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Precision thinning – a comparison of optimal stand-level and pixel-level thinning

Magnus Persson [a], Renats Trubins [b], Ljusk Ola Eriksson [a,b], Johan Bergh [a], Johan Sonesson [c] and Emma Holmström [b]

[a]Department of Forestry and Wood Technology, Linnaeus University, Växjö, Sweden; [b]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Alnarp, Sweden; [c]Forestry Research Institute of Sweden (Skogforsk), Uppsala, Sweden

ABSTRACT

Precision forestry allows decision-making on tree level or pixel level, as compared to stand-level data. However, little is known about the importance of precision in thinning decisions and its long-term effects on within-stand variation, stand economy and growth. In this study, silviculture was optimized for Net Present Value (NPV) in 20 conifer-dominated forest stands in hemi-boreal southern Sweden. The precision-thinning approach, Precision Thinning (PT), is compared with a stand-level approach, Stand Level Thinning (SLT) that is optimized for the same criteria but based on stand-level data. The results suggest no substantial long-term benefit or drawback in implementing thinning decisions based on pixel-level data as compared to stand-level data when optimizing stand economy. The result variables NPV and Mean annual increment of living stem volume (MAI_{net}) were not higher for PT than for SLT. The within-stand variation in basal area (m^2/ha^{-1}) was lower at the end of the rotation compared to the start of the simulation for both SLT and PT. At the end of the rotation, SLT had higher variation in basal area compared to PT. However, pixel-level information enables adapting the silviculture to the within-stand variation which may favour other forest management goals than strictly financial goals.

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Thinning; within-stand variation; stand economy; NPV; Norway spruce; precision forestry; Scots pine

Introduction

In production-oriented forestry, the stand is the smallest spatial unit at which forests are described and managed. The stand pattern in forest landscapes self-reproduces and remains relatively stable over long periods of time. This is due to the heavy influence of natural features of the area, such as topography and spatial variation in soil properties, as well as management considerations based on, for example, adjacency to other land-uses. Furthermore, the current stand size results from a trade-off between inventory costs and what is considered sufficient homogeneity, the latter being related to the in-optimality costs of consistently applying the same treatment to whole stands (O'Hara and Nagel 2013). In precision forestry, silviculture is planned at a smaller scale than the stand, e.g. at pixel level (synonymous to sub-area) or individual-tree level, collected from high-resolution data (Bare and Dyck 2001; Kovacsova and Antalova 2010). In this way, thinning grade and thinning form can be adapted to the conditions at pixel level. The rapid development in forest remote sensing (Holopainen et al. 2014; Kangas et al. 2018; Maltamo et al. 2021) and forest planning (Pukkala 2018, 2019, 2020) opens possibilities to account for within-stand variation. However, it is not known whether economic return and wood production could be improved by taking decisions based on each sub-area within the stand compared to decisions made on stand-level data.

There are several reasons to expect within-stand variation in production stands: abiotic or biotic damage, spatial and temporal variation in site conditions, competition and prior silviculture. Holmström et al. (2019) found that abiotic and biotic agents result in clustered mortality three years after establishment in planted forests of Norway spruce. Skovsgaard (1997) found large variation in basal area growth and variation in thinning response attributed to local variation in site conditions and basal area before thinning. The author further promotes including volume or basal area before thinning as a covariate when estimating thinning response. Since then it has been proven that variation in site productivity within stands is mainly expressed in variation in basal area growth (Skovsgaard 2008). For this reason, within-stand variation in this article is defined by basal area and measured across pixels, i.e. the same unit for which Precision Thinning (PT) is applied.

The timing and intensity of commercial thinning on stand level is affected by several factors. Thinning increases the diameter growth and volume growth of remaining individual trees (Mäkinen and Isomäki 2004a, 2004b; Huuskonen and Hynynen 2006; Nilsson et al. 2010a) and enhances crown development (Vuokila 1981) favouring early thinning. In addition, the manager often conducts a risk assessment for wind damage caused by thinnings (Valinger and Pettersson 1996; Valinger and Fridman 2011) and therefore limits the timing, not by age but by stand height. However, the

CONTACT Magnus Persson magnus.j.persson@lnu.se Department of Forestry and Wood Technology, Linnaeus University, 351 95 Växjö, Sweden
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

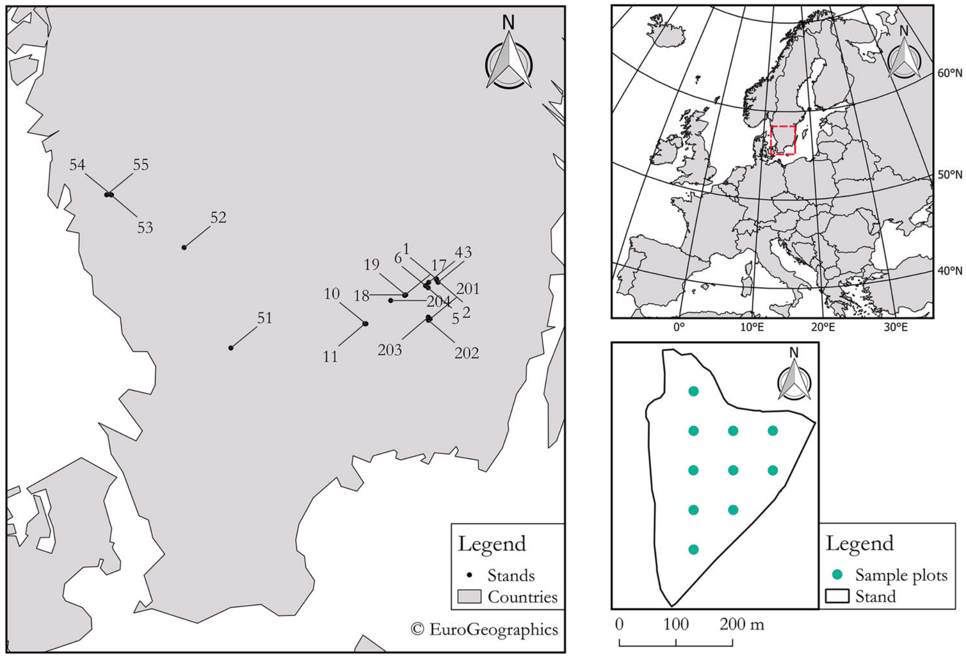

Figure 1. The geographic location of the 20 stands within the study area (left) and an illustration of how the sample plots were distributed within a stand (below right) © EuroGeographics for the administrative boundaries.

revenue from early commercial thinning is mainly from pulpwood. Postponing the thinning will increase the total removable volume and the share of the more valuable sawlogs.

Numerous studies have investigated what factors affect optimal timing of thinning. Cao et al. (2007) found through stand-level optimization that stands with high initial stand density are thinned earlier than sparse stands, since crown closure is reached earlier. Valsta (1992) showed that the relative value increase is higher in sparse stands, which is also an argument for earlier thinning of dense stands. The number and timing of time of thinnings are also dependent on fixed costs, such as moving harvesting equipment (Eriksson 1994; Hyytiäinen and Tahvonen 2002).

Objectives

The objective of this study is to assess the potential gain in economic value and wood production from PT and to examine the within-stand variation. The latter is important since it can affect economic values as well as ecosystem services. Using a survey of 20 conifer-dominated stands at the time of first commercial thinning located in hemi-boreal southern Sweden, the following research questions were pursued: (1) How large was the within-stand variation before first thinning? (2) Does a PT approach lead to higher NPV, and MAI_{net} compared to stand-level management? (3) How does the within-stand variation over time differ between stand-level management compared to a PT approach?

Material and methods

Survey

The study area was situated in southern Sweden, on the forest holding of Sveaskog, a state-owned forest company, owning roughly 3.1 million hectares of productive forest land. It is situated within the hemi-boreal climate zone, where coniferous tree species, such as, Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) and admixtures of deciduous hardwoods, dominate the forest composition.

Before any stand selection, seven different planning districts in Götaland were chosen to be part of the study area. The stands were then obtained from the district database of planned thinnings in winter 2018 and were given a randomized priority order. Each stand was visited in the priority order and if the criteria were met, it was included in the study, otherwise it was discarded and the following stands in the priority list were visited instead. The following criteria were set: (1) the stands had to be Norway spruce- or Scots pine-dominated (>80% standing volume); (2) planned first commercial thinning in-between the vegetation periods 2018 and 2019; (3) mean top height (MTH) had to be between 10 and 17 m; (4) stand size between 4.5 and 10 hectares; (5) Site index (MTH at 100 years refence age) should be in between 26 and 36 m for Norway spruce and 22 and 32 m for Scots pine. This set of criteria resulted in 20 forest stands, of which 10 were dominated by Scots pine and 10 by Norway spruce, distributed on 7 districts in Götaland (Figure 1).

After the limit of 20 stands was reached, the stands were reduced in size by applying a negative buffer of 15 m to the stand borders, which had the objective of removing the stand border variation from being included in the material. Then, 10 circular sample plots with 10 m radius were placed out in every stand using a grid to indicate the centre of each plot (Figure 1). At least 9 of the 10 plots had to be fully contained within the buffered stand boundary and one of the 10 plots could intersect the buffered stand boundary, but not with more than 50% of the sample plot area. Naturally, the stands varied in size and shape which implied that the distance between sample plots was different for each stand. To that end, different distances between the points were tried if any of the previously stated criteria could not be met. All the stands were inventoried after thinning, due to time restrictions.

Field measurements

The field measurements were carried out from January 2019 to June 2019 after thinning. In each sample plot, a centre pole was hammered down, and all trees were numbered starting clockwise from the magnetic north. All trees with a diameter at breast height (DBH, 1.3 m above ground) equal or higher than 40 mm were callipered at breast height. Tree species, vitality traits, tree class and growing traits (forking, etc.) were registered for each tree. Sample trees were sampled from the diameter distribution of each stand, ensuring and equal representation from all diameter classes. Tree height and crown height were later measured for each given sample tree. The full methodology is described in Karlsson et al. (2012).

Statistical modelling

The diameter of the harvested trees was recreated by modelling the sample trees. Simple linear regression was used to model the relationship between diameter at breast height and diameter at stump height, using one function per tree species and stand (Equation (1)).

$$DBH_{est} = \beta_0 + D_{stump} \times \beta_1 \quad (1)$$

where DBH is the diameter at 1.3 m above ground, D_{stump} is the stump diameter above ground (20 cm for Norway spruce and 30 cm Scots pine). The DBH of the harvested trees was predicted using the functions.

Tree height for the callipered trees was estimated using non-linear regression models and Non-linear Least Squares. The relationships between tree heigh and DBH were modelled with the sample trees and Equation (2). (Näslund 1936).

$$H = \frac{DBH^p}{(a + b \times DBH)^p} + 1.3 \quad (2)$$

where a and b are model parameters. Pettersson (1955) set parameter $p = 3$ for Norway spruce and Näslund (1936) set parameter $p = 2$ for Scots pine and other tree species, and likewise was done in this study. For deciduous hardwoods, $p = 2$. Models were made one stand level, demanding at least 15 observations of each tree species. In stands with less than 15 observations per tree species, models based on the whole data set for that tree species were produced. The function was later applied to the calliper trees and the recreated (harvested) trees.

Tree volume of the sample trees was calculated using Brandel's simple volume functions (nr 100-1, Equation (3)) for Norway spruce, Scots pine and Birch all parameterized for southern Sweden (Brandel 1990).

$$V = 10^a \times DBH^b \times (DBH + 20)^c \times DBH^d \times (H - 1.3)^e \quad (3)$$

where DBH = diameter at breast height (cm); H = tree height (m); the parameters a through b were taken from Brandel (1990). The natural logarithm of stem volume and the natural logarithm of DBH on the sample trees form a linear relationship, which was used to estimate the stem volume on each calliper tree and reconstructed trees. Site index was estimated for each sample plot using species-specific site index curves from tree heights (Hägglund 1973, 1974).

Forest development scenarios

Growth was simulated on the measured plots over a full stand rotation, using the decision support system (DSS) Heureka, calibrated for Swedish forests. In Heureka, tree-list data are imported and organized in prediction units (PU), which correspond to the sample plot level and every PU belongs to a treatment unit (TU). Treatments are assigned at TU level with forecast of forest conditions predicted with data at PU level. Forecasts are made using functions for basal area growth, height development, stand mortality and ingrowth, which respond to treatments, such as, thinning, fertilization and final felling (Eggers and Öhman 2020). The output is summarized over PUs in five-year intervals. A range of treatment programmes is generated for each TU. The treatment programme with, in this case, maximum NPV under an interest rate of 2% is taken as the solution for the TU. This programme may or may not represent the global optimum for the TU, as the heuristics that generate the alternatives can overlook the true optimal programme. The thinning guide used in Swedish forestry (Skogsstyrelsen 1984) also sets limitations on the number and kind of schedules that are produced, normally limiting the number of unique thinning alternatives to one or two. An advantage of the approach is that management programmes, including final felling, follow procedures that are not too far off from current standards and, thus, implementable.

The optimization module in Heureka was used for assigning optimal treatment programmes for each plot and stand, using scenario groups called Stand Level Thinning (SLT) and PT. The objective was to maximize NPV and an interest rate of 2% was used. The thinning prescription in the system is framed by the standard thinning guide used in Swedish forestry (Skogsstyrelsen 1984). This means that for every TU, the number of unique thinning alternatives considered in the optimization process is usually one or two.

Stand Level Thinning

SLT reflected the general practice when the treatment is based on average data for the stand. In SLT, each stand was a TU by merging the original 10 sample plots into one tree list. The time and form of thinning and the time of final felling were the same for all PUs within the stand. The optimizations in SLT were carried out on each TU corresponding to 10 sample plots. The achieved treatment programme was manually applied to each sample plot using the stand simulator Standwise, a module of the Heureka system.

Precision Thinning

PT represented the case when thinnings were planned in each PU based on site conditions and basal area in the respective PU. In this scenario harvesting below the legally required standing volume in each sample plot was not possible, which could happen with SLT when the stand-level treatment was referred back to the sample plots. In PT, each sample plot was treated as an individual stand, which did not have to be thinned at the same time as any other sample plot within the same stand. However, the rotation length was restricted to be the same for all sample plots. The rotation length was set equal to the rotation length of SLT for the corresponding stand.

Criteria for the timing of thinnings and final harvest

Every TU was considered to be thinned at the beginning of every new five-year period of simulated growth, but only executed if the set criteria were met, defined by the thinning guidelines and the settings in the Treatment Program Generator (TPG). Thinning guidelines from the Swedish Forest Agency quantify how much standing volume could be removed from a stand at a given MTH, while still meeting the legal requirement for standing volume regulated in the Swedish forestry law 10 §.

Other parameters in TPG-settings were altered from the default settings to better represent recommended silviculture and operational requirements of mechanised forest operations. The parameters "Vary Thinning Grade" were set to "false" and "Max Thinning grade" was set to 60%. Harvesting of strip roads was not included other than in the cost calculations. The official recommendations are to stop the thinning programme at a MTH of 20 m, as the risk for wind felling increases with tree height (Valinger and Fridman 2011). Consequently, the max height for all thinnings was set to MTH of 20 m.

Evaluation

Differences in the single thinning events were compared for the two scenarios, by estimating the mean thinning grade (percentage removal in basal area) and thinning ratio (mean DBH of removed trees/DBH of all trees).

The evaluation of the scenarios was made based on economics, potential stand yield and thinning regime. In Heureka, the net present value (NPV) is calculated through summation of the discounted yearly cash flow from silvicultural treatments in the first generation together with the Land Expectation Value (LEV) (adapted from Faustmann (1849)). LEV is the sum of all discounted costs and revenue associated with forest management throughout time.

$$NPV = \sum_{t=0}^{S} (1+r)^{-t} \times CF_t + (1+r)^{-S} \times LEV \qquad (4)$$

where CF_t = Cash Flow at year t; r = the real discount rate; t = Time point (years); S = Final felling year for the 2nd forest generation; LEV = Land Expectation Value. The second generation followed the same treatment programme as generation 1, with the addition of establishment costs and pre-commercial thinning costs.

Potential stand productivity was evaluated using the mean annual increment of living stem volume (MAI_{net}, m^3 sk ha^{-1} $year^{-1}$). Stem volume was defined as stem volume above the felling cut including the top but excluding branches. MAI_{net} was calculated by dividing stem volume production (not including self-thinning) with the rotation length (years) for each stand and scenario group. The outcome of within-stand variation was expressed with the coefficient of variation and was compared for the simulations.

For visualization purposes, the outcome in PT was benchmarked to the outcome in SLT, by computing the relative difference percentage (RD). The statistical evaluations are based on the actual values for NPV and MAI_{net} and not on RD.

$$\textit{Relative difference}\ (\%) = \frac{x_{PT} - x_{SLT}}{x_{SLT}} \times 100 \qquad (5)$$

Paired t-tests were performed to test if NPV and MAI_{net} were higher for PT compared to SLT, using a significance level of 5%. In addition, any difference in the coefficient of variation for basal area was tested for the two simulations at the end of the rotation. The natural logarithm of both the response and the dependent variable was used if the histogram plots of the data and Shapiro-tests for normality showed non-normal tendency.

Results

Survey

Mean stand site index was 34 ± 1 m for Norway spruce and 27 ± 1 m for Scots pine, corresponding to moderate to high fertility sites for both species. Mean stand basal area in the Norway spruce stands was 27 ± 1 m^2 ha^{-1} with an average stem density of 1939 ± 398 trees ha^{-1} and dominant height of 16 ± 2 m. Similarly, for Scots pine, mean stand basal area was 26 ± 5 m^2 ha^{-1}, the average stem density was 1665 ± 384 trees ha^{-1} and dominant height of 15 ± 1 m. Data for individual stands are shown in Appendix, Table A1.

SLT vs PT

The optimal treatment programmes for both SLT and PT often suggested one or two thinnings within three periods from the start of the simulations. In SLT, the thinning grade averaged 29% (range: 20–38%) and the thinning ratio averaged 0.89 (range: 0.86–0.91). For PT, the average thinning grade was 32% (range: 20–51%). Similar to SLT, the thinning ratio averaged 0.89 (range: 0.83–0.94) in PT for individual plots. A paired *t*-test showed significantly higher thinning grades for PT as compared to SLT, $t(16) = 3.35$, $p = .002$.

A significantly higher MAI_{net} was obtained for PT (M = 10.8, SD = 2.69) as compared to SLT (M = 10.7, SD = 2.67), M diff. = 0.04, $t(199) = 2.92$, $p = .002$. Similar NPV was obtained for SLT (M = 71,647, SD = 28,075) and PT (M = 71842, SD = 28,219). The paired t-test with the alternative hypothesis that PT achieved an overall higher NPV over the rotation was marginally significant (M = 195 SEK/ha), $t(199) = 1.44$, $p = .08$. The relative difference of PT to SLT for each stand is visualized in Figure 2.

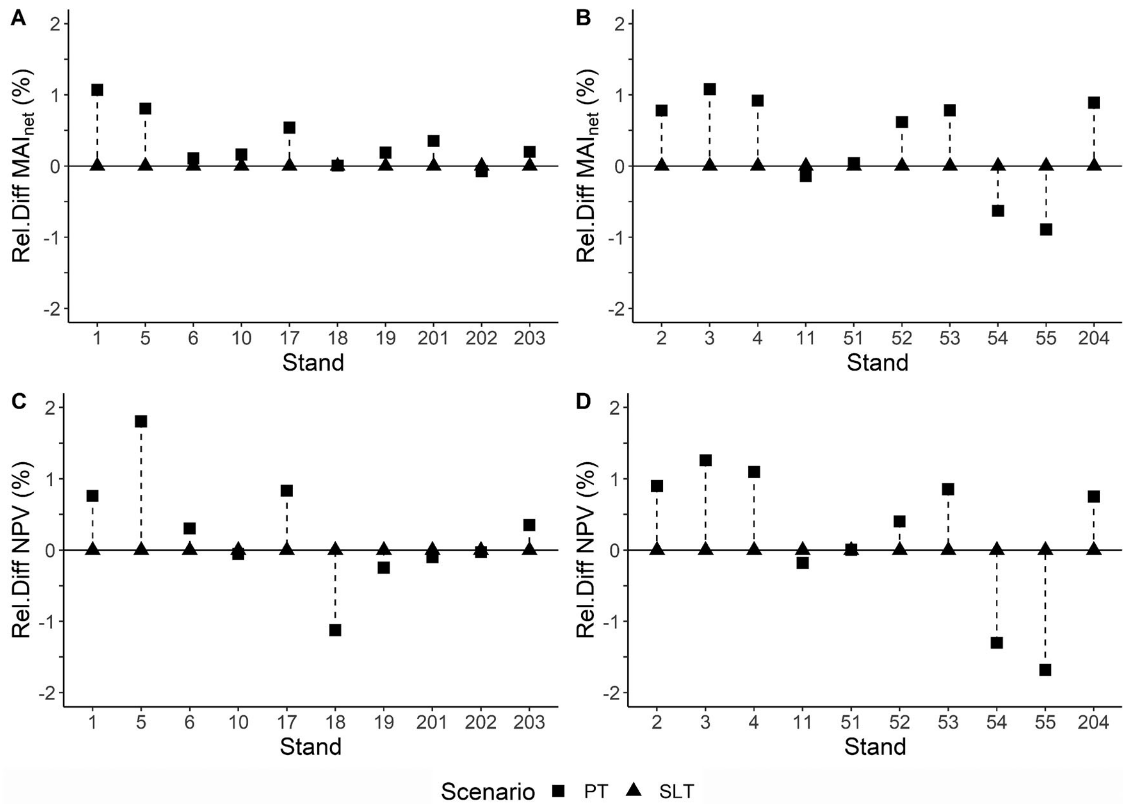

Figure 2. Illustration of the relative difference in MAI_{net} for PT compared to SLT for Norway spruce (A) and Scots pine (B), and the relative difference in NPV for PT compared to SLT for Norway spruce (C) and Scots pine (D).

Variation during the rotation

The within-stand variation in basal area was greatly affected by the thinnings in both SLT and PT (Figure 3 and Appendix, Table A1). The thinnings in both scenarios reduced the coefficient of variation in basal area to the end of the rotation for SLT, $t(19) = -11.57$, $p < .001$ and for PT, $t(19) = -11.95$, $p < .001$.

SLT had significantly higher variation in basal area measured with the coefficient of variation ($M = .12$) compared to PT ($M = .08$) at mid-rotation, $t(19) = 6.47$, $p < .001$, and by the end of the rotation ($M = .08$, $M = .05$), $t(19) = 5.34$, $p <$ 0.001.

Discussion and conclusions

Initial within-stand variation

The within-stand variation in basal area was considerable in both the Norway spruce and Scots pine planted stands (Appendix, Table A1). Initially, these stands are homogeneously managed during regeneration after clearcutting, with the same mechanical soil scarification combined with manual planting in the same seedling density throughout the stand. The lack of correlations between sample plot basal area and distance between plots (see Appendix, Figure A1) indicates that the overall within-stand variation was not primarily caused by gradual change in site index, or site properties, when the delineation of the stand borders was made. The within-stand variation found in the survey is most likely a result of other abiotic and biotic factors. The reason for variation in stem density within the stand, although the spacing at planting was constant, can to some extent be explained by seedling mortality (Holmström et al. 2019). In Norway spruce stands, seedling mortality is often caused by pine weevil damage (Sikström et al. 2020) and in some areas by frost (Nilsson et al. 2010b). In the Scots pine stands, pine weevil damage and ungulate browsing are the most common causes of mortality (Ara et al. 2021). Furthermore, competing vegetation, of grass or woody

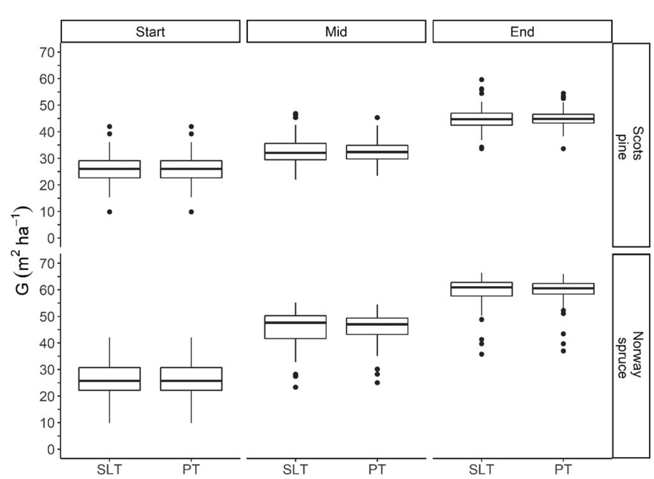

Figure 3. Boxplot-diagrams showing the basal area development for SLT and PT for Scots pine and Norway spruce at the start of the simulation, mid-rotation and at the end of the rotation.

regeneration, and mild damage of the above-mentioned damaging agents also cause growth losses and thereby may be the reason for some local variation in basal area.

Although most of the stands included a considerable variation, they do not represent the full extent of the site-variation existing in production forests. The stands included in this study are managed by Sveaskog, which entails active management and from the company database a further selection was made to only include monocultures (>80% of the dominant species). The deliberate decision to include a 15 m buffer along the stand border probably reduced the variation in the material. Consequently, the variation in stem density, tree species composition and site productivity is most likely even larger in less intensively managed stands.

SLT vs. *PT*

The PT approach did not reach higher economic return (M = 71,842, SD = 28,219) than SLT (M = 71,647, SD = 28,075). A contributing factor explaining the equal results of the scenarios is the low revenue obtained from thinning operations, as compared to the revenue from final felling. The income from thinnings was substantially lower due to less harvested volume and the relatively higher share of pulpwood which lowers the revenue.

Production (estimated with MAI_{net}) proved to be slightly higher for PT (M = 10.8, SD = 2.69) as compared to SLT (M = 10.7, SD = 2.67). This showed that more of the net production was utilized in PT, but the difference was practically negligible on stand level. However, at a larger scale, small increases in production could make a difference, e.g. national scenarios on wood supply, carbon budgets, etc.

PT did not, given these circumstances, provide any clear benefits, but the approach allowed for specifying certain outcomes in each pixel within a forest stand. SLT – the normal spatial level of applying the guidelines – means that thinning of sub-areas depend on the stand as a whole. However, transferring the thinning guidelines to pixel level brings up some issues that need some clarification. In SLT, sub-areas in the same stand, which do not meet the criteria for thinning (basal area level) will be thinned regardless. This is not the case in PT, for which the decision to thin an individual sub-area is independent of other sub-areas in the same stand. In PT, a sub-area with a basal area above the threshhold in the thinning guidelines, could potentially be thinned with a higher thinning grade as compared to SLT. Consequently, for a given stand and period, the threshold for thinning a sub-area is generally higher for PT than for SLT, but the thinning grade may also be higher.

The time window for thinning seems to be rather narrow if the aim is to meet the demands of improving volume production, increasing revenue, and risk management. More volume could be harvested in the thinning operations if the maximum height for thinning was raised, increasing the income in thinning relative to final felling. A higher discount rate would most likely shorten the optimal rotation length (Eriksson 1994), bring the time of thinning forward (Wikström and Eriksson 2000) for both scenarios. Changing these parameters would affect the outcome for each scenario, but we cannot find any reason why this would affect the relative difference in NPV or MAI_{net} between the scenarios.

The results suggest, thus, that there is no difference in optimizing the decision on stand-level data or pixel-level data. This decision is reached under an assumption of perfect information. However, currently, the accuracy in estimation of basal area on pixel level is moderate, making it less certain that thinnings on pixel level are optimally scheduled, adding another argument why pixel-level thinning would not entail economic advantages.

Within-stand variation during the rotation

The thinning programmes (PT and SLT) had a strong effect on the within-stand variation in basal area. The coefficient of variation of basal area for both Norway spruce and Scots pine decreased significantly from the start of the simulation to the end of the rotation for both SLT and PT (Figure 3, Appendix, Table A2). For most stands, the range in basal area was very small after the thinning programmes have been completed (Appendix, Figure A2). The relatively larger range in basal area for stands 2, 3, 10, 204 may be due to low basal area at the start of the simulation for individual sample plots and may not be attributed to the within-stand variation in basal area itself.

In relation to current trends

The results from this study only deal with PT within single, heterogenous stands, however, other methods deal with within-stand variation by redefining the stand boundaries themselves, grouping pixels which are more similar to each other into new stands. This builds on the concept of Dynamic Treatment Units (DTU) (Holmgren and Thuresson 1997; Heinonen et al. 2007). It could be a more effective way to deal with variation since homogeneity within treatment units can be achieved at every treatment occasion without creating large semi-homogenous forest stands. From resilience and ecological points of view, large homogenous stands imply higher risks and lower habitat quality, thus also speaking in favour of the stand-level approach. However, as indicated above, the possibilities to reduce the size of treatment units and to define them flexibly might be limited by the available inventory methods, as well as by scale-dependent harvesting operation costs (Wilhelmsson et al. 2021).

It is likely that accounting for the within-stand variation in basal area (as promoted in this article) might have positive effects when planning for other forest management goals than strictly financial goals. For instance, a variety of types of retention forestry (Gustafsson et al. 2012) is practiced in Sweden, which includes leaving retention areas, leaving retention trees and preserving features (dead trees, old hardwood trees, etc.) during thinning operations and final felling. The retention areas/features have by definition unique qualities not shared which the remainder of the stand, such as tree species composition, age, tree dimensions, etc. Naturally, applying a silvicultural decision based on the average stand condition would be detrimental for the biodiversity values related to these retention areas and retention features.

A major trend in forestry which aims to tackle various environmental and social problems is moving from stand-level management toward a landscape perspective in forest planning. With the rapid development in remote sensing and operations research, it is likely that silviculture soon could be optimized in relation to neighbouring stands and the goals set on landscape level. This kind of optimization procedure may have practical relevance for evaluating different management alternatives for a given stand and allow tree-level management. This does not diminish the need for high-resolution information, in fact, it enhances the importance of having accurate information about the variation at stand level.

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ORCID

Magnus Persson http://orcid.org/0000-0002-5811-1462
Renats Trubins http://orcid.org/0000-0002-3810-3561
Ljusk Ola Eriksson http://orcid.org/0000-0002-1244-1722
Johan Bergh http://orcid.org/0000-0003-4723-1626
Johan Sonesson http://orcid.org/0000-0002-2018-7496
Emma Holmström http://orcid.org/0000-0003-2025-1942

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Appendix

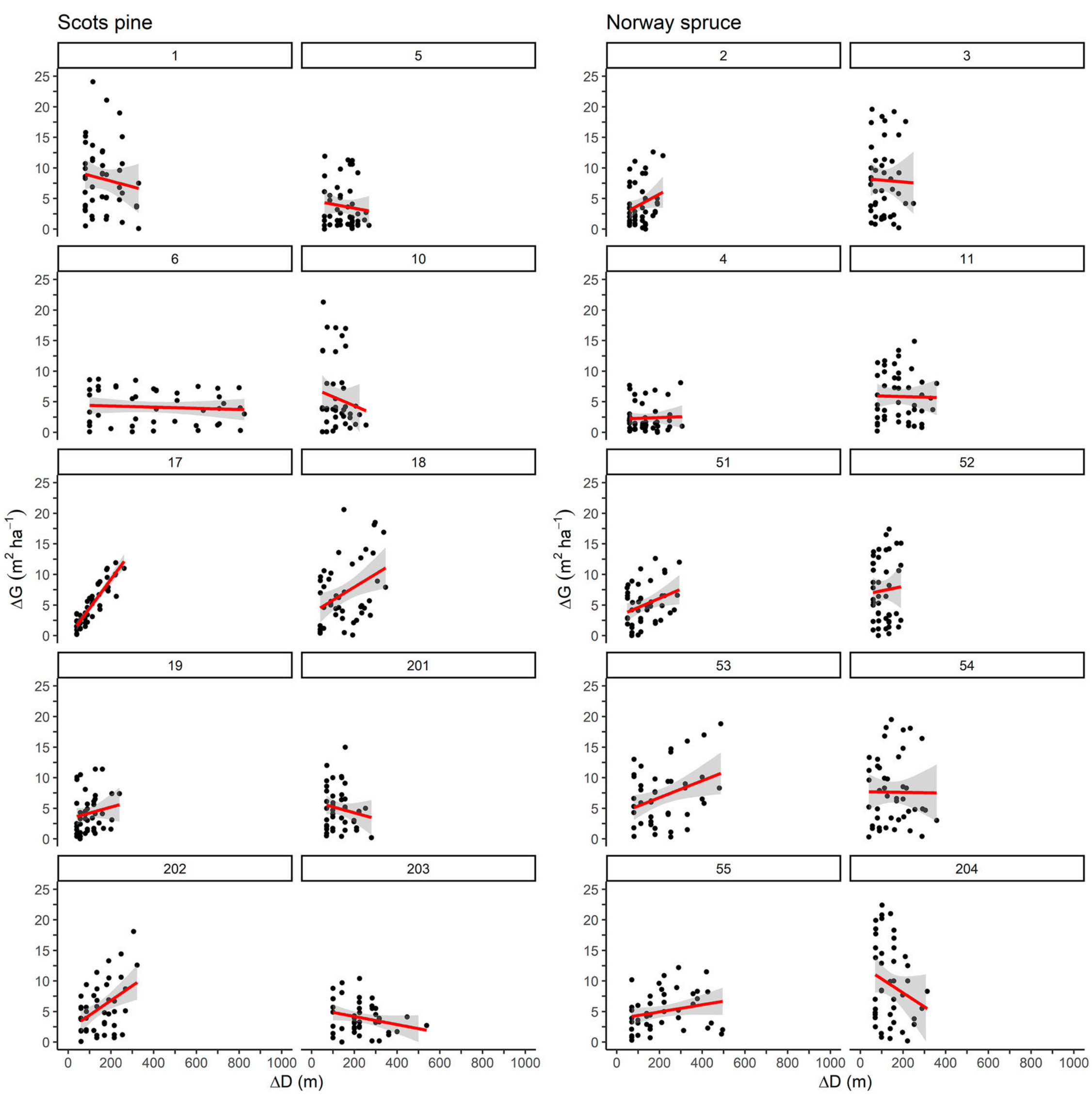

Figure A1. Pair-wise observations of difference in basal area on the y-axis and difference in Euclidean distance (ΔD) in metres on the *x*-axis for each pair of sample plot per stand. A regression line and the confidence interval of the slope have been added in order to indicate a potential presence of spatial correlation between basal area and distance between sample plots within a stand.

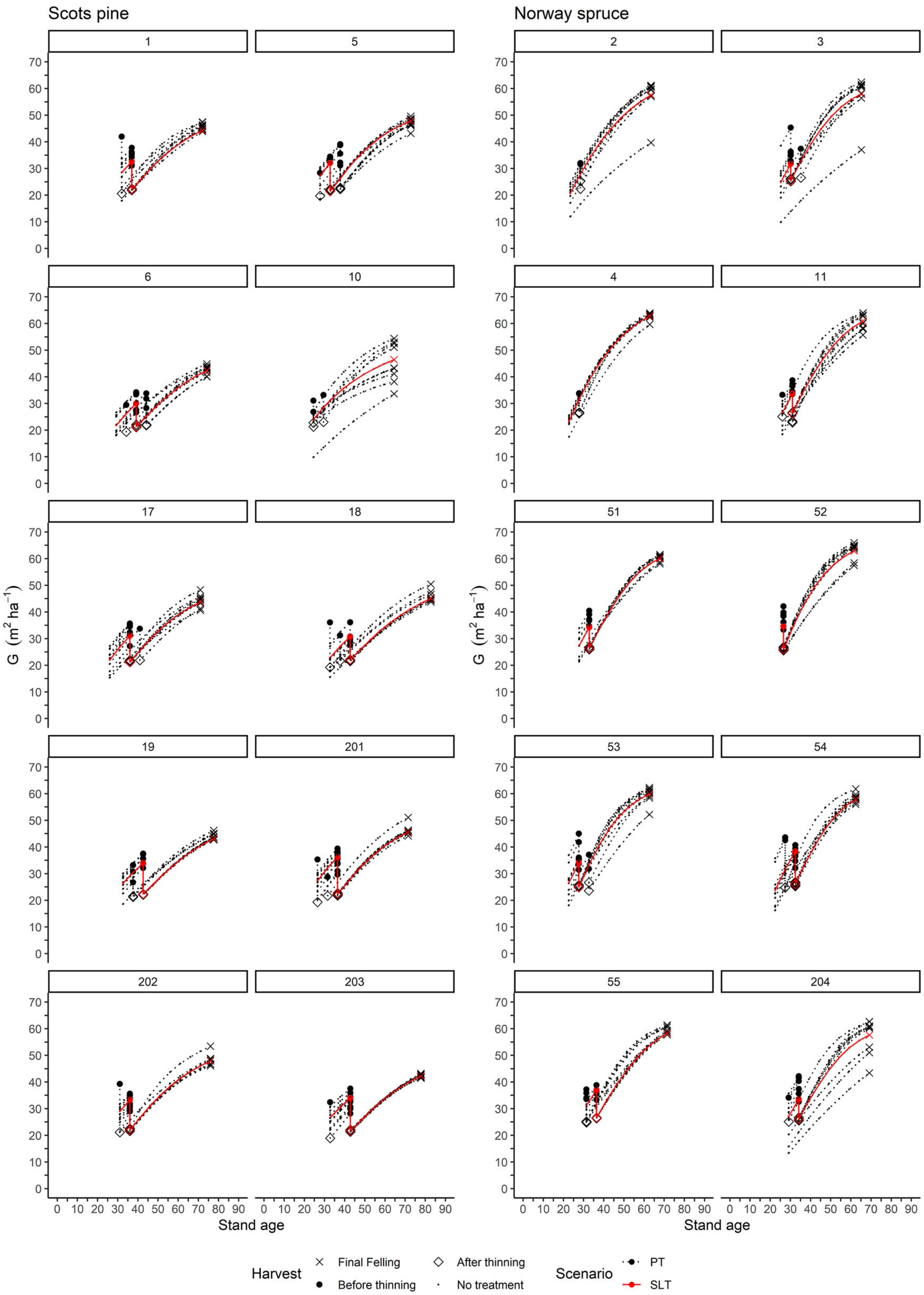

Figure A2. The thinning programme from the start of the simulation to the end of the rotation for individual stands in both SLT and PT. The development for an individual sub-area is shown for PT, while only the average stand development is shown for SLT

Table A1. Stand attributes and statistics (mean, standard deviation and coefficient of variation) at the time of the first commercial thinning. Dominant tree species are SP = Scots pine or NS = Norway spruce, Site index for the dominant species in the stand, Quadratic mean diameter (QMD), basal area (G), basal area weighted height (Hg), stem density (N) and volume (V).

Stand	Species	Site index (m)	Stand age (years)	QMD (mm)	G (m^2 ha^{-1})	Hg (m)	N (trees ha^{-1})	V (m^3 ha^{-1})
2	NS	34.1 ± 0.6 (0.02)	23	146 ± 15 (0.1)	20.6 ± 3.7 (0.18)	12.7 ± 0.6 (0.05)	1538 ± 235 (0.15)	134 ± 26 (0.2)
3	NS	33.6 ± 0.6 (0.02)	25	140 ± 16 (0.11)	24.9 ± 7.5 (0.3)	12.8 ± 0.7 (0.06)	2118 ± 528 (0.25)	164 ± 54 (0.33)
4	NS	35.1 ± 0.3 (0.01)	23	140 ± 6 (0.05)	23.4 ± 2.3 (0.1)	13.4 ± 0.3 (0.02)	1803 ± 224 (0.12)	162 ± 17 (0.1)
11	NS	34.7 ± 0.7 (0.02)	26	144 ± 12 (0.09)	26.6 ± 5 (0.19)	13.9 ± 0.7 (0.05)	2013 ± 326 (0.16)	190 ± 42 (0.22)
51	NS	33.8 ± 0.6 (0.02)	28	154 ± 15 (0.1)	27.4 ± 4.3 (0.16)	14.3 ± 0.7 (0.05)	1873 ± 462 (0.25)	199 ± 31 (0.15)
52	NS	35.9 ± 0.7 (0.02)	27	166 ± 17 (0.1)	34.7 ± 6.4 (0.18)	15.9 ± 0.8 (0.05)	2083 ± 425 (0.2)	279 ± 57 (0.21)
53	NS	34.4 ± 0.4 (0.01)	23	145 ± 10 (0.07)	26.5 ± 5.9 (0.22)	12.2 ± 0.4 (0.03)	1975 ± 232 (0.12)	165 ± 41 (0.25)
54	NS	33.4 ± 0.7 (0.02)	22	123 ± 12 (0.09)	23.8 ± 6.7 (0.28)	11 ± 0.6 (0.06)	2344 ± 302 (0.13)	138 ± 45 (0.33)
55	NS	33.3 ± 0.3 (0.01)	31	173 ± 11 (0.06)	31.2 ± 4.2 (0.13)	15.4 ± 0.4 (0.03)	1745 ± 158 (0.09)	239 ± 36 (0.15)
204	NS	33.5 ± 1.1 (0.03)	29	155 ± 21 (0.14)	27.2 ± 8.1 (0.3)	14 ± 1 (0.07)	1901 ± 435 (0.23)	196 ± 65 (0.33)
1	SP	28.1 ± 0.3 (0.01)	32	172 ± 19 (0.11)	28.5 ± 7 (0.25)	15.2 ± 0.5 (0.03)	1611 ± 566 (0.35)	207 ± 49 (0.24)
5	SP	28.7 ± 0.5 (0.02)	28	160 ± 14 (0.09)	27.3 ± 3.7 (0.13)	13.5 ± 0.5 (0.04)	1777 ± 327 (0.18)	180 ± 26 (0.15)
6	SP	26.7 ± 0.4 (0.02)	29	152 ± 12 (0.08)	21.8 ± 3.5 (0.16)	12.5 ± 0.5 (0.04)	1497 ± 342 (0.23)	135 ± 24 (0.17)
10	SP	29.6 ± 1 (0.03)	25	159 ± 27 (0.17)	24 ± 5.6 (0.23)	15 ± 1.5 (0.1)	1599 ± 238 (0.15)	176 ± 46 (0.26)
17	SP	26.4 ± 0.5 (0.02)	26	153 ± 21 (0.13)	22 ± 4.3 (0.2)	12 ± 0.5 (0.05)	1545 ± 311 (0.2)	132 ± 26 (0.2)
18	SP	26.7 ± 0.2 (0.01)	33	167 ± 25 (0.15)	22.9 ± 6.2 (0.27)	13.8 ± 0.9 (0.06)	1522 ± 632 (0.42)	154 ± 43 (0.28)
19	SP	27.3 ± 0.2 (0.01)	33	166 ± 8 (0.05)	26.4 ± 3.7 (0.14)	14.1 ± 0.3 (0.02)	1656 ± 291 (0.18)	180 ± 26 (0.14)
201	SP	28.3 ± 0.4 (0.01)	26	155 ± 15 (0.1)	27.4 ± 4.2 (0.15)	13 ± 0.6 (0.05)	1777 ± 395 (0.22)	174 ± 27 (0.15)
202	SP	28.9 ± 0.4 (0.01)	31	161 ± 8 (0.05)	29 ± 4.9 (0.17)	14.5 ± 0.4 (0.03)	1854 ± 226 (0.12)	204 ± 39 (0.19)
203	SP	26.5 ± 0.3 (0.01)	33	154 ± 12 (0.08)	26.7 ± 3.3 (0.13)	13.5 ± 0.4 (0.03)	1812 ± 253 (0.14)	177 ± 23 (0.13)

Table A2. Mean stand basal area (G) and statistic within parenthesis (standard deviation and coefficient of variation) at different time points during the simulation for each stand. The start represents the state at the start of the simulation, middle of the simulation is values from the end of the 5-year period which is closest to the middle of the full rotation and end of simulation means the 5-year period in which the final felling occurs. Dominant tree species of the stand are *SP* = Scots pine or NS = Norway spruce.

			Stand Level Thinning		Precision Thinning	
Stand	Species	Start of simulation G (m^2 ha^{-1})	Middle of simulation G (m^2 ha^{-1})	End of simulation G (m^2 ha^{-1})	Middle of simulation G (m^2 ha^{-1})	End of simulation G (m^2 ha^{-1})
2	NS	21 ± 3.7 (0.18)	45 ± 6.2 (0.14)	58 ± 6.4 (0.11)	44 ± 6 (0.14)	57 ± 6.4 (0.11)
3	NS	25 ± 7.5 (0.3)	45 ± 8.9 (0.2)	58 ± 8.3 (0.14)	44 ± 7.2 (0.16)	58 ± 7.5 (0.13)
4	NS	23 ± 2.3 (0.1)	50 ± 2.3 (0.05)	63 ± 1.3 (0.02)	50 ± 2.1 (0.04)	63 ± 1.2 (0.02)
11	NS	27 ± 5 (0.19)	47 ± 5.8 (0.12)	61 ± 4.2 (0.07)	46 ± 4 (0.09)	61 ± 2.9 (0.05)
51	NS	27 ± 4.2 (0.15)	46 ± 4 (0.09)	60 ± 2.5 (0.04)	46 ± 1.3 (0.03)	60 ± 1.2 (0.02)
52	NS	35 ± 6.4 (0.18)	49 ± 6.4 (0.13)	63 ± 4.1 (0.07)	49 ± 4 (0.08)	63 ± 2.9 (0.05)
53	NS	27 ± 5.9 (0.22)	47 ± 5.3 (0.11)	60 ± 3 (0.05)	46 ± 4.8 (0.1)	60 ± 2.9 (0.05)
54	NS	24 ± 6.7 (0.28)	41 ± 5.1 (0.12)	58 ± 3 (0.05)	42 ± 3.1 (0.07)	58 ± 1.6 (0.03)
55	NS	31 ± 4.2 (0.13)	44 ± 3.8 (0.09)	58 ± 2.5 (0.04)	47 ± 3.2 (0.07)	59 ± 1.4 (0.02)
204	NS	27 ± 8.1 (0.3)	45 ± 9.3 (0.21)	58 ± 7.9 (0.14)	44 ± 6.8 (0.15)	58 ± 6.4 (0.11)
1	SP	29 ± 7 (0.25)	34 ± 5.1 (0.15)	44 ± 3.8 (0.09)	35 ± 2 (0.06)	46 ± 1.2 (0.03)
5	SP	27 ± 3.7 (0.13)	35 ± 3.2 (0.09)	48 ± 2.8 (0.06)	33± 2.2 (0.07)	47 ± 1.8 (0.04)
6	SP	22 ± 3.5 (0.16)	29 ± 2.7 (0.09)	42 ± 2.4 (0.06)	29 ± 2.9 (0.1)	42 ± 1.8 (0.04)
10	SP	24 ± 5.6 (0.23)	39 ± 6.9 (0.18)	46 ± 7.5 (0.16)	37 ± 6 (0.16)	45 ± 7 (0.15)
17	SP	22 ± 4.3 (0.2)	30 ± 3.9 (0.13)	44 ± 4.1 (0.09)	30 ± 2.1 (0.07)	44 ± 2.2 (0.05)
18	SP	23 ± 6.2 (0.27)	33 ± 4.3 (0.13)	45 ± 3.4 (0.08)	34 ± 2.1 (0.06)	46 ± 2 (0.04)
19	SP	26 ± 3.7 (0.14)	30 ± 2.7 (0.09)	43 ± 2.7 (0.06)	31 ± 1.6 (0.05)	44 ± 1.1 (0.02)
201	SP	27 ± 4.2 (0.15)	31 ± 2.8 (0.09)	46 ± 1.7 (0.04)	32 ± 1.6 (0.05)	46 ± 1.8 (0.04)
202	SP	29 ± 4.9 (0.17)	35 ± 4.8 (0.14)	48 ± 4.6 (0.1)	35 ± 1.7 (0.05)	48 ± 2 (0.04)
203	SP	27 ± 3.4 (0.13)	29 ± 2 (0.07)	42 ± 1.4 (0.03)	29 ± 0.3 (0.01)	42 ± 0.6 (0.01)