Scandinavian Journal of Forest Research

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

Increasing production value in Scots pine plantation through mixing with lodgepole pine

Johan Kroon, Urban Bergsten & Johan Sonesson

To cite this article: Johan Kroon, Urban Bergsten & Johan Sonesson (2019): Increasing production value in Scots pine plantation through mixing with lodgepole pine, Scandinavian Journal of Forest Research

To link to this article: https://doi.org/10.1080/02827581.2019.1695909

Published online: 03 Dec 2019.

Submit your article to this journal

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=sfor20

SCANDINAVIAN JOURNAL OF FOREST RESEARCH
https://doi.org/10.1080/02827581.2019.1695909

Increasing production value in Scots pine plantation through mixing with lodgepole pine

Johan Kroon[a,b], Urban Bergsten[c] and Johan Sonesson[d]

[a]Skogforsk, Svalöv, Sweden; [b]Department of Forestry and Wood Technology, Linnaeus University, Växjö, Sweden; [c]Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden; [d]Skogforsk, Uppsala, Sweden

ABSTRACT

Mixing tree species could be a silviculture model that allows early harvest of short-rotation trees, while longer-rotation crop trees remain in the stand. We examined the effects on growth and tree characteristics in a planted experiment with lodgepole pine (LP) and elite-bred Scots pine (SP) in mixed (50/50) and monospecific plots in three different spacings (at 28 years of age after planting). The future development under different thinning regimes, including net present value for one rotation, was analyzed using the Heureka simulation software. As expected, LP had higher survival and initially more rapid growth than SP, with highest stand productivity and biomass production in LP monoculture during a rotation period as a result. However, intimate mixtures of SP and LP at the two widest spacings could give greater production and economic benefits, compared to SP in monoculture. It seems that elite-bred SP will differ in competitiveness against LP, depending on spacing for growth and some quality traits (branch and bark thickness, height of green crown). The findings support developing management systems for combining sparsely planted, and expensive, elite-bred SP in mixture with other trees that maintains high stem volume production and secures certain properties of trees and stands.

ARTICLE HISTORY
Received 31 January 2019
Accepted 14 November 2019

KEYWORDS
Pinus contorta; *Pinus sylvestris*; monospecific; species mixture; plantation spacing; growth and yield; silviculture regime

Introduction

The transition from a fossil-based to a bio-based economy requires rapid development of technology to produce various bio-based products and chemicals. This in turn is expected to increase the harvest of forest biomass and put more pressure on forest-based feedstock (Börjesson et al. 2017). The feedstock strategy to this industry should therefore rely not only on biomass/wood production but also on properties of tree parts as engineering material (Backlund et al. 2014b). It could create new demands on forest management, e.g. considering rotation periods, biomass production over time and the properties of the produced material. As a consequence, silvicultural regimes need to meet the feedstock aspects of the new bio-economy. Such regimes could include higher stand stem density and more biomass harvest in early thinnings, instead of pre-commercial thinnings, or a shortening of the rotation time in stands with high biomass, to ensure biomass supply and a more tree-oriented than stand-oriented production to enable more specific material characterization of the produced biomass.

Silviculture with a mixture of tree species can give future opportunity to develop forestry regimes that enhance production value, as it provides a more diverse population of trees. Mixing tree species could be another silvicultural tool that allows early harvest of short-rotation trees, while leaving long-rotation final crop trees remaining in the stand. The creation of mixed stands with high production will be highly dependent on the competitiveness among tree species and how this is handled in the silvicultural system (Pretzsch 2017; Zeller et al. 2017). Mixed forests with different tree species could benefit wood production, economy, and other ecosystem services (Griess and Knoke 2011; Felton et al. 2016; Klapwijk and Björkman 2018). A mixture of tree species can also be motivated when economy or seed shortage motivates a sparse use of some species, as could be the case for improved orchard seeds for certain species, at least in some years (Karlsson and Rosvall 2010). Mixing species could give valuable stand effects, both in terms of stand productivity and tree/wood properties, especially when higher levels of stand density, standing volume and yield are reached (Pretzsch and Rais 2016). The product quality of a tree is affected by its structural characteristics as that influences wood structure and other important properties of the stem. Two trees may have equivalent volumes, despite having large differences in both height and diameter. Although both may yield the same total volume of material if chipped, the differences in stem form described by the height to diameter relationship at 1.3 m can have a large impact on conversion to solid wood products. The final yield of merchantable volume and the value of products are much dependent on conversion methods. Experiments of pine in Sweden have shown significant effects of plant density on yield and stem traits, as spacing affects the biomass allocation throughout the stem (Agestam et al. 1998; Egbäck et al. 2012; Liziniewicz et al. 2012). Wood properties such as wood density, fiber length and knottiness are also expected

CONTACT Johan Kroon johan.kroon@skogforsk.se Skogforsk, Ekebo 2250, SE-268 90 Svalöv, Sweden; Department of Forestry and Wood Technology, Linnaeus University, SE-351 95 Växjö, Sweden

© 2019 Informa UK Limited, trading as Taylor & Francis Group

to be positively correlated with stand stem density (Karlsson et al. 2013). Spacing-genetic studies in Scots pine (*Pinus sylvestris* L., SP) generally show low to moderate interaction effects between genetic entries and spacings (Persson et al. 1995; Gerendiain et al. 2009; Gort and Gerendiain 2009; Egbäck et al. 2012).

Northern Sweden has few native tree species. It has also become clearer that the production capacity of the native tree species can be reduced with an increased damage picture caused mainly by fungi and game. Since the beginning of the 2000s, extensive fungal infestations have been reported in SP in Northern Sweden (Samils et al. 2018). Also, there is an escalating problem with high grazing pressure on SP in Sweden, whereas the non-native tree species lodgepole pine (*Pinus contorta* Dougl. var. latifolia Engelm., LP) is less exposed to ungulate browsing. Extending the use of non-native tree species can help to maintain forest production in these areas. A mixed tree species stock could utilize a high production of LP as a reserve if the SP is damaged. Compared to SP, LP has 30–40% greater wood production, shorter rotation time, similar wood properties and capacity to resist the harsh conditions and diseases in northern Sweden (Elfving et al. 2001).

Increased value on SP could be achieved by adding LP seedlings in mixed SP-LP tree stands, with higher stand density. A cost-effective silvicultural system could be to plant genetically improved SP in a sparse mixture with LP, which might enable: (i) efficient use of highly bred but expensive material of SP, (ii) early biomass harvest of rapid-growing LP and (iii) final harvest of more valuable crop trees of SP. Elite SP is expected to have 20–25% higher growth rate during a rotation than unimproved SP (Rosvall et al. 2001). Furthermore, young LP has higher production of both fatty and resin acids in the wood, while those in SP are greater at older ages (in the heartwood) (Arshadi et al. 2013; Eriksson et al. 2018). Furthermore, these acids have been established as important substitutes for fossil-based fuels (e.g. biodiesel) and other petroleum-based products. In addition, a great part of the biomass of LP is made up of resin-rich needles (Backlund et al. 2014a).

Simulation using growth and yield models is a commonly used tool to explore the future development of tree stands. The Heureka software is a decision support system which simulates stand development for Swedish conditions (Wikström et al. 2011). StandWise is its interactive simulator for stand-level analysis. Net present value (NPV) is the sum of future income and expenses from forestry discounted with a certain interest rate to the current date. Maximizing NPV is a tool for financial evaluation and ranking of stand management alternatives.

In Swedish forestry, LP has a superior production compared to SP, which has called into question their ability to grow together. The main objective of this study was to evaluate production value for elite SP in mixture with LP for a rotation at different tree spacings. The production value is evaluated by stem volume production, tree characteristics and NPV. We hypothesized that SP in a temporary mixture with LP will result in higher production value than for SP in monospecific stands if the silvicultural model is adapted to the mixture.

Materials and methods

Study area

Our field study (Skogforsk ID S23F8810484, Flurkmark) was established in 1988 on boreal forest land (64°03′N, 20°22′E, 155 m.a.s.l) close to the Baltic Sea in Västerbotten county, northern Sweden. The experiment was set up with a factorial design with 11 unique plots completely randomized in three blocks. Each block was planted with separate plantation spacing 3×3, 2×2 or 1×1 m, corresponding to 1111, 2500 and 10,000 stems/ha, respectively. The plot types within each block were either monospecific of pure SP (eight plots) or of pure LP (one plot) or in mixture (50%/50%) (two plots) of the two species ("mixed", systematically planted as every other tree position in a cross-diagonal pattern). The seed material for the SP entries originated from full-sib crosses between tested SP trees within the Swedish tree improvement program of near-local origin, and the LP material consists of open-pollinated stand material from Teslin, Yukon Territory, Canada. This LP provenance has proven well adapted to Swedish conditions in Swedish provenance tests (Lindgren et al. 1988; Ericsson 1993). Filler plants of the seed orchard origin were planted on the outer edges of the trial and inner plots of 64 (8×8) trees were used as assessment unit. The plots of mixed planting of LP and SP were always done with the same seed entries of both species. The trial is on a typical planting site for the region, with a subarctic climate (standard values of precipitation 572 mm and mean temperature sum 825 day ° (www.smhi.se)), on a sandy silty moraine, with a slight sloping (<5%) westerly aspect, with vegetation dominated by bilberry (*Vaccinium myrtillus*). The site index based on site factors was 21 m, defined as the dominant height at a total age of 100 years for SP (Hägglund and Lundmark 1994). Soil preparation to keep plants within blocks at an even spacing was done either manually or with a shallow disc harrow scarification before planting. All plants were treated during the first years after establishment against pine weevil (Ambush®) and voles (Wiltex®). Since some early damage from grazing was observed, a moose fence was established around the experiment in 1994. Cleaning of volunteer regeneration was done in the spring of 1997, with some natural SP regeneration left where the test plants had died, while maintaining the original spacing.

Field assessment and data preparation

The experiment was measured in the fall of 2015, at age 28 years, when all trees were assessed for diameter (cross calipered over bark at 1.3 m above ground level (breast height), DBH and the arithmetic mean from the two values used in the statistical analysis), individual-tree vitality (VIT, with four classes from dead (0) to very good (3) health) and damage (registered by damaging agent and in four severity classes). Stem characteristics were also recorded on each tree: number of ramicorns (Rm), number of double stems and the degree of stem inclination (trees affected by leaning, bending or broken stems). Additional measurements (total height, *H*, height to base of crown, HBC, bark thickness at

1.3 m, BT, and diameter of largest branch in the whorl closest to 1.3 m, BD) were assessed on nine sample trees in each tree species within each plot. Sample trees were chosen among those in the inner plot of 64 trees, i.e. no edge tree in plot was chosen. Sample trees had no visible damage that may have affected height growth and clearly suppressed trees were not selected. Two types of trees were sampled in each plot, seven random and two dominant trees.

Total stem volume including bark was calculated for each sample tree using functions by Näslund (1947) and Eriksson (1973) for SP and LP, respectively. Thereafter, secondary volume functions were constructed (Hoffman 1982; without the correction of the logarithmic bias) to calculate individual-tree volume Vm for all assessed plot stems using the equation as follows:

$$\mathrm{Vm} = e^{(\beta_0+\beta_1\cdot\ln\,\mathrm{DBH}-\beta_2\cdot(\ln\,\mathrm{DBH})^4\,)}, \tag{1}$$

where β_0, β_1 and β_2 are the regression parameters. β_2 was not included in the model if it was not significant.

The inter-species competition was judged from a general stand performance of mixed plots and by characterization of the morphological traits at the individual-tree level in comparison with the pure tree species plots. Obvious stem characteristics that reduce the tree's growing ability are slenderness ratio (*H*/DBH) and the height to the base of crown (BHC).

Statistical analysis

Plot level performance (summarized data in individual plots of Vm (standing volume), average damage and average survival (dead or alive (VIT > 0))) was analyzed according to the design of the experiment with the following model:

$$y_{iklm} = \mu + B_i + \mathrm{Pt}_l + B_i\mathrm{Sp}_k + B_i\mathrm{Sp}_k\mathrm{Pt}_l + e_{iklm}, \tag{2}$$

where *y* is the vector of plot *m* within block *i* from species *k* for plot type *l*, μ is the overall mean and B_i, Pt_l and Sp_k are the fixed effects of the block *i* ($i = 1$–3, three spacings), species *k* ($k = 1$–2, SP or LP) and the plot type *l* ($l = 1$–2, "pure" or "mixed"), respectively. $B_i\mathrm{Sp}_k$ is the fixed interaction effect of block *i* and species *k*, $B_i\mathrm{Sp}_k\mathrm{Pt}_l$ is the fixed interaction effect of block *i* and species *k* within the plot type *l*, and e_{jklm} is the random residual effect. All plots were included in the plot level analysis. The percentage increase or decrease in production resulting from species or plot type was calculated with respect to that for a pure SP plot effect.

Individual-tree level characteristics (DBH, *H*, *H*/DBH, HBC, BT, BD, VIT, Rm and Vm) were analyzed, specifying plot (*P*) as a random class variable, according to the design of the experiment with the following mixed-model:

$$y_{ijklm} = \mu + B_i + P_{j(i)} + \mathrm{Sp}_k + \mathrm{Pt}_l + B_i\mathrm{Sp}_k + B_i\mathrm{Sp}_k\mathrm{Pt}_l + e_{ijklm}, \tag{3}$$

where *y* is the vector of observations on tree *m* within plot *j* in block *i* from species *k* for plot type *l*. μ is the overall mean, and B_i, Pt_l and Sp_k are the fixed effects of block *i* ($i = 1$–3, three spacings), species *k* ($k = 1$–2, SP or LP) and plot type *l* ($l = 1$–2, "pure" or "mixed"), respectively. $B_i\mathrm{Sp}_k$ is the fixed interaction effect of block *i* and species *k*, $B_i\mathrm{Sp}_k\mathrm{Pt}_l$ is the fixed interaction effect of block *i* and species *k* within plot type *l*, and e_{jklm} is the random residual effect.

The statistical analyses were performed using ASReml (Gilmour et al. 2009). Fixed effects were compared using the incremental Wald *F* statistic (type III). A test for homogeneity and to justify the acceptance or rejection of a non-zero estimate ($p > 0.05$) of the random plot variable was performed with the likelihood-ratio test (LRT).

Simulation of stand development

The long-term development of the different plots was simulated with the decision support system Heureka and its application StandWise (Wikström et al. 2011). Heureka simulates growth, mortality and ingrowth in five-year periods using empirical models based on long-term data from the Swedish National Forest Inventory (Fahlvik et al. 2014). Management actions are specified by the user for each period and economic output, as revenues and NPVs are produced based on timber prices and operations costs specified by the user. In our study, we used an up-to-date timber price-list for the Swedish forest owner association (Mellanskog). Logging costs were calculated with functions based on productivity statistics from Swedish forestry (Brunberg 2012). Hourly machine costs were set at 1000 and 1100 SEK for a harvester in thinning and final felling, respectively, and set at 700 and 800 SEK for a forwarder, respectively.

Data were imported to Heureka with information on plots and measured trees. Simulation was made on the two mixed plots and on two monospecific plots of SP (matching the same SP families in mixed and monospecific plots) and on the LP plot, for the two blocks 2 × 2 and 3 × 3, respectively.

Timing of thinning's was decided using the thinning guide software INGVAR (Jacobson et al. 2008). Thinning operation was simulated in the Heureka using the LOEriksson thinning model (Heureka Wiki 2018). In the monospecific plots of LP and SP, thinning from below was simulated with a thinning quotient of 0.9 and a thinning grade of 35% basal area. In the mixed-species plots, two alternative thinning programs was simulated, both aiming at favoring SP as the main crop at final felling because of the higher prices for SP saw-logs. The first thinning program for the mixed plots was following the thinning guide with a 35% thinning grade. To promote SP development, the thinning algorithm was set to prioritize the thinning out of large LP trees with a thinning quotient of 1.2 for this species. Thinning out SP had lower priority and was made with a thinning quotient of 0.9. The second alternative thinning program simply extracted all the LP from the stand, leaving a pure SP stand with a relatively low basal area. Time of final felling was defined as the five-year period achieving the highest NPV using a real interest rate of 2.5%, which would represent the expected value change of an investment with moderate risk in Swedish forestry (Hyytiäinen and Tahvonen 2010). Highest NPV was also chosen as the financial estimate to be able to compare alternatives on an economic basis. Following the thinning guide and rotation length described above resulted in thinning programs with one thinning for the 3 × 3 m spacing across all plots, two thinnings for mixed plots in the 2 × 2 m spacing treatment, but only one

Table 1. Significance (p-value) of fixed design effects from model 2 for plot level performance of average survival, standing volume and average damage.

	Intercept	Sp	B	Pt	$B\times$ Sp	$B\times$ Sp $\times$ Pt
Average survival	<0.001	0.453	0.990	0.353	0.067	0.549
Standing volume	<0.001	0.033	<0.001	0.085	0.454	0.098
Average damage	<0.001	<0.001	0.033	<0.001	0.878	0.005

Note: Sp, species (SP or LP); B, block (1×1 m, 2×2 m or 3×3 m); Pt, plot type (pure or mixed).

thinning in pure SP (mono) plots in this block, and three thinnings for all plots in the 1×1 m spacing.

Results

Mixing and spacing effects on stand-level performance

Overall, the statistical analysis for survival revealed small differences and non-significant effects for all tested experimental design effects ($p > 0.05$). Differences in standing volume and average damage were, however, more affected by the experimental design effects (Table 1).

Average survival was relatively constant across plot and spacings, which indicates that the different spacing treatment did not affect survival. The differences in survival were due to other uncontrolled circumstances connected to early survival and the plant material. The experimental effect of block revealed larger differences in average survival between plot types (pure or mixed-species) only at the closer 1×1 m spacing. Overall spacing did not significantly ($p > 0.05$) affect the average survival at the 3×3 m and 2×2 m spacings for different plot types, even if the average survival was somewhat higher for pure LP (about 77%) than for mixed-species plots (about 73%) or for pure SP (about 67%); while difference in average survival was higher at the closer 1×1 m spacing, where the mixed-species plot (55%) differed significantly compared to pure SP (74%) (t-value = 2.32) and pure LP (69%) (t-value = 1.09) (Figure 1). The frequency of leaning stems was low (and mostly of moderate severity) at 3×3 m and 2×2 m spacing, and was lower for SP than for LP (less than 8% of the stems). Leaning was more severe at the 1×1 m spacing, with about 25% of stems affected for LP and 13% of standing volume lost in the mixed-species plot.

Spacing had significant impact on stand wood production; pure SP stand volume at age 28 was on average 83, 119 and 169 $m^3\ ha^{-1}$ for 3×3 m, 2×2 m and 1×1 m spacings, respectively (Figure 1). Other design effects (Sp and Pt) had smaller and not statistically significant impact on the wood production. The differences in production among species were highest for 1×1 m, where LP production was about 240 m^3 sk ha^{-1}, i.e. 42% higher than SP at the same spacing and twice that of SP at 2×2 m (Figure 1). Double stems accounted for a minor part of the volume production for SP and at the closest spacing of LP, but they account for as much as 8% for pure LP at 3×3 m and 2×2 m spacing. Across all plots, there was a decreased stand volume production with only a few percent for both species if tree with stem breakage or leaning trees was accounted for. An exception was for 1×1 m spacing with a production loss of about 10% in mixed-species plots and in the pure LP plot.

Mixing and spacing effects on individual-tree level characteristics

In total, four mixed-species treatments (monospecific or species-mixing 50%/50%) were considered for individual-tree analysis: pure SP, mixed SP, pure LP and mixed LP. Table 2 shows the outcome of the statistical analysis based on the experimental design.

Stand density and tree spacing had substantial impacts on stem volume production and tree characteristics on all plot types. Differences in individual-tree level characteristics were strongly dependent on the species, mixture and on spacing (Figure 2). Average tree height for plots with different spacing was generally small across species but were substantial for SP in the mixture with LP at the 1×1 m spacing, where the average height was much reduced. The influence on mean tree diameter and stem volume for SP in the mixture with 50% LP was substantial in comparison to pure SP plots, decreasing as tree spacing increased. LP DBH

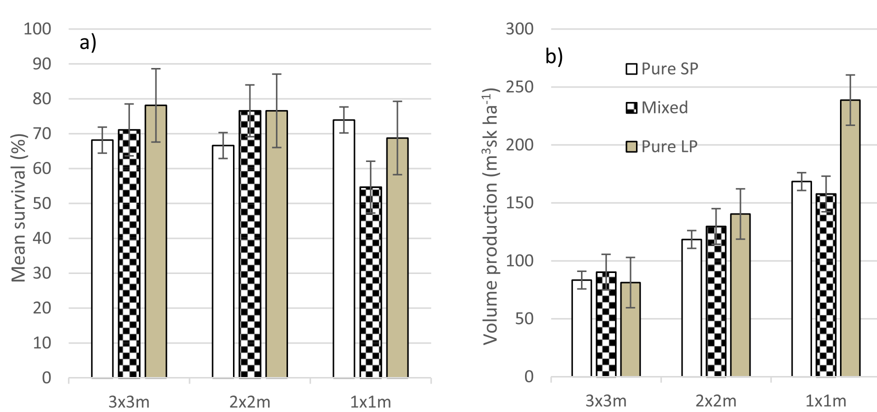

Figure 1. Plot mean survival (a) and plot volume production (b) in pure (monospecific) or mixed (species mixture 50%/50%) plots (with error bars) at age 28 at three different spacings. SP is Scots pine and LP is lodgepole pine.

Table 2. Significance (*p*-value) of fixed design effects and variance estimates from model 3 for total tree height (*H*), diameter breast height over bark (DBH), total stem volume (Vm), height to base of crown (HBC), bark thickness (BT), branch diameter (BD), number of ramicorns (Rm), vitality (VIT) and mean slenderness (*H*/DBH).

	DBH	*H*	Vm	HBC	BT	BD	Rm	VIT	*H*/DBH
Fixed design effects									
Intercept	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Species, Sp (SP or LP)	<0.001	0.005	<0.001	<0.001	0.038	<0.001	0.094	<0.001	<0.001
Block, *B* (1 × 1, 2 × 2 or 3 × 3 m)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.657	<0.001
Plot type, Pt (pure or mixed)	0.013	<0.001	0.027	0.509	0.010	0.035	0.456	0.170	0.002
B × Sp	0.017	0.003	0.406	<0.001	0.027	<0.001	0.473	0.027	0.005
B × Sp × Pt	<0.001	0.009	<0.001	0.137	0.092	0.009	0.982	0.257	0.001
Variance components									
Plot, *P* (%)	3	8	4	20	26		11	4	5
Residual (%)	97	92	96	80	74	100	89	96	95
p-Value (LRT)	<0.001	0.039	<0.001	<0.001	<0.001	n.s.	<0.001	<0.001	n.s.

Note: Variance components are also presented as percentage of total variance. n.s., not significant ($p > 0.05$).

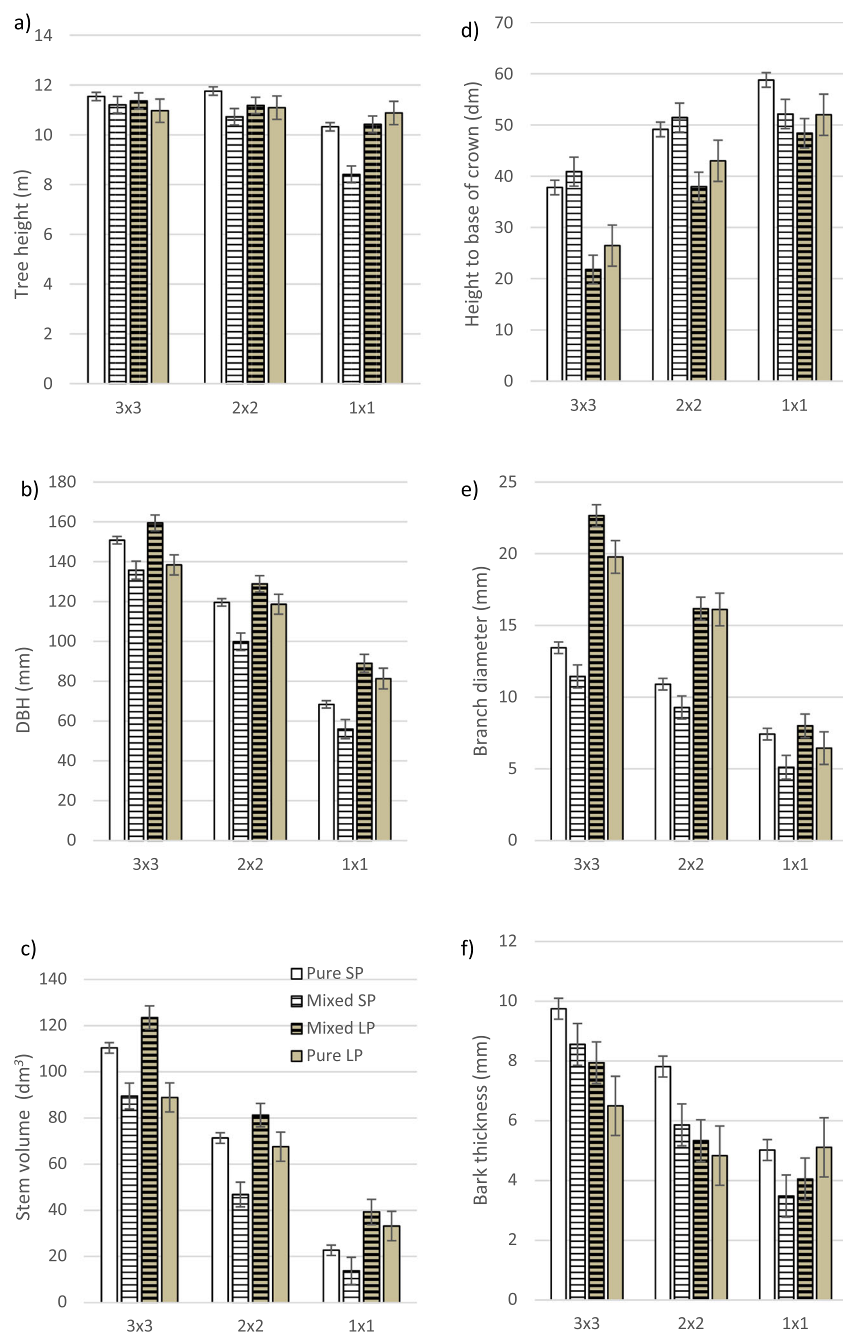

Figure 2. Mean of trait characteristics for SP and LP individuals in pure (monospecific) or mixed plots (with error bars) at age 28 at three different spacings (1 × 1, 2 × 2 and 3 × 3 m). Tree height (a); DBH, diameter breast height (b); Vm, stem volume (c); HBC, height to base of crown (d); BD, branch diameter (e) and BT, bark thickness (f). SP is Scots pine and LP is lodgepole pine.

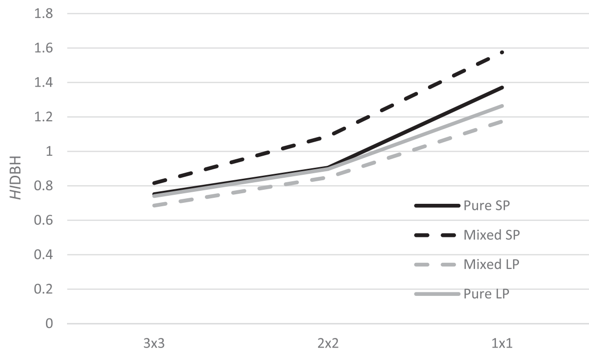

Figure 3. The height to diameter relationship at 1.3 m (*H*/DBH) at different spacings and plot types; pure (monospecific) or mixed plots in the trial. SP is Scots pine and LP is lodgepole pine.

growth in the mixed-species plots was higher than in pure plots. There was, however, no clear trend for LP with increasing spacing. Average stem volume of individual SP trees in the mixture with LP was strongly dependent on spacing and was reduced as spacing decreased. Individual stem volume for SP exceeded LP in monospecific plots, except at the closest 1 × 1 m spacing.

The effects of tree spacing were high for most measured traits, and there was a general relationship across plot type. However, there were also differences between the two species. Pure SP plots showed greater DBH, stem volume, bark thickness and branch diameter, and reduced height of green crown, as spacing became wider. SP trees were, on average, slenderer with smaller branches, less number of ramicorns, thinner bark and lower green crown as spacing between trees decreased (Figure 2).

Differences in structural characteristics of the stem as the mean slenderness (*H*/DBH) are shown in Figure 3.

Mean differences in the vitality of individual trees of SP and LP were also dependent on the species mixture and on spacing (Figure 4(a)). The pattern and general level of vitality were similar across plot types for the two widest spacings, but at 1 × 1 m spacing all plot types with LP showed decreased vitality compared to SP in pure plots. Number of ramicorns increased significantly ($p < 0.05$) as spacing became larger and there were differences between species, but plot type did not have a significant effect (Table 2 and Figure 4(b)).

Stem volume production and NPV during one rotation for early harvest of short-rotation trees

The Heureka analysis focused on early harvest of short-rotation trees of LP which meant that priority in thinning was to harvest LP trees. The 1 × 1 m spacing was not considered suitable for mix analysis in Heureka, as competition had already produced a negative impact on SP growth; however, pure LP at this spacing produced a sizable volume of 239 m^3 ha^{-1} (Figure 1). The tested silviculture model with a LP-SP mixture and with early harvest of LP (100% thinning intensity) gave a large stem volume production and NPV (Table 3 and Figure 5), but the highest values at final felling were when LP remains as part of the stand after first thinning (35% thinning intensity). The simulations resulted in SP at final felling dominating in 2 × 2 m spacing mixed plot type, with 60% of the standing volume. Even if thinning priority was given to LP, only about half of the volume at final felling was SP in the 3 × 3 m spacing. Because of the faster growth of LP, it contributed about 60% (in 2 × 2 m spacing) and 70% (in 3 × 3 m spacing) of the total volume production over the rotation time. Mixed plots at 2 × 2 m spacing produced 14% and 38% greater total volume and 27% and 31% higher NPV compared to their two corresponding pure SP plots. Mixed plots at 3 × 3 m spacing produced 8% and 14% greater total volume and 20% and 27% higher NPV compared to pure SP plots. The simulations of mixed-species plots, where 100% of the LP was removed at the first thinning, did not show greater volume production compared to the monospecific SP plots. However, in contrast to the pattern for volume production, the mixed-species plots always show a higher final NPV compared to the monospecific SP plots (Table 3). For the closest spacing, 1 × 1 m, there was a clear negative effect of the SP volume production, which was considered as an extreme situation for real operation management (due to over density). This spacing gave no reasonable chance for further operational forest management and was therefore not considered in the result of the Heureka simulation (Table 3).

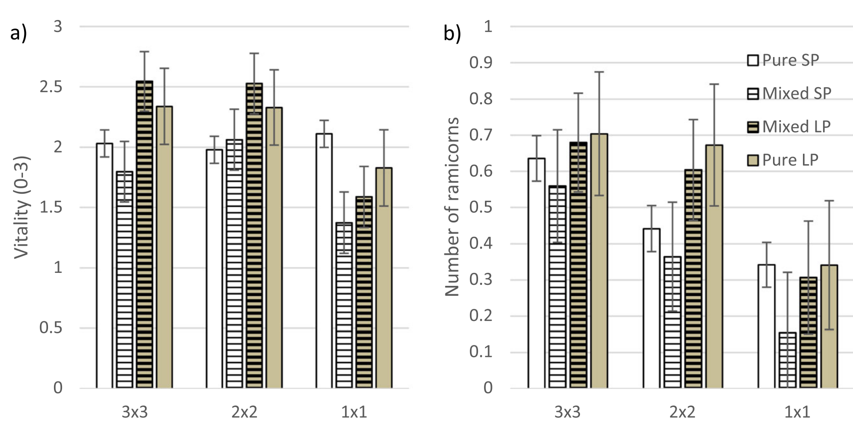

Figure 4. Mean vitality, VIT (a) and mean number of ramicorns, Rm (b) for individual trees of SP and LP in different plot types (mixed or monospecific) at age 28 (with error bars) at three different spacings. SP is Scots pine and LP is lodgepole pine.

Table 3. Stand data from Heureka simulations until progression at final felling.

			Final felling							Total volume prod.			
			Stems (ha^{-1})		DBH (mm)		Stem volume (m^3 sk ha^{-1})			Stem volume (m^3 sk ha^{-1} $year^{-1}$)			
Spacing/plot type/LP thinning regime (%)	Prop. (%)	Age	SP	LP	SP	LP	SP	LP	Total	SP	LP	Total	NPV
Spacing 2 × 2 m													
Pure LP	0	78	27	810	6	35	0	458	458	0	662	662	44,616
A-mixed 35%	43	78	626	271	22	25	240	166	406	240	356	596	41,671
B-mixed 35%	44	73	597	276	22	24	233	163	396	233	309	542	41,161
A-mixed 100%	43	73	730	0	24	0	339	0	339	339	139	478	36,658
B-mixed 100%	44	73	680	0	24	0	317	0	318	318	158	476	39,112
A-pure SP	100	73	570	0	28	0	382	0	382	431	0	431	31,689
B-pure SP	100	73	736	0	25	0	404	0	404	477	0	477	32,394
Spacing 3 × 3 m													
Pure LP	0	73	28	568	6	27	0	383	384	0	474	474	41,435
A-mixed 35%	34	73	224	243	28	31	134	222	356	134	319	453	44,760
B-mixed 35%	43	73	322	244	27	29	186	193	379	186	285	471	43,704
A-mixed 100%	34	73	309	0	33	0	180	0	180	180	161	342	38,135
B-mixed 100%	43	73	410	0	31	0	277	0	277	277	121	398	39,864
A-pure SP	100	73	420	0	31	0	333	0	333	418	0	418	35,353
B-pure SP	100	73	385	0	32	0	330	0	330	477	0	413	36,437

Notes: Mixed plots were originally planted with 50% SP and 50% LP. Prop., proportion of SP at age 28 (start of simulation); NPK, net present value (SEK). A and B are the two plot replicates within block. LP thinning regime (%): mixed 35% = 35% thinning/removal of LP; mixed 100% = 100% thinning/removal of LP.

The progression of stem volume over the rotation (until final harvest) from the Heureka analysis for the tested silvicultural models illustrates growth effects of options (Figure 5). LP trees in mixed plots were either removed completely in an early harvest (100% thinning intensity) or could remain part of the stand after first thinning (35% thinning intensity).

Discussion

How tree species can grow together is an important factor when developing silvicultural regimes with mixture of tree species, as to meet new demands on forest management. Recent papers report that mixed-species plantations can meet desired stand qualities better than monocultures, such

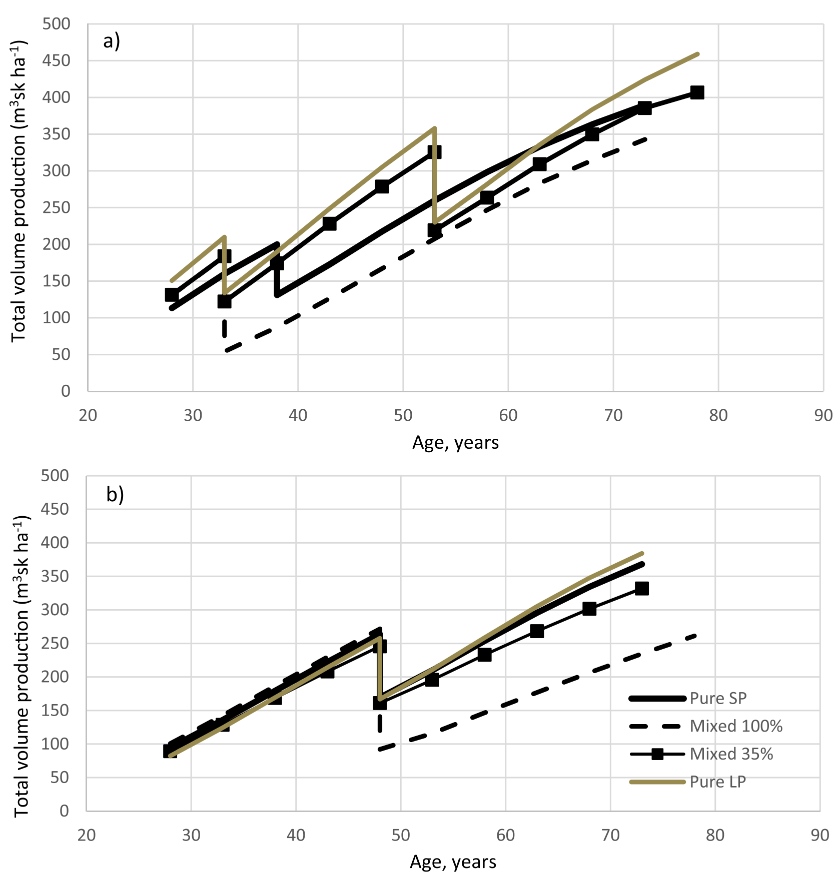

Figure 5. The development of stem volume production up to final felling for monospecific plots, pure SP and pure LP, and for mixed plots under two thinning regimes (35% and 100%). Mixed 35% = mixed 50% SP + 50% LP (35% thinning/removal of LP); mixed 100% = mixed 50% SP + 50% LP (100% thinning/removal of LP), for 2 × 2 m spacing (a) and 3 × 3 m spacing (b).

as to withstand or have the capacity to recover from biotic and abiotic disturbances, also even more specific tree stem qualities, including higher yields (Pretzsch and Biber 2016; Klapwijk and Björkman 2018). In monospecific younger stands, some tree and wood properties are often improved, with decreased spacing and increased competition (Karlsson et al. 2013). Thinning management is thus a possible tool to affect the balance between volume of juvenile and mature wood, volume of short versus long tracheids, etc. Management that also involves mixture of tree species could be an opportunity, as it provides a more diverse population of trees. An ordinary use of the tree species mixture in the Nordic country forestry is when birch is used as a shelter tree for spruce, but also more homogenous system as with spruce-pine mixture, which both can increase forestry value when prerequisites are right (Felton et al. 2016).

The general superior growth of LP over SP in northern Sweden could be an obstacle to manage mixed SP-LP tree stands if the inter-species competition is disadvantaging SP too much. The current experiment was analyzed to shed light on this issue and to evaluate stand productivity and stem characteristics on individual trees.

The field assessment of the current experiment was done with respect to properties that were judged to be able to provide information on how a species mix between SP and LP affects stock productivity and the structural design of individual trees. Differences against the pure tree plots could be related to the future product value and competitive status of the mixed plot trees in order to be able to be used in the future stock. The slenderness of trees can be important for stem quality as it is closely related to branch and crown structure, and branch increment. The results highlight important impact and interactions of stand density and inter-tree competition in monospecific and mixed plots of SP and LP, respectively.

Effects of species mixture and spacing on stand growth and individual-tree characteristics after 28 years

Mixing species did not increase total volume production across spacings, compared to monospecific plots, but differences were small, suggesting that mixed SP-LP planting could be an alternative to fulfill certain stand and tree properties targets. Across all spacings, LP always produced more stand volume and the productivity difference was greatest at 1×1 m. This was an expected result, as LP generally grows better than SP (Elfving et al. 2001). The most-used operational spacing, 2×2 m, describes the logical result for a stem density that is suitable for both species, as the total volume production is between that of pure SP and pure LP (Figure 1). Mixing at the widest spacing, 3×3 m, showed no obvious effects of competition between the two species. Effect of spacing, however, illustrates that LP at low stem density is affected by stem breakage and other damage connected to stem quality. The possibility for SP to compete with LP and grow well was maintained at the two widest spacings. SP at the closest spacing (1×1 m) was not productive in mixture with LP, which is proven by more stem damage, with a slenderness ratio near the limit of self-thinning conditions, and trees with obvious low competitiveness. The closest experimental spacing illustrates that inter-species competition is more severe for SP if stem density is too high and that pure LP planting is a better option at higher stem densities.

Our study (cf. results for height to base of crown, bark and branch thickness) shows that adding LP gives an inter-species effect that could be used in management to improve some SP properties. This follows common silviculture practice to use “trainer trees” in mixed stands to improve the quality development of a more valuable crop trees (Pretzsch et al. 2017). Another possibility by a mixture of LP and SP, and extraction of most LP in thinning, is the early harvest of more fatty and resin acids compared to early thinning of SP (Arshadi et al. 2013). The greater early biomass production from dense LP stands (as shown here in Figure 1) has been suggested by Backlund (2013) as a cost-efficient source of forest material suitable for biorefinery applications. Pure LP stands regenerated by direct seeding might therefore be most suitable for cost-effective short to mid-term biomass production on forest land in northern boreal forests. Already after four decades a substantial biomass production of LP is achieved after direct seeding in northern Sweden (Backlund 2013).

Stand development at early harvest of LP and keeping SP as dominant species

The forest development was followed until final harvest for plots with mixture and comparable pure control plots of SP using the Heureka software. The mixture was tested for two different thinning systems with an attempt to keep SP as the dominant species. At final felling, the total stem volume production in mixture plots did always benefit from the higher growth of LP compared to SP. Highest total stem production during the rotation was reached when LP was kept until final felling (35% thinning intensity) regardless of spacing. However, there was a clear negative production effect from an early harvest of all LP (100% thinning intensity) at the widest spacing, 3×3 m. This was not the case at the 2×2 m spacing as high SP volume production was secured by increased number of trees per plot and as there seemed to be no negative competition effect from LP on SP production. NPV showed that there was clear benefit from an early harvest of the short-rotation crop (LP) and that overall stand production was not jeopardized by low production of SP (Table 3).

Market timber value of SP in Sweden is today higher than for LP, even though age related wood characteristics could be similar. However, the study did not include further investigation concerning changes in simulation parameters (e.g. change in timber prize, interest rate, treatment schedule, rotation length, etc.) which could have an impact on the outcome of the comparison. The outcome should therefore mainly be viewed as a result of production differences between the species, at different spacings and mixtures, at current timber prizes and operation costs in normal forest management.

Analysis of forest development in Heureka might be affected if the modeling conditions are much different to normal forest stand in Sweden, for which the system is based. This might be the case for mixed stands where there is strong competition among species or in stand where the site productivity is out of the normal range. This was not the case for the analyzed spacing units but for the omitted 1 × 1 m spacing.

Conclusion

The study investigated species mixture and its effect on wood production and individual-tree characteristics. The outcomes showed that there seems to be possible advantages of mixing LP and SP at typical spacings in forest regeneration. SP is not as tolerant of close spacings and strong competition as LP, and LP has greater survival and initially more rapid growth than SP. As hypothesized, greater total stem volume production could be achieved when SP is mixed with LP, if the proper spacing and silvicultural management is applied. Certain features as reduced branch thickness and increased height to green crown after 28 years, which indicate a possible reduction of production of juvenile compared to mature wood of SP, might be improved in such a tree mixture. Intimate mixtures of SP and LP could be productive and provide greater economic benefit, compared to SP in monoculture. This would be especially important for elite-bred SP, because tree improvement is focused on stem volume production. These findings support and motivate the development of a silvicultural system for sparsely planted expensive, elite-bred SP in mixture with LP.

Acknowledgements

This study was funded by Brattås foundation. The authors are grateful to Kristina Ulvcrona Ahnlund, Daniel Eriksson, Mehrdad Arshadi, and Tommy Mörling at SLU for valuable work in relation to the reported project.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Brattåsstiftelsen för skogsvetenskaplig forskning [Grant No. F14:17].

References

Agestam E, Ekö P-M, Johansson U. 1998. Timber quality and volume growth in naturally regenerated and planted Scots pine stands in SW Sweden. Studia Forestalia Suecica 204: 1–17.

Arshadi M, Backlund I, Geladi P, Bergsten U. 2013. Comparison of fatty and resin acid composition in boreal lodgepole pine and Scots pine for biorefinery applications. Ind Crops Prod. 49:535–541.

Backlund I. 2013. Cost-effective cultivation of lodgepole pine for biorefinery applications. Diss. Umeå: Sveriges lantbruksuniv., Acta Universitatis Agriculturae Sueciae, 2013:81. ISSN 1652-6880.

Backlund I, Arshadi M, Hunt AJ, McElroy CR, Attard TM, Bergsten U. 2014a. Extractive profiles of different lodgepole pine (*Pinus contorta*) fractions grown under a direct seeding-based silvicultural regime. Ind Crops Prod. 58:220–229.

Backlund I, Karlsson L, Mattsson L, Bergsten U. 2014b. Biorefinery product potentials using tree biomass as feedstock – a survey on opportunities and threats to the new wood products industry. Biomass Bioenergy. 70:207–216.

Börjesson P, Hansson J, Berndes G. 2017. Future demand for forest-based biomass for energy purposes in Sweden. For Ecol Manage. 383:17–26.

Brunberg T. 2012. Skogsbrukets kostnader och intäkter 2011. Uppsala, Skogforsk.

Egbäck S, Liziniewicz M, Högberg K-A, Ekö P-M, Nilsson U. 2012. Influence of progeny and initial stand density on growth and quality traits of 21 year old half-sib Scots pine (*Pinus sylvestris* L.). For Ecol Manage. 286:1–7.

Elfving B, Ericsson T, Rosvall O. 2001. The introduction of lodgepole pine for wood production in Sweden – a review. For Ecol Manage. 141:15–29.

Ericsson T. 1993. Provenance qualities of the *Pinus contorta* breeding base in Sweden: front cover. Sweden: Skogforsk. Report, p. 1.

Eriksson H. 1973. Volymfunktioner för stående träd av ask, asp, klibbal och contorta-tall [Tree volume functions for ash, aspen, alder and lodgepole pine in Sweden (*Fraxinus excelsior* L., *Populus tremula* L., *Alnus glutinosa* (L.) Gaertn., *Pinus contorta* Dougl. var. latifolia Engelm)]. Department of Forest Yield Research, Royal College of Forestry, Research Notes No. 26.

Eriksson D, Arshadi M, Kataria R, Bergsten U. 2018. Lipophilic extractives in different tree fractions and forestry assortments of *Pinus sylvestris* due for thinning or final cutting. Scand J For Res. 33(6):1–9.

Fahlvik N, Wikström P, Elfving B. 2014. Evaluation of growth models used in the Swedish forest planning system Heureka. Silva Fenn. 48:1–17.

Felton A, Nilsson U, Sonesson J, Felton AM, Roberge J-M, Ranius T, Ahlström M, Bergh J, Björkman C, Boberg J, et al. 2016. Replacing monocultures with mixed-species stands: ecosystem service implications of two production forest alternatives in Sweden. Ambio. 45:124–139.

Gerendiain A, Peltola H, Pulkkinen P, Kellomäki S. 2009. Effects of genetic entry and competition by neighbouring trees on growth and wood properties of cloned Norway spruce (*Picea abies*). Ann For Sci. 66:806–814.

Gilmour A, Gogel B, Cullis B, Thompson R. 2009. ASReml user guide, 3rd edn. Hemel Hempstead: VSN International Ltd.

Gort J, Gerendiain AZ. 2009. Differences in fibre properties in Scots pine (*Pinus sylvestris* L.) genetic entries grown at different spacing and sites. Silva Fenn. 43:355–368.

Griess VC, Knoke T. 2011. Growth performance, windthrow, and insects: meta-analyses of parameters influencing performance of mixed-species stands in boreal and northern temperate biomes. Can J For Res. 41:1141–1159.

Hägglund B, Lundmark J E. Handledning i Bonitering, Del 3. Skogsmarksflora. Skogsstyrelsen, Jönköping.

Heureka Wiki. 2018. Control table treatment model. https://www.heurekaslu.se/w/index.php?title=ControlTable_Treatment_Model&oldid=10015.

Hoffman C. 1982. Berechnung von Tariffen für die Waldinventur. Forstw Cbl. 101:24–36.

Hyytiäinen K, Tahvonen O. 2010. Economics of forest thinnings and rotation periods for Finnish conifer cultures. Scand J For Res. 17:274–288.

Jacobson S, Pettersson F, Sikström U, Nyström K, Övergaard B. 2008. INGVAR-gallringsmall och planeringsinstrument. Uppsala, Skogforsk. Resultat 10:1–4.

Karlsson L, Mörling T, Bergsten U. 2013. Influence of silvicultural regimes on the volume and proportion of juvenile and mature wood in boreal Scots pine. Silva Fenn. 47:1–17.

Karlsson B, Rosvall O. 2010. Ökad tillgång och användning av förädlade plantor. Uppdrag om förbättrat växtodlingsmaterial, Jo2008/1883 (in Swedish).

Klapwijk MJ, Björkman C. 2018. Mixed forests to mitigate risk of insect outbreaks. Scand J For Res. 33:772–780.

Lindgren K, Lindgren D, Rosvall O. 1988. Förflyttningsrekomendationer för provenienser av contortatall i Sverige. Arbetsrapport Från SLU. 27:1–47.

Liziniewicz M, Ekö PM, Agestam E. 2012. Effect of spacing on 23-year-old lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) in southern Sweden. Scand J For Res. 27:361–371.

Näslund M. 1947. Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i södra sverige samt i hela landet. Medd Statens Skogsforskningsinst. 36:3–36.

Persson B, Persson A, Ståhl E, Karlmats U. 1995. Wood quality of *Pinus sylvestris* progenies at various spacings. For Ecol Manage. 76:127–138.

Pretzsch H. 2017. Individual tree structure and growth in mixed compared with monospecific stands. In: Pretzsch H, Forrester DI, Bauhus J, editors. Mixed-species forests. Berlin, Heidelberg: Springer; p. 271–336.

Pretzsch H, Biber P. 2016. Tree species mixing can increase maximum stand density. Can J For Res. 46:1179–1193.

Pretzsch H, Forrester DI, Bauhus J. 2017. Mixed-species forests: ecology and management. Berlin, Heidelberg: Springer.

Pretzsch H, Rais A. 2016. Wood quality in complex forests versus even-aged monocultures: review and perspectives. Wood Sci Technol. 50:845–880.

Rosvall O, Jansson G, Andersson B, Ericsson T, Karlsson B, Sonesson J, Stener L-G. 2001. Genetiska vinster i nuvarande och framtida fröplantager och klonblandningar. Redogörelse Skogforsk. 1:41.

Samils B, Barklund P, Kaitera J, Stenlid J. 2018. Geographic distribution of Cronartium flaccidum and Peridermium pini in Sweden and Finland. In: Schoettle AW, Sniezko RA, Kliejunas JT, editors. Proceedings of the IUFRO joint conference: Genetics of five-needle pines, rusts of forest trees, and Strobusphere; 2014 June 15–20; Fort Collins, CO. Proc. RMRS-P-76. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 219.

Wikström P, Edenius L, Elfving B, Eriksson LO, Lämås T, Sonesson J, Öhman K, Wallerman J, Waller C, Klintebäck F. 2011. The Heureka forestry decision support system: an overview. Math Comp For Nat Resour Sci. 3:87.

Zeller L, Ammer C, Annighöfer P, Biber P, Marshall J, Schütze G, del Río Gaztelurrutia M, Pretzsch H. 2017. Tree ring wood density of Scots pine and European beech lower in mixed-species stands compared with monocultures. For Ecol Manage. 400:363–374.