Forest Ecology and Management 489 (2021) 119040

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Varying rectangular spacing yields no difference in forest growth and external wood quality in coniferous forest plantations

Mostarin Ara [a,*], Ignacio Barbeito [a,b], Björn Elfving [c], Ulf Johansson [d], Urban Nilsson [a]

[a] Swedish University of Agricultural Science, P.O. Box 49, SE-23053 Alnarp, Sweden
[b] Université de Lorraine, AgroParisTech, INRAE, UMR Silva, Nancy, France
[c] Swedish University of Agricultural Science, SE-90183 Umeå, Sweden
[d] Swedish University of Agricultural Sciences, SE-31325 Simlångsdalen, Sweden

ARTICLE INFO

*Keywords:*
Lodgepole pine
Norway spruce
Scots pine
Planting design
Stand heterogeneity
Stem ovality

ABSTRACT

Historically square or almost square spacing design has been used in plantation forest, as it has been claimed to maximize productivity. In this study, based on field experiments established in the mid-1980s, we tested the effect of square or different rectangular planting designs (2 × 2, 1.33 × 3, 1 × 4, 0.8 × 5, 1.46 × 1.46 × 4 m) on productivity, stand heterogeneity, and external wood properties of three coniferous species: Scots pine, Lodgepole pine, and Norway spruce. Stand production (volume, diameter), external wood properties (ovality, branch thickness, living crown height, height-diameter ratio), and stand heterogeneity (Gini coefficient) were not significantly affected by the different rectangular designs. Based on this evidence, we propose that more flexibility is available than previously thought for rectangular spacing layouts and consequently for the choice of planting spots and machinery operations.

## 1. Introduction

Competition among trees is a complex and dynamic process. It is a key variable in tree and forest stand growth and influenced by several factors including initial spacing (Weiskittel et al., 2011). Initial spacing determines the number of trees per unit area. Several studies have confirmed the effect of initial spacing on the growth and external wood quality of Scots pine, Norway spruce, and Lodgepole pine (Pettersson, 1993; Pfister et al., 2007; Kellomäki et al., 1989; Liziniewicz et al., 2012). As initial spacing pre-determines the productivity and quality of a future stand, it is important to regulate the initial spacing during the establishment of forest plantations. The initial density of trees at the time of establishment has been of long interest to plantation managers but the specific geometry of planting arrangements has received less attention.

The most common planting pattern used is a square, or almost square, design, where the spacing between and within rows of trees is similar. In rectangular spacing, the distance between rows is different from the spacing within rows, but the same number of trees per hectare can result from different rectangularity (Sharma et al., 2002). Rectangular spacing facilitates forest operations including the movement of machinery between rows, helping reduce the area disturbed after soil scarification. Rectangular or irregular spacing also gives more flexibility when choosing planting spots. Although rectangular spacing has some indisputable advantages, square or nearly square designs are often recommended. Rectangular spacing is often discouraged because of a belief that it reduces productivity compared to square designs because the growing space between rows would not be used efficiently.

Several studies have found no effect of rectangularity on stand-level growth or external wood quality. A study of Loblolly pine (*Pinus taeda* L.) in four sites in North Carolina and Virginia showed no difference among rectangular spacing patterns on tree volume growth but differences in the crown form (Sharma et al., 2002). A study of maritime pine (*Pinus pinaster* L.) in southern France found no difference in stand characteristics between square and rectangular planting designs (Paulista et al., 1991). In Lithuania, a study of Scots pine showed no effect of rectangular planting design on stem quality (Malinauskas, 2003). Besides these studies on conifers, several publications have examined the effect of rectangular spacing on broadleaved species. Gerrand and Neilsen (1998) found no difference in the growth and branch thickness between square and rectangular designs in *Eucalyptus* spp. in Tasmania. Experiments on hybrid poplar in British Columbia (Johnstone, 2008) found no growth differences between rectangular and square spacing patterns. All these studies compared the rectangular spacing effect on a single species.

* Corresponding author.
*E-mail address:* mostarin.ara@slu.se (M. Ara).

https://doi.org/10.1016/j.foreco.2021.119040
Received 17 December 2020; Received in revised form 1 February 2021; Accepted 3 February 2021
Available online 26 February 2021

However, to our knowledge, the effect of varied rectangular spacing (mild vs extreme) has never been experimentally confirmed for different species.

Swedish forests are dominated by planted Norway spruce (NS) and Scots pine (SP). Northern Sweden is dominated by Scots pine whereas Norway spruce is more common in southern Sweden. The North American Lodgepole pine (LP) (*Pinus contorta* Dougl. var. *latifolia*) was introduced to Sweden on a large scale in the mid-1960s and used as a substitute for the native Scots pine (Engelmark et al., 2001) which means it is planted mostly in northern Sweden. During the planting of seedlings, a square rectangular design in a 2 × 2 m arrangement is traditionally used as it is claimed to maximize productivity. No study has yet tested the validity of this claim for coniferous forest plantations at high latitude.

Considering the research gap mentioned above, we aimed to test the impact of different planting designs on the growth and external wood quality in three coniferous plantations in Sweden, on each of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L.), and Lodgepole pine. We answered the following question: For a given species, is there any significant difference in volume production, external wood quality, and stand heterogeneity among different planting designs?

## 2. Materials and methods

### 2.1. Experimental design

In the mid-1980s, three spacing trials were established in Sweden. Lodgepole pine was planted in northern Sweden, Scots pine in central Sweden, and Norway spruce in southern Sweden (Fig. 1). Geographical conditions are very different in three experimental sites in terms of temperature and precipitation. Mean annual temperatures during the period 1980–2010 were 2.4, 4.4 and 7.8 °C and mean annual precipitation during the same period were 609, 721 and 1006 mm year$^{-1}$ in climate stations close to the lodgepole pine, Scots pine and Norway spruce stands respectively. The planting was done in a complete randomized block design with three replicates in each trial and five square and rectangular designs within each block (Fig. 1). The five designs were: square spacing 2 × 2 m; single-row spacing 1.33 × 3, 1 × 4 and 0.8 × 5 m; double-row spacing 1.46 × 1.46 × 4 m. To minimise the effect of neighbouring plots, one row of trees was planted as a buffer zone surrounding each treatment. Each plot was around 20 m × 30 m and the initial planting density was 2500 seedlings ha$^{-1}$ for all treatments.

### 2.2. Field measurements

Measurements were done between 2008 and 2020 (Table 1). The following variables were recorded: diameter at breast height (DBH), tree height (H), height to the living crown (HL), and diameter of branch thickness (BT) of the two thickest branches in branch-whorls closest to the breast height along and across the rows. DBH was measured for every planted tree using callipers in two perpendicular directions (along and across the row) and recorded to the nearest mm. BT was registered in all experiments in 2020 and we measured diameter of two thickest branch for each sample tree. In addition to tree species, status (removed, retained, dead), and the damage was recorded. For about 20 selected sample trees per plot, H, HL, and BT were measured. These trees were selected according to tree size (DBH) with a higher probability for larger trees (Nilsson et al., 2010). If damage affected height or diameter growth, then those trees were not considered for sampling. One thinning was carried in the Norway spruce and Scots pine stands. First thinning was done at age 27 in Scots pine and at age 29 in Norway spruce. No commercial thinning was done in Lodgepole pine stands. The percentage of removed basal area was 28–35% for Norway spruce and 26–37% for Scots pine.

**Table 1**
Trees species, location, year of the establishment, time of measurement, and site index for the experimental sites

| Site no | Location | Year of establishment | Tree species | Site index[1] | Years of measurements | |
|---|---|---|---|---|---|---|
| | | | | | Year 1 | Year 2 |
| 1 | Northern Sweden | 1982 | Lodgepole pine | 28 | 2011 | 2020 |
| 2 | Central Sweden | 1983 | Scots pine | 30 | 2008 | 2020 |
| 3 | Southern Sweden | 1983 | Norway spruce | 39 | 2008 | 2016[2] |

[1] Source of site indices: LP: Liziniewicz et al. (2016), SP: Elfving and Kiviste (1997), NS: Elfving (2003).
[2] Branch thickness (BT) was measured in 2020.

### 2.3. Data analysis

The single tree stem volume of Norway spruce and Scots pine was estimated using the functions developed by Brandel (1990) while Lodgepole pine volume was estimated with a function developed by Eriksson (1973). DBH, HT, and HL were used to calculate Norway spruce stem volume, while only DBH and HT were used for Scots pine and Lodgepole pine calculations. Stem volume for all trees was estimated by assigning volume to caliper trees in diameter classes using an algorithm described in Nilsson et al. (2010). In addition to volume production,

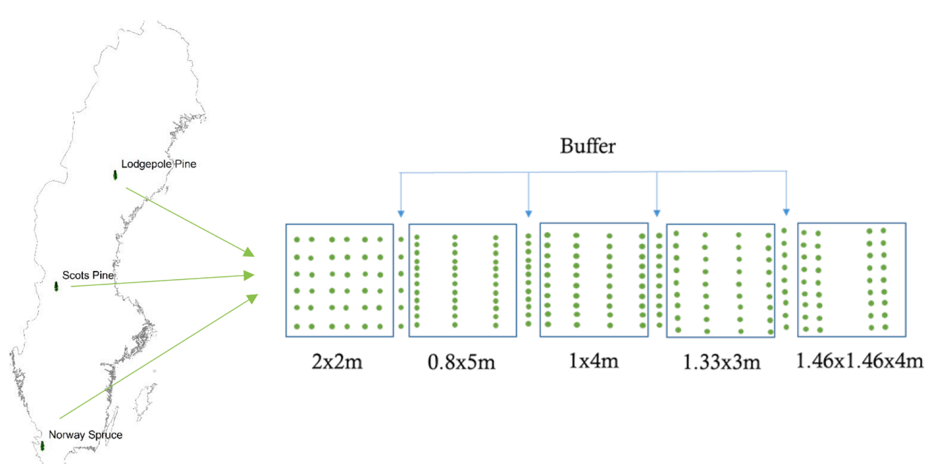


**Fig. 1.** Location of the three experiments of conifer plantations in Sweden and the five planting designs tested in each site.

Periodic Annual Increment (PAI) was calculated for each species using the total volume yield difference between the two measurements. Site index (top height (m) at total age 100 years) was estimated with generally applied site curves from measured heights at the last measurement.

Along with stem volume production, we also analysed the diameter distribution of individual trees to observe the effect of planting design on stand heterogeneity by fitting a two-factor Weibull distribution (with shape and scale parameters) to each plot’s distribution. This distribution was chosen because it is flexible with desirable properties and logically defined on an interval with fixed end-points (Mukhopadhyay, 2000). The parameter estimates for each treatment were determined using maximum likelihood estimation (Mukhopadhyay, 2000). The Gini coefficient can ranges from 0 to 1, where 0 indicates that all trees are of equal size and 1 indicates perfect inequality. The greater the value of the Gini coefficient, the more structurally heterogeneous the stand is (Cordonnier and Kunstler, 2015).

Individual tree diameters were used to calculate shape and scale parameters for each planting design for all the replicates and species.

Stand heterogeneity was also quantified computing Gini coefficients of stem diameters within the different stands and rectangular designs. The *ineq* package in R version 3.2.5 (R Core Team, 2015) was used to calculate the Gini coefficients.

The effects of different planting designs on external wood-quality properties that may affect the value of lumber and stability of the tree and stand was described by stem ovality, branch thickness (BT) at breast height, height to the first living crown (HL), and height-diameter ratio (HD).

Stem ovality was calculated using the two-directional DBH of individual trees. Relative ovality was calculated by subtracting the two-directional diameter of the tree and divided it by the average diameter of the tree. The mean value of the thickest branch diameter (BT) was calculated for each planting design. The height of the lowest living branch of sample trees was measured and the HD ratio was calculated for all trees using calipered diameter and estimated height. Stand-level values for all external wood quality parameters were calculated by averaging individual tree’s values.

A linear mixed model was chosen to study the effect of planting design on response variables because of the hierarchical structure of the data. The response variables were total volume production, PAI, spatial heterogeneity in diameter, and stand-level external wood quality. Block (replication) was used as a random effect and planting design as an independent variable. The model was run separately for each species using the *lmerTest* R package. Differences among planting designs for all measured variables were analysed using ANOVAs. A significance level of $p = 0.05$ was chosen as a threshold for all the analyses. A mixed model with ANOVA analysis follows as below:

$$y_{ijk} = \mu + b_k + \alpha_i + \varepsilon_{ijk} \tag{1}$$

where $y_{ijk}$ is the response variable (total volume production, PAI, stand heterogeneity, or external wood quality) of the *k*th replicate of spacing design ($k = 1.0.3$), $\alpha_i$ is the fixed effect for the *i*th initial spacing treatment ($i = 1,\ldots,5$) and $\varepsilon_{ijk}$ is the error term.

## 3. Results

### 3.1. Volume production and periodic annual increment

Total volume production was not significantly affected by the planting design for any of the species and for any of two measurements assessed in this experiment (Fig. 2; Table 2). PAI was not significantly affected by different planting design for any of the species (Fig. 3; Table 2).

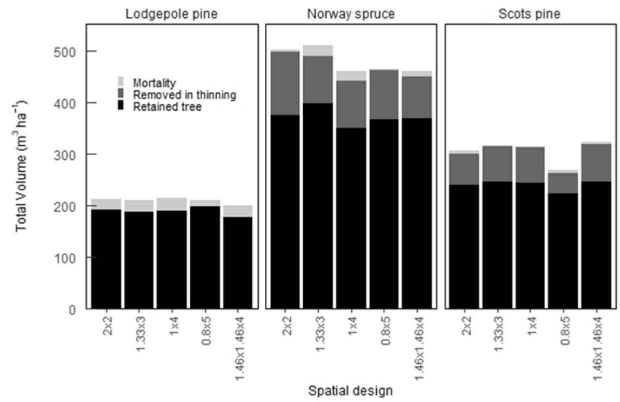


**Fig. 2.** Total volume production at the last measurement in 2016 (Norway spruce) or 2020 (Lodgepole pine and Scots pine) using different planting designs.

**Table 2**
P-values for ANOVAs testing differences among different spacing patterns for growth parameter of Norway spruce, Lodgepole pine, and Scots pine

| Tree species | P-value | | | | | |
|---|---|---|---|---|---|---|
| | Volume | PAI | Shape | Living crown height | HD | Gini index |
| Norway spruce | 0.93 | 0.80 | 0.15 | 0.32 | 0.26 | 0.56 |
| Lodgepole pine | 0.98 | 0.94 | 0.34 | 0.81 | 0.60 | 0.32 |
| Scots pine | 0.38 | 0.26 | 0.21 | 0.27 | 0.87 | 0.50 |

### 3.2. Stand heterogeneity and diameter distribution

The diameter distribution and heterogeneity of stands were not affected by planting design for any of the tree species (Table 2). The Weibull distribution shape parameter and the Gini index did not indicate any differences in diameter distribution among planting designs in the last measurement (Fig. 3; Table 2) or in the first measurement (data not shown).

### 3.3. External wood quality

External wood quality properties measured in this study did not depend on different planting designs for Norway spruce, Scots pine, and Lodgepole pine. The spatial design has an insignificant effect on the branch thickness (BT) and there was no difference in branch thickness depending on their orientation to the row (Table 3). Stem ovality also did not differ significantly at any planting design for all the species in the last measurement (Table 3) or in the first measurement (data not shown).

The height of the living crown (Fig. 3) and height-diameter ratio (Fig. 4) were also not significantly different among different planting designs for any of the species used in this experiment (Table 2).

## 4. Discussion

### 4.1. Volume production and periodic annual increment

For a given site quality, a square planting design might be expected to produce faster growth as the stand reaches the canopy closure faster. However, our study provides experimental evidence contrary to that claim. We did not find a significant difference in the volume production of three conifer species between the square and the various rectangular designs tested. Our finding agrees with several previous studies where different rectangular designs and species were used. In Finland, the

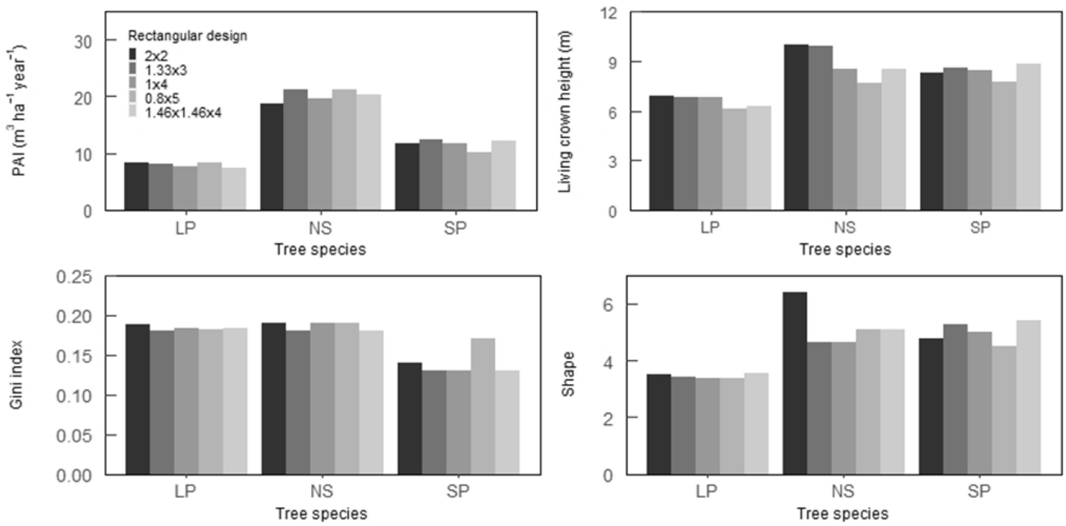


**Fig. 3.** Periodic annual increment (PAI), Living crown height, Gini index and shape of the Weibull distribution of Lodgepole pine (LP), Norway spruce (NS), and Scots pine (SP) in last measurement under different planting design.

**Table 3**
External wood quality parameters (stem ovality and BT) of Norway spruce, Scots pine, and Lodgepole pine and corresponding P-values from ANOVA analysis at different spacing designs

| Rectangular design | Norway spruce | | | Scots pine | | | Lodgepole pine | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ovality (%) | BT (mm) | | Ovality (%) | BT (mm) | | Ovality (%) | BT (mm) | |
| | | Along | Across | | Along | Across | | Along | Across |
| 2 × 2 | 3.1 | 5.1 | 5.1 | 2.2 | 13.1 | 13.1 | 3.4 | 16.6 | 16.6 |
| 1.33 × 3 | 4.1 | 5.2 | 5.5 | 2.3 | 16.1 | 15.5 | 3.6 | 15.7 | 15.5 |
| 1 × 4 | 4.0 | 4.2 | 5.1 | 2.2 | 13.9 | 14.0 | 3.6 | 16.2 | 16.6 |
| 0.8 × 5 | 3.4 | 3.3 | 4.2 | 2.2 | 14.9 | 14.8 | 4.6 | 16.1 | 16.3 |
| 1.46 × 1.46 × 4 | 3.3 | 5.0 | 5.8 | 2.2 | 14.8 | 15.2 | 4.6 | 16.6 | 17.1 |
| p-value | 0.38 | 0.21 | | 0.42 | 0.96 | | 0.84 | 0.58 | |

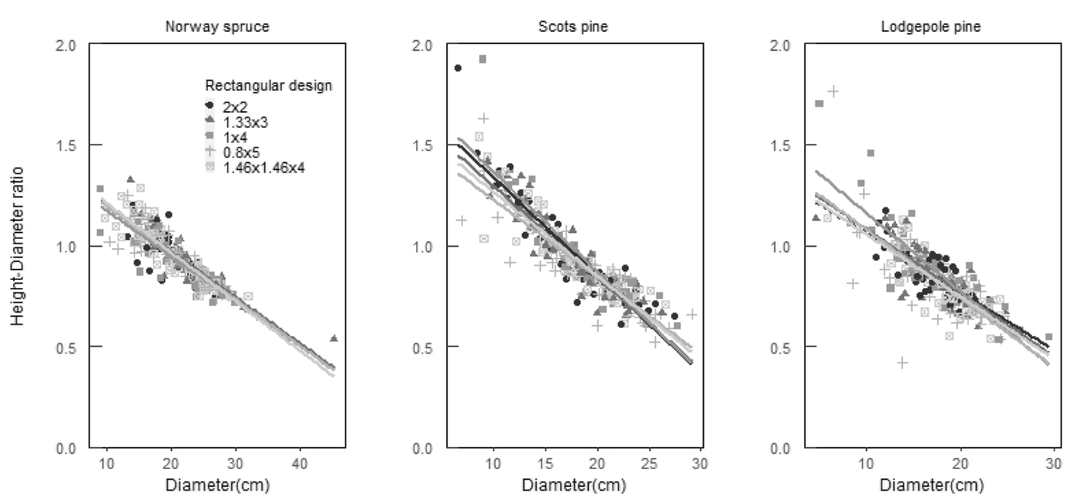


**Fig. 4.** Height-diameter ratio (HD) as a function of the diameter (DBH) for Norway spruce, Scots pine, and Lodgepole pine (left to right respectively) among different planting designs.

effect of planting design was investigated in a 17-year-old Scots pine plantation using three different planting designs with a tree density of 2500 trees ha$^{-1}$. The planting designs used were 2 × 2 m, 1.15 × 3.5 m, and 0.8 × 5m (Salminen and Varmola,1993). Result from our study support this results since not even the most extreme rectangular design tested (0.8 × 5 m) affected stem-wood production or stem-wood growth significantly. Niemistö (1995b) used 2 × 2 m, 1.15 × 3.5 m, and 0.8 × 5 m spacing designs in a silver birch experiment in Finland. The age of the birch stand ranged between 17 and 22 years at different sites. Niemistö (1995b) found slightly less volume increment when row to row distance exceeded tree to tree distance by three times or more. This was not the case in our study. But the Niemistö found that the effect of rectangular spacing on volume increment started to diminish when birch stands started to get older. The reason could be that with increasing age, birch was abler to use the free space left between rows.

Sharma et al. (2002) studied Loblolly pine in Virginia and North Carolina from age 5 to 16 years and used two different rectangular spacing, 1.83 × 2.44 m, and 1.22 × 3.66 m. Gerrand and Neilsen (1998) compared production between square and rectangular planting design using the Scotch plaid design for 5-year-old *Eucalyptus* spp. in Tasmania. Also, Johnstone (2008) studied the growth and production of hybrid poplar at different ages (1–9 years) in British Columbia with a spacing of 1.5 × 4.5 m and 2.25 × 3 m. Paulista et al. (1991) studied maritime pine in France using two different rectangular designs (2 × 2 and 1 × 4). No statistically significant difference was found in volume production among different rectangular designs for any of these studies.

Not even extreme rectangular designs (0.8 × 5 m) yielded differences in growth and production of the three different tree species in our study. Similar results at this spacing were found for Scots pine (Salminen and Varmola, 1993) in Finland. Several studies on various species have shown no effect of spacing during planting on growth or wood quality (Scots pine & Norway spruce: Pettersson (1993), Norway spruce: Pfister et al. (2007), Scots pine: Kellomäki et al. (1989), Lodgepole pine: Liziniewicz et al. (2012)). Therefore, the findings of our study confirmed previous results indicating that the number of trees per unit area is important but that the spatial arrangement of trees up to a rectangularity of 0.8 × 5 m is not.

### 4.2. Stand heterogeneity and external wood quality

We found no effect of rectangular design on individual diameter distribution for the three species used in this study. This finding is consistent with previous studies on birch (Niemistö, 1995b) in Finland where three different rectangular designs were used. A similar lack of effect of rectangular design on diameter distribution was also observed at different ages (5–16) of loblolly pine in Virginia and North Carolina (Sharma et al., 2002; see above).

Salminen and Varmola (1993) found a significant effect of rectangular design on the stem ovality of 17-year-old Scots pine in Finland. This observation disagrees with our findings. This could be explained by the age of the experiments. The Scots pine plantation in Finland was much younger than our plantation (17 compared to more than 30 years) and ovality may be more expressed in young trees. Niemistö (1995a) found no effects on the stem ovality for birch when the stand age was between 14 and 17 years. Moreover, Malinauskas (2003) did not find any effects of planting design on the ovality of 25-year-old Scots pine in Lithuania. In our study, there were no significant effects on stem ovality in the Norway spruce and Lodgepole pine stands which indicates that these species react similarly to Scots pine and birch to rectangular planting designs.

We found no significant effect of planting design on branch diameter across or along rows for any of the three species examined in this study. Salminen and Varmola (1993) found a tendency for thicker branches across the rows than along the rows for Scots pine but the difference was minor and not statistically significant. Gerrand and Neilsen (1998) also found no effect of rectangularity on the branch thickness of *Eucalyptus* species.

### 4.3. Limitations of the study and opportunities for alternative rectangular planting designs

We estimated PAI from the last two measurements when the stands were around 30 years old. However, the normal rotation length of Norway spruce, Scots pine, and Lodgepole pine in Sweden is between 50 and 80 years. Therefore, the experimental stands will not be harvested for several decades. Even if the spacing of trees within rectangularly-spaced rows has increased due to thinning, future tree development might be affected by the rectangular design.

Our study, together with many other studies in Europe and North America, indicates no effect of rectangular design on mid-rotation growth, external wood quality, and stand heterogeneity of coniferous plantations. Without losing yield or reducing external wood quality, rectangular spacing provides an opportunity for a flexible plantation layout. One potential option that is derived from this is the opportunity to select the best microsites instead of planting systematically in square spacing. Moreover, the area between rows may facilitate intermediate forest operations such as commercial thinning and mid-rotation fertilization. Five-meter distances between tree rows may reduce damage during selective thinning operations. Also, continuous scarification with a 5-meter distance between rows will reduce the total disturbed soil area as compared to a square design.

## 5. Conclusions

The different planting designs did not affect the volume production, external wood properties, or stand heterogeneity of the three conifer species studied. Consequently, different rectangular designs could be used without a loss in yield or external wood quality and could facilitate higher flexibility of plantation and machinery operations. The results provided experimental evidence showing the potential of applying different rectangular designs in plantation forests.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

Thanks to all who helped in forest data collection. Thanks to FRAS (Future Silviculture of southern Sweden) research programme to fund M.A to conduct this study. We also thank two anonymous reviewers for providing valuable suggestions in this article.

## References

Brandel, G., 1990. Volume functions for individual trees, Scots pine (Pinus sylvestris), Norway spruce (Picea abies), and birch (Betula pendula & Betula pubescens). Department of Forest Yield Research. Report, 26, Garpenberg: Swedish University of Agricultural Sciences.

Cordonnier, T., Kunstler, G., 2015. The Gini index brings asymmetric competition to light. Perspect. Plant Ecol., Evol. System. 17, 107–115.

Elfving, B., 2003. Övre höjdens utveckling i granplanteringar. SLU, Inst för skogsskötsel, Arbetsrapporter. 185, 1–8 (in Swedish).

Elfving, B., Kiviste, A., 1997. Construction of site index equations for *Pinus sylvestris* L. using permanent plot data in Sweden. For. Ecol. Man 98, 125–1124.

Engelmark, O., Sjöberg, K., Andersson, B., Rosvall, O., Ågren, G.I., Baker, W.L., Barklund, P., Björkman, C., Despain, D.G., Elfving, B., Ennos, R.A., Karlman, M., Knecht, M.F., Knight, D.H., Ledgard, N.J., Lindelöw, Å., Nilsson, C., Peterken, G.F., Sörlin, S., Sykes, M.T., 2001. Ecological effects and management aspects of an exotic tree species: the case of Lodgepole pine in Sweden. For. Ecol. Manage. 141 (1–2), 3–13. https://doi.org/10.1016/S0378-1127(00)00498-9.

Eriksson, H., 1973. Volymfunktioner för stående träd av ask, asp, klibbal och contortatall. Skogshögskolan, Inst. f. skogsproduktion, Rapporter och Uppsatser 26, 26 s., Stockholm (In Swedish).

Gerrand, A.M., Neilsen, W.A., 1998. Comparing square and rectangular spacings in Eucalyptus nitens using a Scotch plaid design. For. Ecol. Manage. 129 (1–3), 1–6. https://doi.org/10.1016/S0378-1127(99)00166-8.

Johnstone, W.D., 2008. The effect of initial spacing and rectangularity on the early growth of hybrid poplar. West. J. Appl. For. 23 (4), 189–196.

Kellomäki, S., Oker-blom, P., Valtonen, E., Nen, V., 1989. Structural development of Scots pine stands with varying initial density: effect of pruning on branchiness of wood. For. Ecol. Manage. 27, 219–233.

Liziniewicz, M., Ekö, P.M., Agestam, E., 2012. Effect of spacing on 23-year-old Lodgepole pine (Pinus contorta Dougl. var. latifolia) in southern Sweden. Scand. J. For. Res. 27 (4), 361–371. https://doi.org/10.1080/02827581.2011.639798.

Liziniewicz, M., Nilsson, U., Agestam, E., Ekö, P.M., Elfving, B., 2016. A site index model for Lodgepole pine (Pinus contorta Dougl. var. latifolia) in northern Sweden. Scand. J. For. Res. 31 (6), 583–591.

Malinauskas, A., 2003. Influence of initial density and planning design on the quality of Butt Logs in Scots Pine (Pinus sylvestris L.) plantations. Baltic Forestry 9 (2), 10–15.

Mukhopadhyay, N., 2000. Probability and Statistical Inference. Marcel Bekker Inc, NY.

Niemistö, P., 1995a. Influence of initial spacing and row-to-row distance on the crown and branch properties and taper of silver birch (*Betula pendula*). Scand. J. For. Res. 10 (1–4), 235–244.

Niemistö, P., 1995b. Influence of initial spacing and row-to-row distance on the growth and yield of silver birch (*Betula pendula*). Scand. J. For. Res. 10 (1–4), 245–255.

Nilsson, U., Agestam, E., Ekö, P.-M., 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 programs on stand level gross- and net stem volume production. Studia Forstalia Suecica 219, 1–46.

Pettersson, N., 1993. The effect of density after precommercial thinning on volume and structure in Pinus sylvestris and Picea abies stands. Scand. J. For. Res. 8 (4), 528–539.

Pfister, O., Wallentin, C., Nilsson, U., Ekö, P.M., 2007. Effects of wide spacing and thinning strategies on wood quality in Norway spruce (Picea abies) stands in southern Sweden. Scand. J. For. Res. 22 (4), 333–343. https://doi.org/10.1080/02827580701504951.

Paulista, U.E., Em, P.D.E.P., Biológicas, C., 1991. Effects of plantation density and spacing on competitive interaction among half sib families of maritime pine. Can. J. For. Res 22, 482–489.

R Core Team, 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Salminen, H., Varmola, M., 1993. Influence of initial spacing and planting design on the development of young Scots pine (Pinus sylvestris L.) stands. Silva Fennica 27 (1), 21–28.

Sharma, M., Burkhart, H.E., Amateis, R.L., 2002. Spacing rectangularity effect on the growth of loblolly pine plantations. Can. J. For. Res. 32 (8), 1451–1459. https://doi.org/10.1139/x02-079.

Weiskittel, A.R., Hann, D.W., Kershaw Jr, J.A., Vanclay, J.K., 2011. Forest Growth and Yield Modeling. John Wiley & Sons, United States.