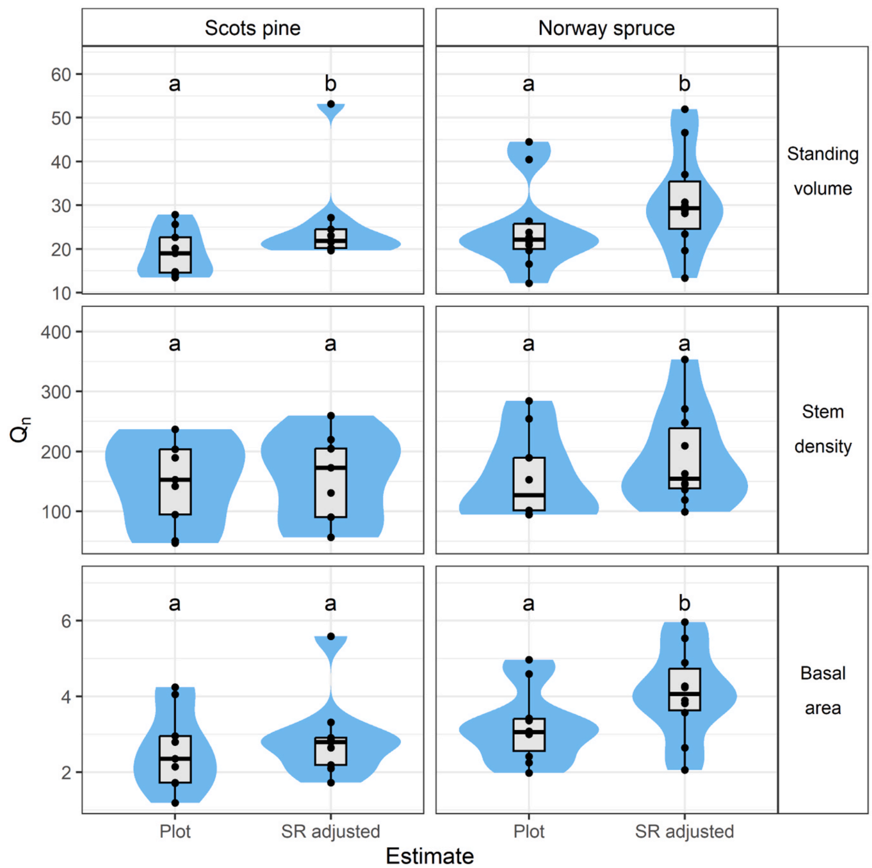

Fig. 5. Box-and-violin plots showing the original stand level estimates (Plot) and the strip road-adjusted estimate (SR adjusted) of the of within-stand variation of standing volume, stem number and basal area after thinning. Blue violins represent the frequency distribution of Q_n for each attribute. Different lower-case letters indicate statistically significant differences (α = 0.05, paired *t*-test).

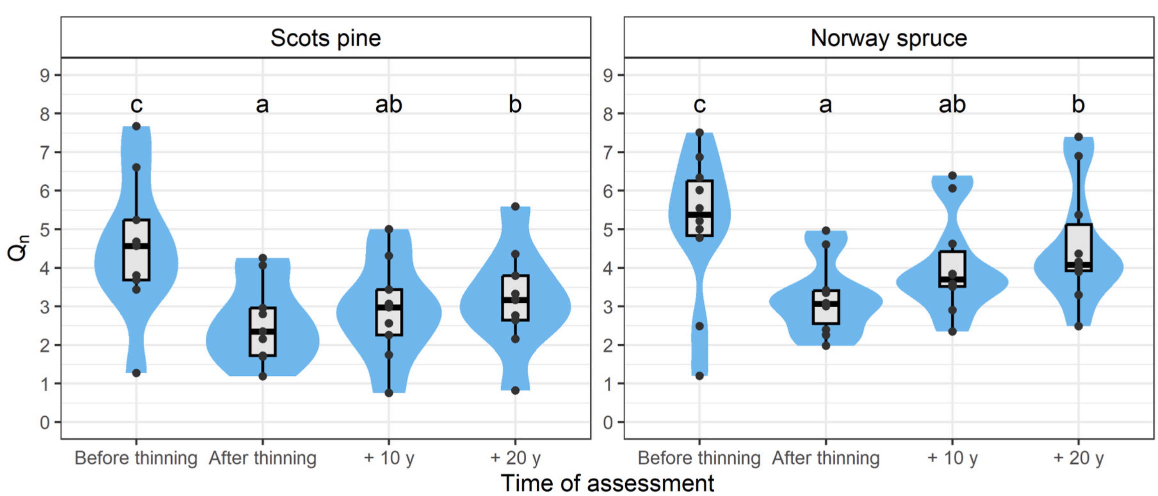

Fig. 6. Box-and-violin plots of within-stand variation in basal area before, directly after and 10 and 20 years after thinning for Scots pine and Norway spruce. Different lower-case letters indicate statistically significant differences (α = 0.05, *post hoc* comparison using Tukey contrasts).

added value in adapting the thinning regime to the WSV in basal area for the stands in this study when optimising for stand economy (Persson et al., 2022). On the other hand, this motivates optimisation towards management goals that are not solely focused on stand economy and volume production as neither is reduced.

There are forest management practices, besides the context described in this article, which further increase WSV in stand attributes. A large share of the boreal forests in the Nordic countries are managed based on the retention principles of the Forestry Stewardship Council (FSC), where at least 5–10% of the standing volume should be broadleaves and, in addition, retention trees should be left at final felling and retained in the future stands (FSC, 2020). Retention forestry blurs the stand borders and motivates adapted silvicultural treatments which account for the increased WSV. The rapid development in Precision Forestry methodologies may facilitate balancing environmental and biodiversity goals with the production-oriented goals.

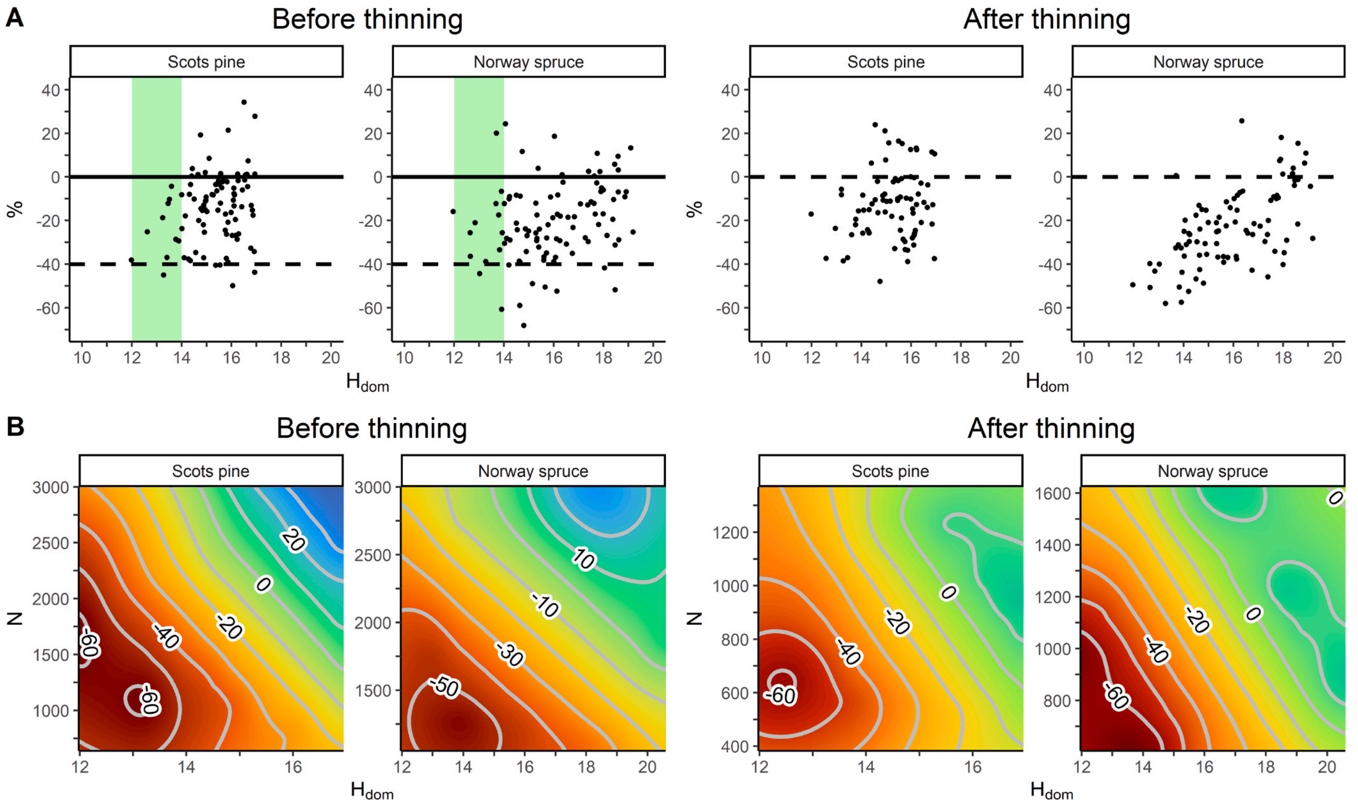

Fig. 7. **A**: The compliance with the upper target in the thinning guide over dominant height (H_{dom}) for individual plots (left), and the compliance with the lower target in the thinning guide over dominant height (H_{dom}) for individual plots (right). The solid horizontal line (left) indicates the upper basal area target, the green, vertical area (left) represents the recommended height interval for first thinning according to the thinning guidelines (12 – 14 m), and the dashed horizontal lines represent the basal area target after thinning (left and right). **B**: The predicted compliance (red-blue color gradient) with the basal area targetas a function of stem number (N) and dominant height (H_{dom}) before thinning (left) and after thinning (right). The predicted compliance is expressed as the relative difference (%) to each target (upper and lower).

Table 2
Summary of the species-specific models estimating compliance with the upper target before thinning (Compl. UT) and the lower target after thinning (Compl. LT). Predictors are significant at p <.05 (*), p <.01 (**) and p <.001 (***).

		Fixed						Random	
	Response attribute	Parameter	Estimate	SE	*t*	*d.f.*	*p*	Estimate	SE
Scots pine	Compl. UT	Intercept	-289.3	37.8	-7.7	79	<.001***	Intercept	14.4
		Stem number	0.029	0.003	11.4	79	<.001***	Residual	9.3
		Dominant height	14.8	2.3	6.3	79	<.001***		
Norway spruce	Compl. UT	Intercept	-195.9	19.5	-10.1	88	<.001***	Intercept	8.5
		Stem number	0.03	0.003	10.7	88	<.001***	Residual	10.3
		Dominant height	6.9	1.1	6.5	88	<.001***		
Scots pine	Compl. LT	Intercept	-280.1	45.4	-6.2	67	<.001***	Intercept	13.3
		Stem number	0.05	0.008	6.3	67	<.001***	Residual	10.7
		Dominant height	14.8	2.7	5.4	67	<.001***		
Norway spruce	Compl. LT	Intercept	-243.2	21.1	-11.5	78	<.001***	Intercept	9.5
		Stem number	0.06	0.007	8.6	78	<.001***	Residual	9.4
		Dominant height	11.2	1.1	9.2	78	<.001***		

4.1.3. Effect of thinning on within-stand variation

We hypothesised that WSV in all stand attributes were reduced by thinning. However, only the WSV in basal area, standing volume and stem number were lower after thinning than before thinning. Thinning did not affect WSV in dominant height, mean height and mean diameter, for slightly different reasons. Thinning was carried out from below and did not directly affect the largest trees which make up dominant height. Mean diameter and Lorey's mean height are basal area weighted estimates, and small trees get a low weight, hence, the thinning did not affect the estimate too much as mostly the smallest tress were removed. However, standing volume and basal area, which are both per unit area estimates, e.g. X ha^{-1}, were directly affected by reductions in stem number, hence their respective WSVs were easily affected.

There was a difference between the original plot estimate and the strip road-adjusted estimate of WSV for standing volume for both Scots pine and Norway spruce, and also for WSV in basal area for Norway spruce. The difference suggests that the forced harvest in the strip roads further reduced the WSV in the listed attributes.

The WSV in basal area was reduced immediately after thinning and did not return to pre-thinning WSV levels within a 20-year period after thinning. The reduction of WSV in basal area should also reduce the WSV in growth as basal area largely determines growth after thinning (Hasenauer et al., 1994; Pienaar, 1979). However, the increase in WSV in basal area after thinning is likely a result of slight WSV in basal area after thinning in combination with WSV in site index. Therefore, WSV in basal area is not constant, but reducing WSV in basal area during thinning has long-term effects. The growth and yield models used in the Heureka system (Elfving, 2010) are robust and work well for many forest types and different development stages. Thus, the projections made in Heureka are reliable and should provide a good estimate of the WSV development for basal area.

4.2. Thinning practices

4.2.1. Compliance with the thinning guideline

We explored the compliance with the upper target in the thinning guideline as a function of stem density and dominant height at the time of thinning. Not surprising, our results suggest that the compliance increases with elevated stem number and increasing dominant height for both species. The Swedish Forest Agency recommends that the thinning regimes for Scots pine and Norway spruce are initiated within 12 – 14 m in dominant height (Bergquist et al., 2016). However, this study showed that few plots were thinned within this height interval and that few of them complied with the basal area target. At a stem number of 2250 N ha^{-1}, full compliance with the thinning guide was reached at a dominant height higher than 15 m for Scots pine and 17 m for Norway spruce. This suggests that the upper basal area target was difficult to achieve for the plots in the survey even at relatively high stem number. Subsequently, the resulting management implication is likely to postpone the first thinning until a higher basal area is reached, as exemplified by the late thinning (dominant height > 14 m) occurring in our survey. There are clear incentives to conduct late thinning, as the harvester productivity increases with the average stem volume of the harvested trees (Eriksson and Lindroos, 2014). The thinning cost has increased in the last two decades from 15 to 20 € per m^3 in Sweden, which may have contributed to pushing the time of thinning forward (Eliasson, 2022). However, there are risks associated with delaying thinning that may outweigh the short-term risk of thinning being a net cost, such as wind throw (Valinger and Pettersson, 1996a,b).

The question lingers whether the deviation from the upper basal area target is due to problems associated with the forest or the reasoning behind the upper thinning guide target itself. The upper basal area target in the thinning guideline is based on estimates of the maximum basal area at crown closure for a given dominant height, tree species and site index (Söderberg, 1986) and thinning is recommended at this stage to maximise growth while avoiding competition-induced mortality. However, it is likely that the upper target in the thinning guidelines is based on assumptions about forest growth that do not reflect forest conditions today. In a subset of regenerated stands in southern Sweden, from a recent nationwide survey (swe. "Föryngringskollen"), only 1700 N ha^{-1} of the planted seedlings were found one growing season after establishment. This was attributed to 1) mortality, facilitated by non-optimal regeneration methods (soil scarification, plant size, lack of favourable planting spots) and pine weevil attacks, and 2) an exaggerated number of reported planted seedlings (Öhlund et al., 2023). Thus, naturally regenerated seedlings of different tree species, age, breeding value, etc. would have to make up for the lost trees. Recent studies also show that trees are more slender today than they were in the mid-1900 s, thus, trees of the same height now contain less stem volume and have a lower tree basal area (Appiah Mensah et al., 2023), which should equate to lower stand production. Thus, the identified problem likely depends on a combination of low stem number at the end of the establishment phase and the use of thinning guidelines that assume a higher basal area early in the rotation. Consequently, the upper threshold should probably not be adhered to in stands that do not reach the upper basal area target within the recommended height interval.

4.2.2. Low stand density post thinning

We explored the compliance with the lower target in the thinning guideline as a function of stem density and dominant height after thinning, and our results suggest that the compliance increases with elevated stem number and increasing dominant height for both species. After thinning, the stands of both tree species had a lower basal area than what is recommended in the thinning guidelines, but it did not drop below the legal limit (§10, the Swedish forest act). It is likely that the combination of low stand density before thinning, and the moderate thinning intensity resulted in low stand density post thinning. We can only speculate about the reasons, but part of the explanation could be a predetermined high demand for pulp and timber, leading to high volume harvests from each stand, possibly combined with inadequate data for decision-making.

One way to understand the spatial distribution of the forest resource within the stands and overcome overharvesting is to get a better estimate of and assess the forest resource prior to thinning. Since the data collection for this study, the method for automated follow-up of thinning operations (Hannrup et al., 2015; Möller et al., 2021) has been implemented in all larger forest companies and has since then proved to be an efficient tool for avoiding overharvesting.

Although the stands were thinned below the recommended basal area, it does not mean that maintaining a profitable net production over the rotation is at risk for Norway spruce compared to a light thinning programme, not least because of the strong growth response to elevated nutrient availability (Svensson et al., 2023) commonly associated with reduced competition. However, for Scots pine, losses in net production should be expected (Nilsson, Agestam, et al., 2010).

While repeated heavy thinning down to low stand density reduces net production, it is a valid climate mitigation and adaptation strategy. Soil water availability is the limiting growth factor in southern Sweden for Scots pine and Norway spruce (Bergh et al., 2005), and both species are more prone to experience growth anomalies during drought periods (Aldea et al., 2023). Thinning, and especially heavy thinning, has been shown to increase growth recovery after periods of drought and to maintain resilience of Scot pine and Norway spruce (Sohn, Hartig, et al., 2016; Sohn, Saha, et al., 2016), as water use is temporary reduced in the years after thinning. A probable, but unexpected outcome of the thinning practices in this survey is improved growth recovery and increased resilience in response to the extreme summer drought of 2018 in northern Europe (Yiou et al., 2020). As severe drought events are likely to become more frequent in northern Europe (Spinoni et al., 2017), it might be beneficial to maintain a low stand density at the expense of stand production. Drought responses in even-aged stands in Sweden have however not been studied in detail (Felton et al., 2023), pointing to a research avenue worth exploring.

The results from this study regarding specific stand attributes, thinning intensity and WSV are only valid for the included stands and should not be used to make direct inference elsewhere, as the pre-existing conditions do not necessarily exist in other forests or do not apply to other landowners in or outside of Sweden. However, in a broad perspective, our findings in terms of how WSV complicates the application of thinning guidelines at first thinning and how it is dealt with in the thinning have implications beyond this study. It is also likely to become more relevant in the future, as WSV is seen as a "natural" and necessary part of planted coniferous forests in Fennoscandia, and since site-specific silviculture based on forest resource maps and Precision Forestry methods is likely to increase.

5. Conclusions and recommendations

Norway spruce stands with increasing WSV in stem number and WSV in site index had a higher WSV in basal area production. This was not observed for Scots pine and could be attributed to the lower environmental growth stress of Scots pine compared to Norway spruce. Thinning reduced WSV in standing volume, basal area and stem number and simulation results suggest that it will take 20 years for the WSV in basal area to increase again for both Scots pine and Norway spruce.

Variation in regeneration survival densities and insufficient young stand tending may cause WSV in stem number, basal area and standing volume and decrease the thinning guidelines compliance at the time of first thinning. We recommend ensuring good establishment practices to safeguard high survival and maintain an appropriate stem number throughout the establishment phase as well as the thinning phase. Also, we advocate for a revision of the thinning guidelines to account for the low stem densities and/or to account for the WSV in stem number when using the thinning guidelines.

CRediT authorship contribution statement

Magnus Persson: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources. **Martin Karl-Friedrich Bader:** Software, Methodology, Supervision, Writing – review & editing. **Emma Holmström:** Conceptualization, Methodology, Resources, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Deepl Editor for language editing and to find more appropriate wording. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

Appendix 1

Derivation of the Q_n estimator

The Q_n estimator is a robust measure of scale, similar to the median absolute deviation (MAD) and the interquartile range (IQR). More common – non-robust – scale estimators are the standard deviation and coefficient of variation, however, these are more sensitive to outliers. The Q_n estimator is more efficient than the median absolute deviation (MAD) and has a breakdown point of 50%, meaning that it can resist up to 50% of outliers in the data.

The Q_n estimator is based on the pairwise differences of the data values. It is defined as:

$$Q_n = C_n \bullet \left\{ |x_i - x_j|; i < j \right\}_{(k)}$$

where C_n is a normalisation constant, and $\left\{ |x_i - x_j|; i < j \right\}_{(k)}$ is the k-th order statistic of the absolute differences of the data values. The value of k is chosen as:

$$\mathrm{k} = \binom{h}{2} = \frac{h(h-1)}{2}$$

where $\mathrm{h} = \lceil \frac{n}{2} \rceil + 1$ and $\lceil \cdot$ is the ceiling function.

Procedure:

1. Compute the absolute difference between all data points in the sample.
2. Sort the differences in ascending order and select the k-th smallest value which is the order statistic of the equation.
3. Multiply the order statistic with C_n which by default is 2.2219. The multiplication with C_n normalises the Q_n estimator and makes it consistent with the standard deviation of a normal distribution as the sample size increases (which would reduce the impact of outliers on the standard deviation).

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