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Production and profitability of low density Norway spruce (*Picea abies* (L.) Karst.) plantation at 50 years of age: case study from eastern Latvia

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Abstract. Norway spruce (*Picea abies* (L.) Karst.) is one of the most important commercial tree species, for which wider spacing are being advocated to reduce management costs and improve radial growth. Nevertheless, little is known about tree and stand parameters at the larger age in stands of extremely low density. The aim of our study was to assess growth and economic profitability of 50 years old low density Norway spruce plantation in Latvia. Allometric parameters for all trees of Norway spruce clonal plantation planted in 1964 with two spacings (1×3 m and 5×5 m) were measured and profitability were estimated. Norway spruce plantation with wider (5×5 m) spacing ensured significantly larger tree diameter and height (35 cm and 25 m, respectively) than trees from higher density trial. However, mean net present value (3% interest rates) was non–significantly ($P = 0.12$) different between 5×5 m and 1×3 m spacings, 2,571.9 ± 355.6 and 3,085.8 ± 452.9 € ha^{-1}, respectively. Values observed in low density (5×5 m) plantation fitted well in the-observation of impact of density and stand parameters drawn based on National inventory data, showing a considerable potential to use plantations with low density in practice.

Key words: initial spacing, target diameter, clonal plantation, net present value.

INTRODUCTION

In northern Europe, Norway spruce (*Picea abies* (L.) Karst.) is one of the most important commercial tree species, used for board as well as pulp and paper production (Gerendiain et al., 2008; Neimane et al., 2015). Due to the economic importance of coniferous trees, intensive tree breeding has been applied (Jansons et al., 2015) and substantial amounts of studies has addressed the silvicultural treatments required to ensure their vitality and growth under a changing climate (Bergh et al., 2005; Hébert et al., 2016; Matisons et al., 2017). Studies have reported larger radial increment and higher resistance against different biotic and abiotic factors, e.g. windstorms, root–rot, and dendrophagous insects, in stands and plantations with lower density at young age (McClain et al., 1994; Gardiner & Quine, 2000; Hébert et al., 2016). Due to this, as well as decreased intraspecific competition between trees, low density plantations usually are characterized by lower mortality (Peltola et al., 2000; Slodicak & Novak, 2006; Akers et al., 2013); except in sites with severe browsing pressure, where higher density might reduce the browsing damage occurrence and increase the number of surviving trees (Edenius et al., 2002; Díaz–Yáñez et al., 2017). Drawbacks of low density stands often are smaller yield (standing volume) per hectare, presumably higher risk of stem cracks in drought–prone sites, and lower stem quality due to larger branch diameters and consequently also slower natural pruning (Mäkinen & Hein, 2006; Pfister et al., 2007; Zeltiņš et al., 2016; Baders et al., 2017). From an economic point of view this might be compensated by reduced costs of establishment and pre–commercial thinning as well as length of rotation period (cutting by target diameter, if possible) (Willcocks & Bell, 1994; Zhang et al., 2002; Hynynen et al., 2010). However, economic profitability (net present value (NPV)) of timber production and total investments of forest stands with different planting density are seldom analysed (Coordes, 2013).

In eastern Europe initial spacing in Norway spruce stands was kept rather high (4,000–6,000 trees ha^{-1}) in the second half of the 20th century and reduced to around 2,000 trees ha^{-1} in most of countries from the beginning of this century (Mangalis, 2004; Gizachew et al., 2012). Current trends are toward wider initial spacing (often in combination with improved soil preparation, planting and/or fertilization) in order to boost the profitability of management of Norway spruce stands (Gizachew et al., 2012; Dzerina et al., 2016; Jansons et al., 2016). However, little is known about tree and stand parameters at the age with maximized volume production in stands of extremely high spacing (Hein et al., 2007; Gil, 2014; Hébert et al., 2016). Such information would be of a practical value, when setting the lower limit for the planting density as well as for elaboration of legal requirements for pre–commerical thinning. Therefore, the aim of our study was to assess growth and economic profitability of 50 years old low density Norway spruce plantation. For this purpose, tree and stand parameters (e.g., tree diameter at breast height, mean annual increment), as well as NPV were assessed.

MATERIALS AND METHODS

The study was carried out in a Norway spruce clonal plantation, located on fertile mineral soil with normal moisture regime, suitable for this tree species, *Oxalidosa* forest type (Bušs, 1976) in eastern Latvia (56º42´N, 25º53´E). The site index for spruce at the experimental site (the dominant height at 100 years; Matuzānis, 1983) was 36.0 m. According to data from the Latvia Environmental, Geology and Meteorology Centre, mean annual temperature at study area is around + 6 °C with annual mean precipitation of 640 mm. Plantation was established in 1964 using vegetatively propagated planting material from 20 plus–trees. Two trials at spacing of 1×3 m (3,330 trees ha^{-1}) and 5×5 m (400 trees ha^{-1}) in 15 and 21 rows (100 m long), respectively, were established beside each other in two adjacent replications. Weed control was carried out in planting year and first year after planting; no thinning was conducted prior the sampling. No measurements in the trials before age of 50 years were carried out.

The plantation of Norway spruce was sampled in August 2016. All trees in plantation were measured at mature age, i.e., age of 50 years. Some allometric parameters such as diameter at breast height (DBH) (± 0.05 cm), height (H) (± 0.1 m), height to its first living and dry branch (± 0.1 m) were measured for all trees. Dried and damaged trees were recorded and, if possible, the cause of damage (e.g., ungulates, stem deformations) was indicated.

Slenderness (H/D ratio) and basal area were calculated for all trees. The crown ratio was calculated by dividing total tree H by crown length. The individual tree standing volume has been calculated according to the formula by Liepa (1996):

$$v = \psi H^{\alpha} DBH^{\beta \lg L + \varphi} \quad (1)$$

where v – stem volume with bark, m^3; H – tree height, m; DBH –stem diameter at breast height, cm; ψ, α, β, φ – coefficients depending on tree species (for Norway spruce 2.3106 10^{-4}, 0.78193, 0.34175, 1.18811, respectively).

Total volume and basal area of each trial were computed as the sum of the individual trees. Site index was calculated based on dominant tree height at age 50 according to Matuzānis (1983). Survival of trees in trials was expressed in percentage relation of live trees in the year of measurements to the number of trees in the year of establishment.

Mean annual increment (MAI) (standing volume divided by stand age) and mean tree diameter of each spacing were compared with data from 10 National forest inventory (NFI) sample plots at the age from 45 to 52 years, located on comparable forest types with a site index of 30 to 36 m in the same region of Latvia. Only sample plots with lowest current density (360–1,280 trees ha^{-1}) available from NFI data were selected for the comparison, though, it was not known what factors and when caused the reduction of number of trees per ha to such a low level in these stands.

To compare the net present value (NPV) between both spacings, the volume of stemwood assortments of individual trees was calculated according to Ozoliņš (2002). According to the joint–stock company 'Latvia's State Forest' Quality requirements of round timber (2016), five classes by length and diameter of segments for Norway spruce stems were set (Table 1).

Table 1. Characteristics of Norway spruce timber assortments

	Large	Middle	Small I	Small II	Pulpwood
Top–diameter, cm	28	18	14	10	6
Length, m	3.6	3.6	3.6	3.0	3.0

Monetary value of each sampled tree was calculated based on average assortment prices. Net present value of final felling (50 years) was calculated with the 1%, 3%, 5%, and 10% interest rates. In calculations, the costs of regeneration (soil preparation, planting, planting material), two weed controls, as well as logging (wood preparation, delivery, transportation) costs were taking into account. All the costs of treatments were equal for both spacings, since the contracts were done per ha basis, except the costs of planting material. Average assortment prices and all included forest management costs for the years 2006–2016 were obtained from Central Statistical Bureau (CSB, 2016).

Analysis of variance (ANOVA) was used to analyse the existence of significant differences among the spacings for tree quantitative parameters (DBH, H, H/D ratio etc.) and NPV. When the differences were significant according to ANOVA, the multiple post hoc comparison test (Tukey's Honest Significant Difference (HSD) test) was performed. Proportion of damaged trees as well as survival of trees were evaluated using the generalized linear model (GLM) applying binomial residual distribution ('logit'). Additional, mean values ± 95% of confidence interval (CI) were calculated. The obtained data were statistically analysed using R v.3.3.1 (R Core Team, 2016).

RESULTS AND DISCUSSION

At age of 50 years, spacing significantly ($P < 0.001$) affected the survival of trees. Higher survival was observed in wider spacing (5×5 m) – 69.5%, lower – in narrower spacing – 30.3%. It is in accordance with other studies, suggesting a notable impact of intraspecific competition (Amateis et al., 1997; Akers et al., 2013) and thus increase of survival of trees from narrowest (1×3 m) to widest (5×5 m) spacing. However, such studies typically do not include the extremely wide spacing as in our trial. Higher survival of trees with increased spacing has also been found in younger stands in other studies for *Pinus* sp. (e.g., Baldwin Jr. et al., 2000; Hébert et al., 2016). Survival can be linked to natural selection, i.e., gradual reduction of proportion of slower–growing (less fit) genotypes (Gerendiain et al., 2008).

Damages – mainly bark striping by cervids (96–100% from observations) – in trial with 5×5 m spacing was significantly ($P < 0.001$) less frequent than in trial with 1×3 m spacing, reaching 9% and 75%, respectively. This might indicate that greater branchiness decreased the level of damaged trees in 5×5 m spacing (Vospernik, 2006; Månsson & Jarnemo, 2013; Baders et al., 2017). Statistically significant differences of H or DBH between groups of damaged and un–damaged trees were not observed, but it does not exclude the negative impact of it on stem quality due to fungal infections (Arhipova et al., 2015; Burneviča et al., 2016).

Mean DBH and H of the trees were significantly ($P < 0.001$) different between spacings (Table 2): widest spacing 5×5 m had larger DBH and H, likely due to the light, nutrient resources and moisture availability (Vospernik et al., 2010). This trend has been also observed in other studies, including spacings from 2×2 m to 4×5 m at the age of 24 to 33 (Deans & Milne, 1999; Pfister et al., 2007). The widest 5×5 m spacing produced significantly ($P < 0.001$) greater stem volume per individual tree (59%) than the denser 1×3 m spacing (Table 2).

Table 2. Spacing effect on measured Norway spruce tree parameters and mean stand characteristics

Tree parameters	1×3 m	5×5 m	*F* value (DF = 1, 1,261)	*P* value
Tree DBH ± CI, cm	24.29 ± 0.61	36.52 ± 0.66	694.7	< 0.001
Tree height ± CI, m	21.5 ± 0.3	25.1 ± 0.3	261.0	< 0.001
H/D ratio	0.92 ± 0.17	0.70 ± 0.01	401.9	< 0.001
Crown ratio	0.52 ± 0.01	0.75 ± 0.01	607.2	< 0.001
Height of first living branch ± CI, m	10.2 ± 0.3	6.3 ± 0.3	329.7	< 0.001
Height of first dry branch ± CI, m	0.6 ± 0.04	0.5 ± 0.02	34.3	< 0.01
Tree stem volume, m^3	0.54 ± 0.03	1.31 ± 0.06	676.5	< 0.001
Stand characteristics	1×3 m	5×5 m		
Basal area, m^2 ha^{-1}	42.5	27.1	×	×
Standing volume, m^3 ha^{-1}	453.5	301.8	×	×
Site index, m	24.8	27.4	×	×
Number of measured trees	736	521	×	×

DBH – diameter at breast height; CI – confidence interva; DF = degree of freedom.

Impact of spacing on tree H observed in our study, in contrast to impact only on tree DBH and stem volume (reported by Tong & Zhang, 2005; Mäkinen & Hein, 2006; Hébert et al., 2016) could be explained by highly variable densities, revealing differences in light accessibility and competition (Oker–Blom & Kellomäki, 1982; Hébert et al., 2016).

Between trials the observed differences of mean H/D ratio was significantly ($P < 0.001$) influenced by spacing, increasing from 0.70 to 0.92 in lowest and highest spacing, respectively (Table 2). Significantly ($P < 0.001$) larger H/D ratio in 1×3 m spacing, being in accordance to results of other studies (Mäkinen & Isomäki, 2004). The H/D ratio was highly variable in 1×3 m spacing, ranging from 0.55 to 1.59, likely due to notable suppression as competition between individual trees increase (Cremer et al., 1982; Fahlvik et al., 2005) and uneven distribution of remaining trees. Spacing 5×5 m overall had lower H/D ratio (ranging from 0.51 to 0.92) due to faster DBH increase (Slodicak & Novak, 2006), suggesting higher tree stability against environmental stresses (Valinger & Pettersson, 1996; Karlsson et al., 2000; Peltola et al., 2000).

Spacing had a significant effect on the tree crown parameters (Table 2). Height to the first living branch, as well as crown ratio were significantly different between both spacings, showing better natural pruning as well as shorter tree crowns in narrower spacing (Bachofer & Zingg, 2001; Pfister et al., 2007). Although, spacing had a significant effect on height to first dry branch, observed differences were small, underlying slow overall natural pruning of Norway spruce (Mäkinen & Hein, 2006). These differences were not considered in the calculations of assortment structure in our study, thus providing an actual upper limit for the net present value (NPV) in all assessed densities of plantations.

In the low density Norway spruce stands with un–known management history (National forest inventory (NFI) data), the mean standing volume ± CI was 276.7 ± 56.7 m^3 ha^{-1}, ranged from 194 to 422 m^3 ha^{-1}. The mean tree diameter of NFI stands significantly correlated (r = – 74) with stand density, as found also by McClain et al. (1994) and Deans & Milne (1999) (Fig. 1A). However, stand density in the assessed range (NFI data; 360 to 1,280 trees ha^{-1}) had only slight link with its mean annual increment (MAI) (Fig. 1B).

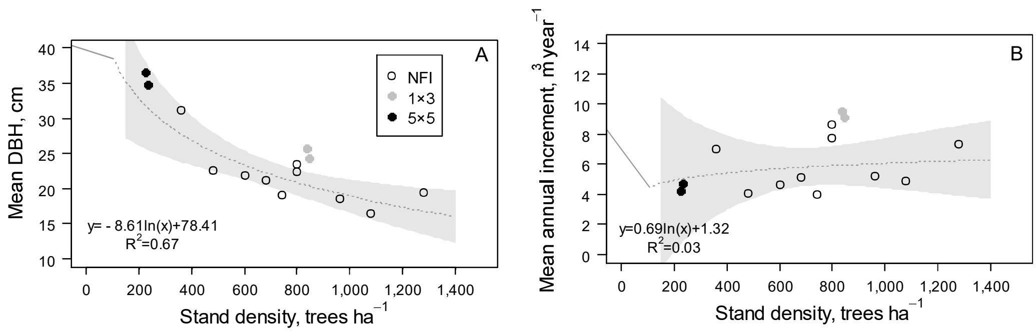

Figure 1. The mean tree diameter at breast height (DBH) (A) and mean annual increment (B) ± 95% confidence interval (grey area) in trials (filled circles) and forest stands (National forest inventory – NFI data) with different density.

Nevertheless, values of both DBH and MAV observed in the widest 5×5 m spacing mostly occurred within the CI of the observations from NFI data. Although, mean DBH was notably higher, the MAV in widest 5×5 m spacing appeared to be lower; indicating that over reduced density may not provide similar NPV as in denser stands (Fig. 1).

For the comparison of economic profitability between both spacings, NPV over the 10 years period with different wood prices and interest rates were calculated (Table 3).

Table 3. Comparison of net present value (NPV), € ha^{-1} in both 1×3 m and 5×5 m spacings with different interest rates (i) (1%, 3%, 5%, 10%) for the years 2006 to 2016

Year	i =1%		i =3%		i = 5%		i = 10%	
	1×3 m	5×5 m	1×3 m	5×5 m	1×3 m	5×5 m	1×3 m	5×5 m
2006	8,655.9	7,031.0	2,836.4	2,409.9	678.2	696.1	-527.0	-260.9
2007	13,068.3	10,154.6	4,487.0	3,577.0	1,304.5	1,137.6	-472.7	-224.6
2008	8,749.8	6,914.0	2,721.4	2,270.7	485.7	548.7	-762.8	-413.0
2009	6,094.9	4,829.8	1,961.3	1,559.9	428.2	347.2	-427.9	-330.0
2010	8,308.5	6,696.0	2,617.8	2,232.6	507.3	577.2	-671.2	-347.2
2011	8,778.2	7,097.3	2,739.4	2,346.8	499.8	585.0	-750.9	-398.9
2012	8,820.6	7,221.3	2,727.9	2,384.2	468.3	590.3	-793.5	-411.5
2013	10,872.1	8,835.8	3,517.0	2,991.1	789.2	823.5	-734.0	-387.0
2014	11,503.3	9,020.2	3,676.6	3,038.0	774.0	819.4	-846.9	-419.5
2015	10,528.2	8,165.2	3,326.5	2,733.0	655.6	718.3	-835.8	-406.7
2016	10,425.1	8,185.1	3,332.2	2,748.2	701.8	731.9	-767.2	-394.1
Mean NPV	9,618.6 ± 1,268.6	7,650.0 ± 959.2	3,085.8 ± 452.9	2,571.9± 355.7	663.0 ± 166.9	688.7 ± 135.8	-690.0 ± 98.8	-363.0 ± 44.4

Variation of NPV in both trails was linked to fluctuations in timber prices, reaching the highest level before Global economic crisis in 2007 and dramatically declining right after it (Campello et al., 2010). Higher NPV (with 1, 3 and 5% interest rates) were in trial with narrower spacing (1×3 m) than in trial with wider (5 x 5 m) by 20, 17, and 4%, respectively, despite the additional costs of planting material. Differences in NPV between 1×3 m and 5×5 m spacings with the interest rates 3% and 5% were non–significant (P = 0.12 and 0.79, respectively).

Wider spacing may become a cost saving alternative for the forest owners setting higher interest rate for their investment, however, the financial return is very much affected by the fluctuations of round wood prices. Although, it should be remembered that our calculations did not include the branch or wood quality parameters, likely reducing the value of timber in plantation with wider spacing. Furthermore, the positive effect of establishment costs and valuable timber assortments in low density plantations may be applied only ensuring high survival of tree in young age (Zhang et al., 2002; Hynynen et al. 2010).

CONCLUSIONS

Low initial density (400 trees ha^{-1}) ensured significantly larger diameter and height (35 cm and 25 m, respectively) of Norway spruce at the age of 50 years than higher initial density (3,333 trees ha^{-1}). Notably (34%) lower yield at the point of final harvest still ensured similar income for the forest owner from the investment in establishment of the plantation with the interest rate 5%, but the actual profitability (NPV) was much dependent on the market prices of roundwood assortments.

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