Pre-commercial thinning regimes in Norway spruce stands on former agricultural lands in Latvia

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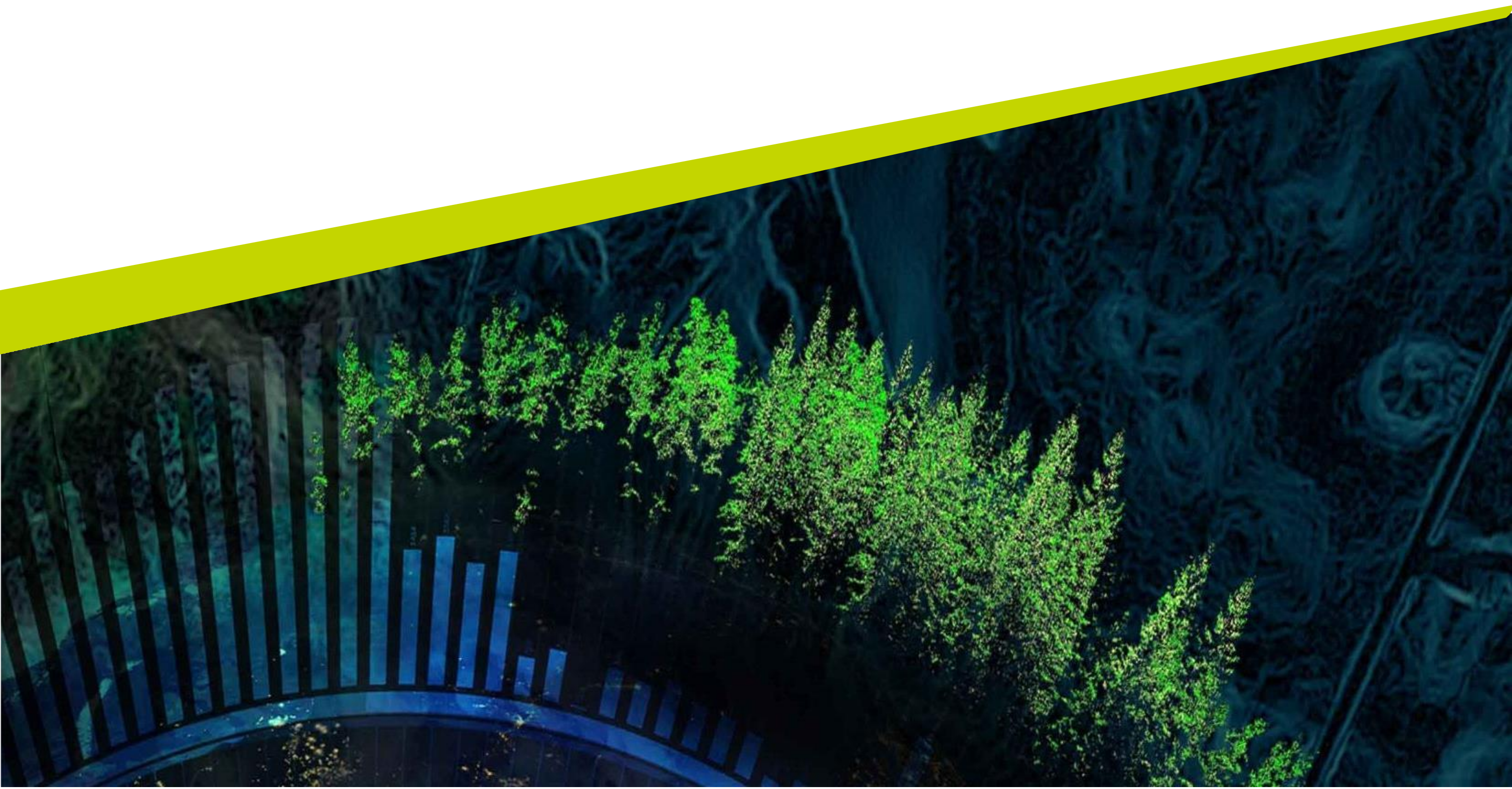

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Keywords: pre-commercial thinning, spacing, Norway spruce, former agricultural land, net present value, land expectation value.

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ABSTRACT

This study evaluated the effects of varying intensities and spatial patterns of pre-commercial thinning on stand structure and economic outcomes in Norway spruce (Picea abies) plantations established on former agricultural land in eastern Latvia. It was hypothesized that increased thinning intensity and spatial heterogeneity would lead to improved stand structural diversity and enhanced long-term economic returns.

We hypothesized that :

- Thinning regimes with lower intensity (e.g., retaining 1500 trees ha^{-1}) will produce higher total stand volume and long-term economic return, whereas higher intensity thinning (e.g., 500 trees ha^{-1}) will promote faster diameter growth but lead to lower cumulative yield and reduced profitability.
- Selective thinning that retains the 1,000 largest-diameter trees per hectare (1,000 U) will result in greater total stand volume and higher long-term economic return at rotation age compared to uniform thinning with evenly spaced trees (1,000 E), due to the enhanced growth potential of larger, more vigorous trees.

To test these hypotheses, four silvicultural treatments were implemented using a randomized complete block design across 20 × 20 m plots:

- 1500 E – 1500 trees per hectare were retained with even spacing between them.
- 1000 E – 1000 trees per hectare were retained, also evenly spaced.
- 1000 U – 1000 trees per hectare were left, but these were selected based on having the largest diameters, not spaced evenly.
- 500 E – 500 trees per hectare remained, evenly distributed across the area.

Over 17 years, tree diameter at breast height (DBH) and height were measured, and stem volume was calculated using species-specific height–diameter and volume functions to fill in data gaps. Stand attributes were statistically compared using one-way ANOVA followed by Tukey's Honest Significant Difference (HSD) test. Economic performance was evaluated through single-rotation net present value (NPV) and Faustmann's land expectation value (LEV), applying a 2.5 % discount rate and accounting for establishment costs, reforestation subsidies, pre-commercial thinning revenues, and final harvest income.

Our results confirm that wider spacing (500 E) accelerates diameter growth but reduces total stand volume. Contrary to our second hypothesis, the 1000 U treatment did not outperform 1000 E Both intermediate density regimes yielded similar outcomes in terms of volume, basal area, and economic returns. This similarity is likely attributable to competition among the largest retained trees within the plots.. Although these trees initially had a size advantage, their proximity may have intensified competition for light and resources, limiting their subsequent growth.

The economic analysis indicates that, although the 500 E treatment achieves harvestable dimensions earlier, it results in lower net present value (NPV) and land expectation value (LEV) compared to other treatments. In contrast, the 1500 E regime delivers the highest long-term profitability due to greater total volume production, which compensates for its higher establishment costs. While risks such as pests, windthrow, and market fluctuations may lead some managers to prefer lower initial densities for reduced exposure, our findings suggest that even spacing at 1500 trees ha^{-1}

is optimal for maximizing financial returns. A density of 1000 trees ha^{-1} with even spacing remains a reasonable compromise for those prioritizing operational simplicity and reduced risk.

Keywords: pre-commercial thinning, spacing, Norway spruce, former agricultural land, net present value, land expectation value.

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1.1 The effect of spacing on diameter and volume growth, quality of timber, and diameter distributions.

Pre-commercial thinning (PCT) improves forests' diameter growth and helps benefit the biggest and best trees in quality without any undesirable features like double tops, big branches, and damage to the main stem (Pitt et al., 2013). PCT is applied to proactively reduce stand density and can substitute natural, competition-driven mortality by selectively removing suppressed or less vigorous trees. (Pothier, 2001; Simard et al., 2004; Weiskittel et al., 2009).

A Latvian study compared forest stands that had undergone early pre-commercial thinning with those that remained untreated (e.g. Zālītis, 2017). The treated stands were either thinned at a young age or established with a relatively low initial planting density (approximately 1 000 trees per hectare). The results highlighted the importance of reducing competition between trees early in stand development. Specifically, competition should be minimized before trees reach a height of 2–5 m. When pre-commercial thinning was conducted before trees exceeded 5 m in height, the total growing stock after 20 years was approximately 5 m^3 ha^{-1} higher compared to untreated stands (e.g. Zālītis, 2017)

Thinning in dense young stands after the trees have reached a height of 10 m does not significantly stimulate the growth of the remaining dominant trees. Such thinning interventions are primarily justified when the forest owner aims to produce small-diameter assortments such as pulpwood and low-grade timber, rather than to enhance future crop tree growth (e.g. Zālītis, 2017).

A thinning experiment in Finland showed that performing pre-commercial thinning (PCT) in Norway spruce stands before saplings reached 1 m in height improved subsequent growth rates by 21–32% compared to thinning carried out after saplings had grown taller. The study recommends very early intervention because competing hardwood species can overtop spruce at this stage, forcing it to adapt to shaded conditions. Once shading species are removed, spruce requires time to readjust its needle structure to full light, delaying growth recovery. Furthermore, early thinning tends to be less expensive due to smaller tree dimensions. (Uotila & Saksa, 2014)

An experiment conducted in a lodgepole pine plantation in British Columbia demonstrated that close spacing, defined as 1.8 to 2.4 meters between trees, resulted in the highest stand volume per hectare and smaller average branch diameters compared to wider spacing. Specifically, at 1.8 m spacing (approximately 3,000 trees per hectare), individual trees averaged around 0.048 m^3 in volume. In contrast, wider spacing of 5.5 m (about 300 trees per hectare) produced trees with larger crowns, greater bole diameter, and per-tree volumes up to 0.144 m^3, though the total stand volume per hectare was significantly lower. These findings highlight the trade-off between maximizing individual tree dimensions and optimizing total wood production per unit area. (Johnstone, 1990)

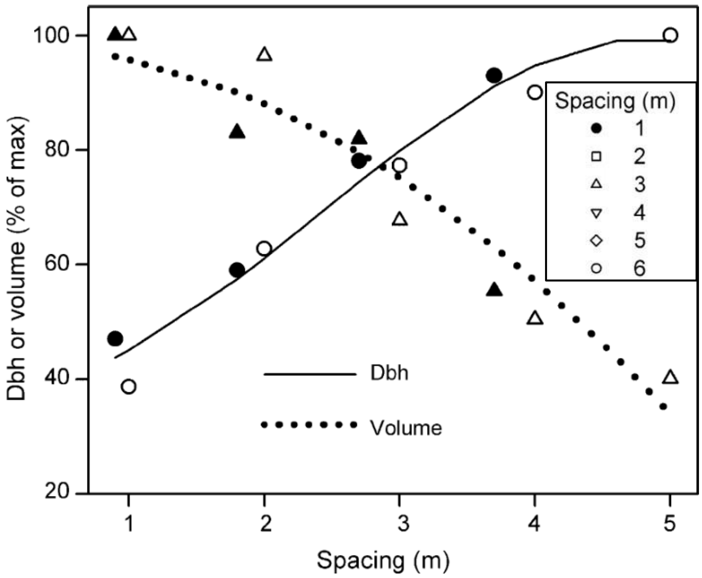
Even though spacing impacted diameter growth significantly the same cannot be said for height growth, which showed no significant difference in all spacing variants.

By comparison, in the spacing 747 stems/ha mean total volume per tree where more than double comparison of 2991 stems/ha, and for the past 5 years volume growth per tree was 3 times higher in the wide spacing than in the 2990 stems/ha(Johnstone, 1990)

In a spacing experiment in Douglas Fir the average DBH increased by 100 % from 8.5 to 17 cm when spacing was increased from 1 m to 3 m, but when spacings 4 to 6 m were compared, the diameter increase was only from 19.8 to 22.7 cm (6 %) (Harrington et al., 2009). The same can be said about the slenderness ratio, crown width, crown length, crown ratio, basal area, and Stand Density Index %.(Harrington et al., 2009)

The impact of competition on tree diameter growth has been shown in many other studies. In an experiment in Germany, the mean tree diameter at breast height at the age of 28 was 30.7 cm, and the mean height was 15.7 m in the spacing of 350 trees per hectare. (Mäkinen & Hein, 2006). In the spacing of 700 trees per hectare, DBH was 25.9 cm, and height 16 m, and in the spacing density of 1600 trees per hectare mean DBH was 20.7 cm, and the mean height was 17.2 m.

Average DBH and stand volume after 25 years of establishing of stand intersected when spacing was 2.9 m (Fig. 1).(Harrington et al., 2009) It shows an optimal way to consider both variables to have both reasonably fast DBH and volume growth. Spacing over 3 m between trees didn't drastically improve DBH growth when comparing when spacing was increased from 1 m to 3m.



Source: (Harrington et al., 2009)

Figure 1. Regression Relationship between dbh and stand volume.

1.2 EFFECTS AND RISKS OF LOW STAND DENSITY

High stand density and late precommercial thinning have been used to improve timber quality in terms of branch size. Since wide spacings help to increase branch longevity, it also means that the branches will be bigger in diameter. In a German spacing experiment, the mean diameter of the thickest branch in spacing 350 trees per hectare was 5.5 cm, in spacing 700 – 4.5 cm, and in 1600 – 3.8 cm.(Mäkinen & Hein, 2006) In addition, the height of the first living branch is higher in dense stands.

However, the smaller the size of the branch is the slower the growth of the tree since there is less area of leaves that are responsible for photosynthesis.(Mäkinen & Hein, 2006)

In Latvia, it is allowed for second-class spruce sawlogs to have all types of branches (dead, living, etc.) below 80 mm in diameter. Even the thickest branch in the previous German experiment did not exceed that since it was only 71 mm in diameter for the biggest measured branch.(Greģe-Staltmane, 2013)

To have shorter rotation periods, we need to focus more on diameter growth. Since branch width in spares densities does not drastically reduce Norway spruce timber quality, sparse spacings can be used for improving diameter growth and reducing rotation length.(Mäkinen & Hein, 2006).

Another benefit of wide-spacing forestry practices is that the wider the spacing, the lower the tree mortality. In the UK experiment of Stika spruce in the spacing of 5.49 x 5.49 m, mortality was only 3 %, while in the spacing of 1.83 x 1.83 m, it was 60 %.(Moore et al., 2009) Of course, tree mortality was used to determine how much timber we can get from commercial thinning. Still, knowing that spacing has an impact on tree mortality, it may be more cost-effective to establish a forest stand with wider spacings. What's interesting is that the biggest volume in this experiment wasn't in the densest stand but the middle one, where spacing was 3.66 x 3.66 m, with a mortality of 20 %. Another benefit of wide-spacing forestry practices is that the wider the spacing, the lower the tree mortality.

In the UK experiment of Stika spruce in the spacing of 5.49 x 5.49 m, mortality was only 3 %, while in the spacing of 1.83 x 1.83 m, it was 60 %. Of course, tree mortality was used to determine how much timber we can get from commercial thinning, but knowing that spacing has an impact on tree mortality, it can be cheaper to establish a forest stand with wider spacings. What's interesting is that the biggest volume in this experiment wasn't in the densest stand but the middle one where spacing was 3.66 x 3.66 m, with a mortality of 20 %. (Ulvcrona & Ahnlund Ulvcrona, 2011)

Another problem in spruce forests is root rot, which can be reduced if the rotation periods are kept short, so wide spacing can achieve this goal. Old fields and fields where there were grazing before have been proven to be more susceptible to root rot than old coniferous or hardwood sites (Sierota, 2013). Thinning Spruce stands helps spread root rot through infected stumps, so forest practices where no thinning will be done will reduce the risk of spruce getting root rot. (Thor, 2005; Vollbrecht & Agestam, 1995)

It has been proven that spacing rectangularity has no significant effect on tree height, diameter development and volume, and basal area growth per hectare, also it does not impact mortality.(Ara et al., 2021; Brand et al., 2012; Sharma et al., 2002)

Although square spacing has traditionally been considered optimal for tree growth due to uniform competition among trees, recent findings suggest that rectangular spacing results in similar growth outcomes as long as the number of trees per hectare remains constant. This indicates that the spacing layout itself (square vs. rectangular) may be less influential than the overall tree density. (Ara et al., 2021; Brand et al., 2012; Sharma et al., 2002)

Moreover, rectangular spacing can offer practical operational benefits, such as reduced planting costs and improved accessibility for thinning operations. In the study by Aras (2021), the use of 5-meter row spacing was sufficient to accommodate forwarders, effectively establishing early skidding corridors. This not only simplifies mechanized thinning but also reduces future stand damage and operational costs. Therefore, the benefits of rectangular spacing might not stem from biological growth responses, but rather from facilitated forest management practices.

1.3. PLANTATION ESTABLISHMENT

It is possible to reduce soil scarification costs by using disc trenching, as research has shown that planting trees in a rectangular design does not affect tree growth speed by comparing to square planting (Ara et al., 2021) The key factor influencing stand development is the number of trees per unit area, rather than their exact spatial arrangement.

In the experiment conducted by Ara et al. (2021), trees were planted at a density of 2,500 individuals per hectare, corresponding to a 2 × 2 m spacing. In comparison, Latvian forest restoration regulations stipulate a minimum density of 800 saplings per hectare, which translates to a minimum area of 12.5 m² per tree. This requirement could be met with a spacing arrangement such as 2.5 × 5 m. While the experimental design used a considerably higher planting density than the national minimum, this does not imply any contradiction. Higher densities are often used in experimental settings to analyze growth dynamics under intensive conditions, whereas practical reforestation efforts may adopt wider spacing following legal thresholds and cost-efficiency considerations.(Ara et al., 2021)

Increasing row spacing while maintaining column width reduces the number of trenches required during disc trenching, leading to lower soil scarification costs. Additionally, wider row spacing facilitates future management operations such as fertilization and thinning, minimizing damage to the remaining trees. (Ara et al., 2021)

Back in 1998 and 1999 abandoned farmland owners whose soil fertility was not suitable for growing agriculture crops or there were other reasons why farming was abandoned could apply for EU subsidies for the afforestation of annual ~140 USD per ha. Subsidies were given not only for stand establishment but also for stand tending during the first 3 years after establishment.(Weber, 2000)

The European Union (EU) provides financial support for afforestation on agricultural land through subsidies that cover a portion of the total establishment costs. The aid intensity—that is, the percentage of total eligible costs covered by public funding—is typically set at 60%, though this rate may increase under certain conditions. Factors such as the landowner’s age (e.g., under 40 years), agricultural education, or the size and location of the planting area may make one eligible for enhanced support. Therefore, while a substantial share of the afforestation costs is subsidized, the remaining portion (typically 40%) must be covered by the landowner. This funding is granted per eligible applicant, not per hectare, meaning the total amount of support depends on the size of the project and the characteristics of the applicant. (Latvian Cabinet of Ministers, 2023b, 2023a)

In addition to afforestation subsidies, financial support is also available for agro-technical care, which involves clearing weeds around newly planted trees, and for pre-commercial thinning, an early silvicultural intervention aimed at improving stand quality. Both of these measures also have an aid intensity of 60%, requiring the landowner to contribute the remaining share of the costs.

1.4. MAIN OBJECTIVE AND HYPOTHESIS

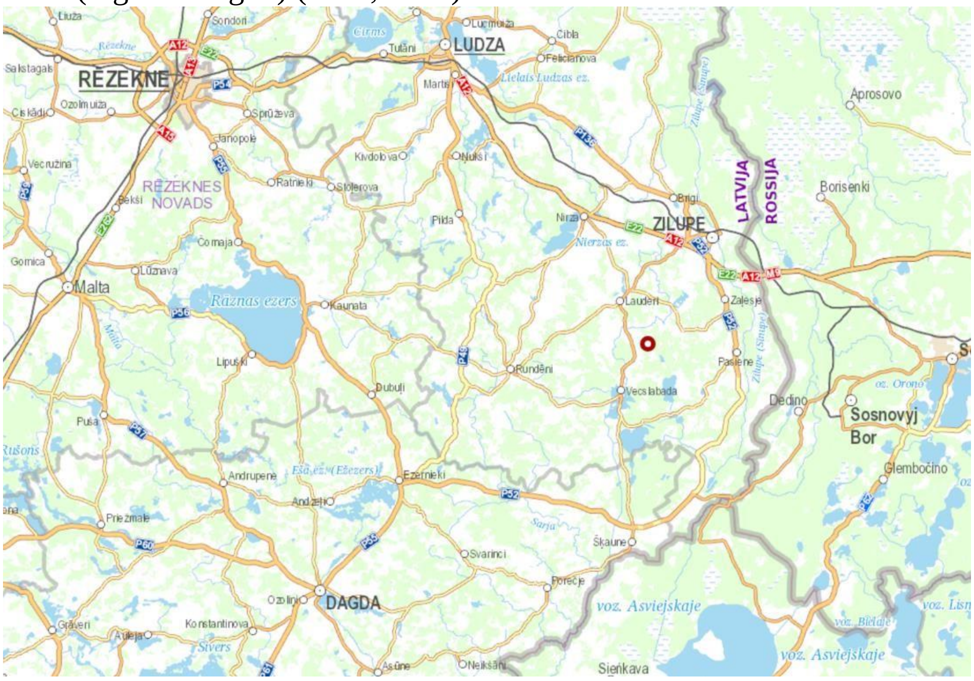
The main objective of the thesis is to examine the effects of different intensities and single tree selection in PCT on the growth of future stands.

Hypothesis: Pre-commercial thinning (PCT) with wider spacing results in reduced total volume production by the end of the rotation period. However, this reduction is offset by eliminating the need for future thinnings and by enabling a shorter rotation length due to accelerated diameter growth. Furthermore, the spatial arrangement of the retained trees (i.e., even vs. uneven spacing) is hypothesized to have minimal influence on long-term volume production.

2. Materials and methods

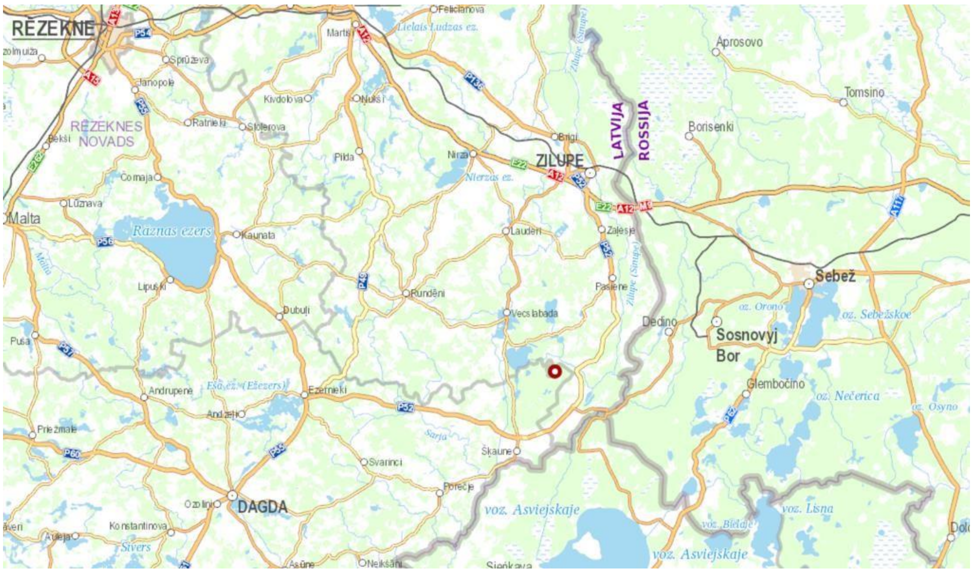
2.1 STUDY SITE

The experimental sites were located in East Latvia, near the border with Russia—the closest town in Latvia is Zilupe. The experiment consisted of 2 stands with fertile soil. (Fig. 2 & Fig. 3).(Loks, 2020)



Source: balticmaps.eu

Figure 2. First Stand location (56°17'58.4"N 28°01'37.6"E).



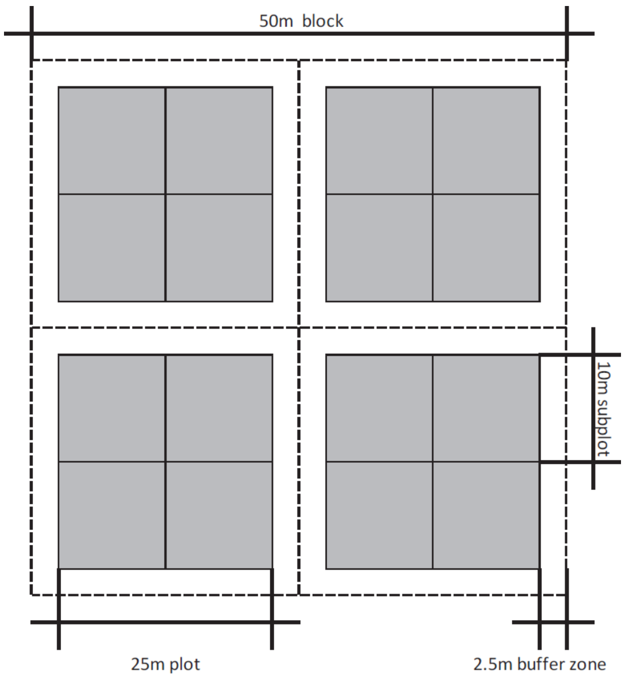
Source: balticmaps.eu

Figure 3. Second Stand location (56°12'26.7"N 28°03'54.2"E).

The height of selected stands was 11-13 m, they were 17 years old, and the first pre-commercial thinning had been done when the stands were 13 years old. Sites with homogeneous site conditions were chosen, so plots would have as equal as possible growing conditions.. All study sites were regenerated with 2000 seedlings/ha with a spacing of 1,6×3 meters.(Loks, 2020)

2.2. Experimental design

A randomized complete block design was used in the experiment (Fig. 4). The area was divided into 4 similar parts, and in each part a square block of the size 50 x 50 m^2 was established. Each square plot consisted of 4 plots with a size of 20 x 20 m with a 2.5 m buffer zone where the same PCT treatment has been done. Each 20 x 20 m plot was divided into 4 10 x 10 m subplots.



Source: (Loks, 2020)

Figure 4. Scheme of randomized complete block design.

2.3 PCT TREATMENTS

In total, in the year 2020. 4 PCT treatments have been used:

- Even spatial distribution of trees after PCT, leaving 500 trees ha^{-1} (500E)
- Even spatial distribution of trees after PCT, leaving 1000 trees ha^{-1}, favouring even spatial distribution between trees (100E)
- Even spatial distribution of trees after PCT, leaving 1000 trees ha^{-1} with the largest dbh (1000U)
- Even spatial distribution of trees after PCT, with density defined from the density of the plot with the lowest density before PCT (1500 trees ha^{-1}) (1500E).

In total, there were 32 square plots with a total area of 2 ha.(Loks, 2020)

PCT in 2020 was done by removing all non-target species, damaged trees, or bad-quality trees, favoring good-quality trees. An effort was made to have an even spacing between retained trees (depending on thinning intensity).(Loks, 2020)

2.4 MEASUREMENTS AND DATA PROCESSING

All trees were measured in dbh (mm), and height (m) was measured for 20 trees in each plot.

To compare each treatment, the quadratic mean diameter was calculated (QMD)

$$QMD = 100 * \sqrt{\frac{4Ba}{\pi N}} \tag{1}$$

- Ba sum of basal area of all trees at the breast height (m^2 ha^{-1})
- N – number of trees per hectare

basal area for each individual tree (Ba)

$$Ba = \frac{\pi d^2}{40000} \tag{2}$$

- d – diameter of tree (cm)

Basal area weighted mean height (Hbaw)

$$Hbaw = \frac{\sum_{i=1}^{n} ba_i h_i}{\sum_{i=1}^{n} ba_i} \tag{3}$$

- n – number of tree objects

- ba_i – basal area at breast height for tree object (m^2 ha^{-1})
- h_i – height for tree object (m)

Standard deviation SD

(4)

$$Sd = \sqrt{\frac{\sum(x-\bar{x})^2}{(n-1)}}$$

- x – sample means of observations
- n – sample size

Since height was not measured for all trees within each sample plot, tree heights for unmeasured individuals were estimated based on their diameter using a Näslund-type height–diameter function. (Nigul et al., 2021; Wykoff et al., 1982)

(5)

$$h(d) = 1.3 + (\frac{d}{a + b * d})^3$$

- $h(d)$ – tree height for a specific diameter
- d – diameter at breast height
- a, b – model parameters, estimated separately for each treatment group

Volume for all sample trees with height measurements with diameter at breast height (dbh) above 5 cm were calculated using Brandel's Function (Brandel 1990). For sample trees with dbh below 4 cm Anderssons function (Andersson 1954) was used. For trees with dbh between 4-5 cm, a weighted volume is calculated with Brandel and Andersson functions. All calculated volumes were converted from cubic decimeters to cubic meters.

(6)

$$V_{Brandel} = (10^{-1.02039} * (dbh^{2.00128} * 20)^{-0.47473} + h^{2.87138} * (h - 1.3)^{-1.61803})/1000$$

$$V_{Andersson}=0.22+0.10860*dbh^2+0.01712*dbh*h+0.008905*dbh*h^2)/1000$$

(7)

- dbh – diameter at breast height (cm)
- h – tree height (m)

To evaluate stand development over time, individual tree volume growth was calculated.

(8)

$$Volume\ growth = \frac{V_{2024} - V_{2017}}{7}$$

- V_{2024}, V_{2017} – Individual tree volume for the representative year

To assess long-term productivity, the mean annual increment (MAI) was calculated as:

(Fahlvik N., 2014; Tomter et al., 2016; Uotila & Saksa, 2014)

(9)

$$MAI=\frac{V_{final}\pm V_{thinnigs}}{Age}$$

If we want to evaluate at which age we receive the highest land expectation value (LEV), we need to calculate net present value (NPV) first.(Susaeta & Demers, n.d.)

(9)

$$NPV = \sum\left(\frac{net_{thin}}{(1+r)^t}\right) + \frac{net_{final}}{(1+r)^T} - regen - pct$$

- net_{final}- revenue from final harvest EUR
- net_{thin} – revenue from thinning in EUR
- t - The year when thinning is conducted
- T - the year when the final harvest is conducted
- p– discount rate (2.5 %)
- $regen$ – stand establishment cost (seedlings, soil scarification and planting cost) EUR
- pct – precommercial thinning cost (EUR)

Land expectation value (LEV) was calculated using Faustmann's (1849) formula to compare the economic return of different spacing treatments. (Helmedag, 2018)

(10)

$$LEV = NPV * \left(\frac{(1+r)^T}{(1+r)^T - 1}\right.$$

- NPV – net present value
- r – discount rate
- T – rotation age

2.5. STATISTICAL ANALYSIS

Since we have one independent variable—treatment—we used one–way ANOVA to compare all of the treatments and see their impact on stand volume**.** (Åhle & Wold, 1989)

$$F = \frac{MSB}{MSW} \quad (11)$$

Where:

- MSB – mean square between groups
- MSW – mean square within groups

If ANOVA indicates a significant overall effect of treatment ($p < 0.05$), we then apply Tukey’s Honest Significant Difference test to conduct all pairwise comparisons, identifying which treatment means differ significantly and which remain statistically similar.(Abdi & Williams, 2010)

$$HSD = q_{a,k,v} \times \sqrt{\frac{MS_{within}}{n}} \quad (12)$$

- $q_{a,k,v}$ - studentized range critical value (α-level, k groups, ν = N-k df)
- MS_{within} - Within-group mean square from ANOVA
- n - per-group sample size

3. RESULTS

The results showed that treatment 500 E had significantly lower yearly volume growth compared to all other treatments, and treatment 1500 E showed the highest estimated mean and was significantly higher than all other treatments (Figure 4). No significant differences were observed between treatments 1000 E and 1000 U. (Appendix 1.)

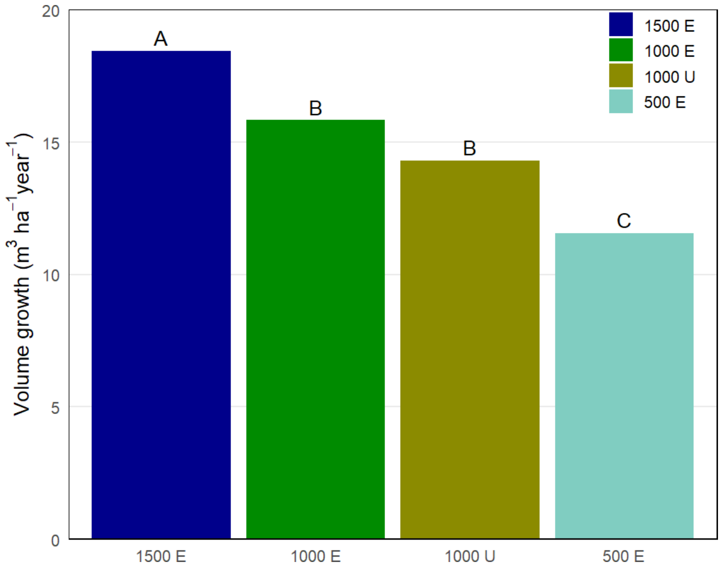


Figure 5. Yearly volume growth (m3 ha $^{-1}$ year -1). The grouping letters indicate statistically significant differences, where treatments sharing the same letter cannot be shown to differ significantly from each other.

Volume and basal area were highest in the 1500 E treatment and lowest in the 500 E treatment in both 2017 and 2024 (Fig. 6). The 1000 E and 1000 U treatments did not differ significantly in either volume or basal area. In contrast, quadratic mean diameter (QMD) exhibited an inverse trend: the largest QMD was observed in the 500 E treatment, while the smallest was in the 1500 E treatment. This reflects the expected outcome that wider spacing promotes individual tree growth in diameter. Treatments had no statistically significant effect on mean tree height across treatment groups (Fig. 5).

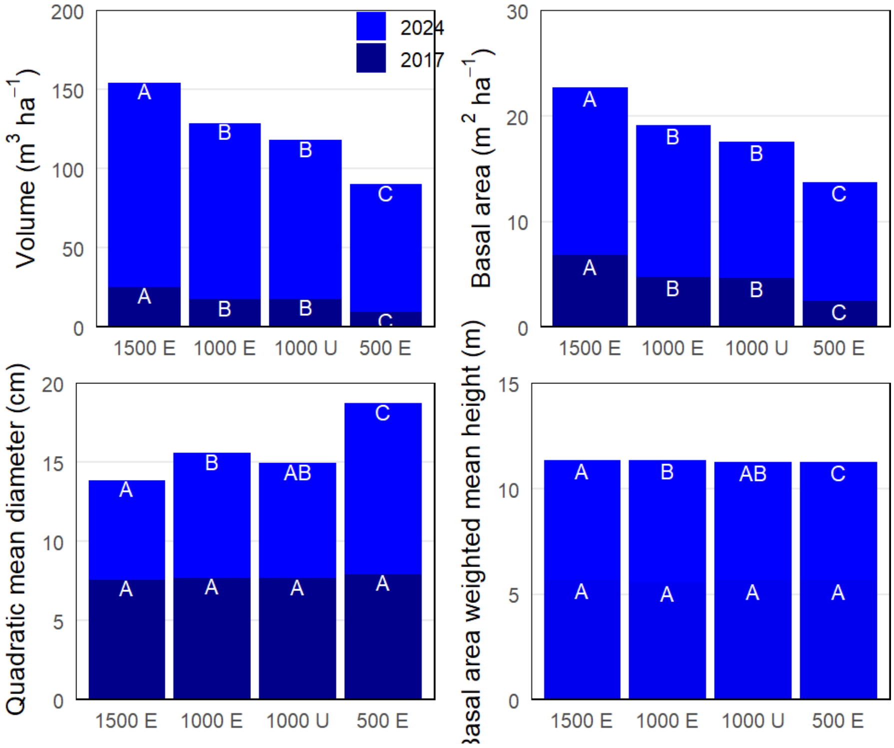


Figure 6. Comparison of Stand Parameters Across Different Years.

When comparing the 500 largest trees, the 500 E treatment exhibits the highest estimated mean volume at 90.2 m³/ha and is significantly greater than the 72.8 m³/ha in the 1000 U treatment, because 500 E alone occupies Tukey group b while 1000 U, 1000 E (81.9 m³/ha) and 1500 E (75.7 m³/ha) all fall into group a or ab. This indicates that neither increasing density beyond 1000 trees per hectare nor choosing an even versus uneven layout increases mean volume—only the 500 E treatment achieves a significantly higher volume (Appendix 2).

When comparing the trees in the group of the 500 – 1000 largest trees, no significant differences were observed between the treatments. (Appendix 3.)

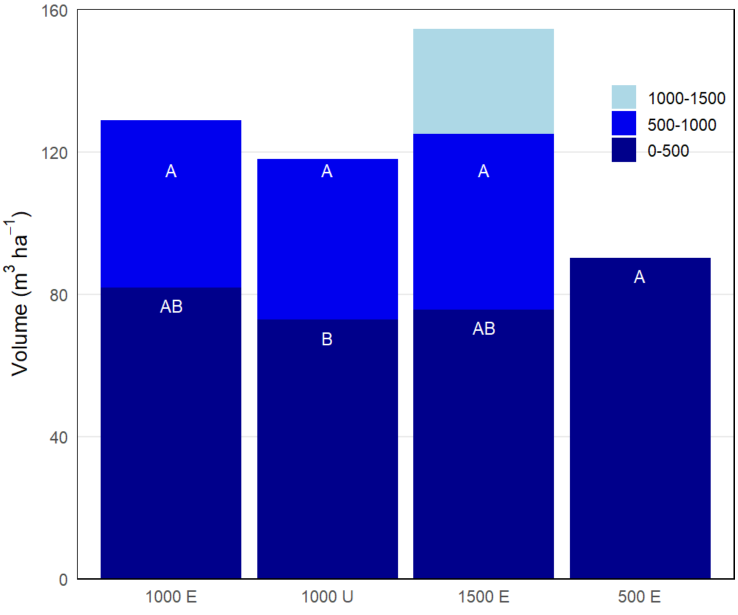


Figure 7. Comparison of volume across different groups of the largest trees.

When analyzing future projections of stand development, the results indicate that the Mean Annual Increment (MAI) reaches its peak at the age of approximately 45 years across all spacing treatments (Fig. 7). This suggests that, within the specific site and soil conditions of the study area, the volume productivity of Norway spruce (Picea abies) culminates around the same rotation age regardless of initial stand density. This outcome also corresponds with the economically optimal clear-cutting age, as determined by the maximum Land Expectation Value (LEV). It should be noted, however, that the peak age of MAI can vary depending on site quality, including factors such as soil fertility and climatic conditions.

At the age of 20, trees in the 1,000 E and 1,000 U treatments had a higher proportion of individuals exceeding the commercial thinning threshold of 0.06 m^3 in volume compared to other treatments. These trees were predominantly found in the 500–1,000 largest trees per hectare class. In contrast, the 1,500 E treatment, while having the highest total standing volume per hectare, contained a greater share of smaller trees, many of which were still below the harvestable volume threshold. The 500 E treatment showed the lowest total volume and basal area and also had fewer trees above the 0.06 m^3 mark. This volume threshold—equivalent to a DBH of approximately 12–13 cm—is generally accepted by forestry companies in Latvia as the minimum for economically viable thinning interventions.

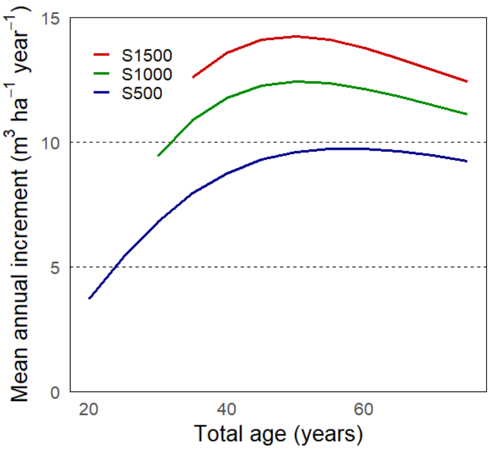


Figure 8. Comparison of MAI across different treatments.

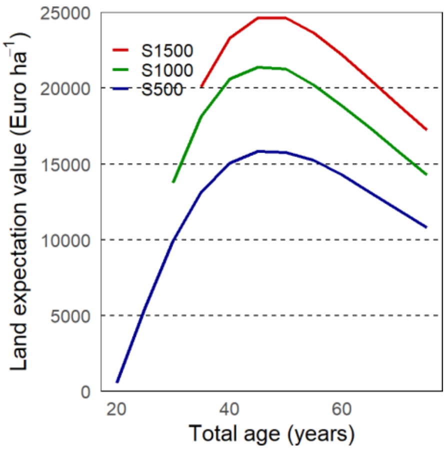


Figure 9. Figure 8. Comparison of LEV across different treatments.

LIMITATIONS

Since the experiment was carried out on fertile former agricultural land, the observed growth and economic performance may not directly translate to less fertile forest soils. Site productivity should therefore be considered when applying these results more broadly.

It is acknowledged that thinning can influence tree taper, potentially affecting the accuracy of volume estimates based on standard allometric equations such as those by Brandel or Andersson. Since these models are typically fitted on datasets from unthinned or uniformly managed stands, the change in stem form after thinning — particularly in low-density treatments, could introduce bias in volume estimation. This is especially relevant in the S500 treatment, where reduced competition may encourage thicker crowns and altered bole shapes. While our study did not include taper measurements or stem form assessments to directly evaluate this effect, the consistent application of volume models across all treatments allows for relative comparisons. Future research could incorporate taper-specific volume models or use taper functions calibrated for thinned stands to improve precision.

While this study focuses on total volume and LEV as indicators of economic return, it does not account for the distribution of volume among different tree size classes. In practice, a greater share of volume concentrated in larger-diameter trees often translates into higher financial value due to better assortments (e.g., sawlogs) and more efficient harvesting. Consequently, treatments that promote early diameter growth may offer improved economic outcomes beyond what is reflected in aggregate volume or LEV calculations. Future research could incorporate price differentiation by assortment or simulate value-based thinning strategies to capture this effect more precisely.

DISCUSSION

In forestry, the primary objective is often to achieve the target diameter as quickly as possible. In Latvia, the target diameter for Norway spruce varies between 27 and 31 cm, depending on the site index, with the highest value (31 cm) designated for fertile lands (Constitutional Court of Latvia, 2024).

In addition to economic considerations, the timing and intensity of thinning also influence stand health. For example, denser treatments like 1,500 E may delay the first profitable thinning due to a higher proportion of undersized trees. However, postponing thinning increases the risk of mechanical damage during later interventions, such as root and stem injuries, which can serve as entry points for fungal pathogens and attract bark beetles.(López-Andújar Fustel et al., 2024; Olga Miezīte, 2015; Wallentin, 2007) o reduce the likelihood of such damage and associated infections, thinning operations are commonly recommended during winter, when frozen soil conditions protect root systems.

The results suggest that the S500 treatment, which focuses on early selection of the most vigorous individuals, can be an effective strategy when the goal is to minimize management interventions. This approach eliminates the need for subsequent commercial thinning and may lower operational costs. However, it also produces the lowest total volume per hectare and fewer marketable-sized trees by age 20, limiting potential for intermediate income. In contrast, treatments retaining 1,000 or 1,500 trees per hectare support earlier commercial thinning opportunities, making them more suitable for owners prioritizing periodic revenue generation.

Despite their differing initial densities and thinning regimes, all treatments in this study exhibited a convergent optimal age of 45 years for both Mean Annual Increment and Land Expectation Value. This suggests that while early growth dynamics and thinning opportunities vary, the biological and economic rotation age remains similar across treatments when site conditions are held constant. Therefore, the choice between spacing regimes may depend more on cash flow preferences, operational flexibility, and long-term risk management, rather than on differences in final harvest timing.

The 1000 U and 1000 E treatments produced nearly identical post-thinning volumes, with only a slight, non-significant tendency toward lower volume in the 1000 U treatment. This indicates that selecting the largest individuals does not result in a meaningful growth advantage over evenly spaced thinning when tree density is held constant. Therefore, even spacing may be preferable from an operational standpoint, as it simplifies layout and management without sacrificing productivity.

However, an unevenly established planting regime may offer advantages in terms of cost reduction. For instance, a 5 × 2 m spacing pattern requires fewer soil scarification ditches than the standard 3.16 × 3.16 m spacing, thereby lowering site preparation costs. Additionally, this arrangement can be beneficial during commercial thinning, as it naturally provides space for machine access without the need to create additional forwarding trails. This spatial configuration can thus improve both economic efficiency and operational practicality.

Treatments with lower planting densities, such as the 500 trees per hectare regime, incur significantly lower establishment costs, which can improve long-term investment profitability. In Latvia, the cost for 1,000 container-grown Norway spruce seedlings is 285.56 EUR including VAT (or 236 EUR excluding VAT). Based on this, seedling expenses alone range from 428.34 EUR/ha for the 1,500 seedlings per hectare treatment to just 142.78 EUR/ha for the 500 seedlings per hectare treatment. In addition, lower densities can reduce site preparation expenses, such as soil scarification, due to fewer planting rows. These cost reductions contribute to a higher net present value (NPV), as lower upfront investment enhances the financial return of forest stands. (Latvian State forest, 2025)

Assuming a discount rate of 2.5%, as commonly used in Nordic Forest economics (Brukas et al., 2001), LEV analysis demonstrates that the highest long-term financial return is obtained from the densest treatment (1,500 trees ha^{-1}), while the lowest return is associated with the sparsest treatment (500 trees ha^{-1}) (Fig. 8). These results may appear counterintuitive, given the faster diameter growth and earlier harvest potential in lower-density stands. However, the substantially higher cumulative volume production in denser stands compensates for higher establishment costs, thus yielding a greater LEV when returns are evaluated across infinite cycles of rotation — a key assumption of Faustmann's perpetual forest model.

In Latvia, the felling of Norway spruce is legally permitted once the average stand diameter reaches 31 cm. According to the simulation results, the 500 trees per hectare treatment achieves this target diameter sooner, around the age of 33, while the 1500 trees per hectare treatment reaches it approximately at the age of 38. (fig. 9.)

Although the difference is only about five years, it highlights the accelerated diameter growth in lower-density stands due to reduced intraspecific competition. This can be an important consideration in management planning, especially where early income or rotation flexibility is desirable.

Furthermore, earlier diameter attainment may provide opportunities for earlier harvesting decisions without compromising legal or silvicultural standards. (Constitutional Court of Latvia, 2024)

This study evaluated the impact of different stand density treatments (500, 1000, and 1500 trees per hectare) on the growth, yield, and economic performance of Norway spruce (Picea abies) stands in Latvia using empirical field data and long-term simulations.

Results showed that lower initial spacing (S500) promoted faster diameter growth, allowing stands to reach the legally required average DBH of 31 cm for clearcutting sooner — around the age of 33 compared to age of 38 for the densest treatment (S1500).

However, despite this earlier operability, the highest Land Expectation Value (LEV) was achieved in the S1500 treatment, driven by its greater cumulative volume production. All treatments, regardless of spacing, exhibited an optimal rotation age of 45 years, both in terms of LEV and Mean Annual Increment (MAI), suggesting that site productivity and discount rate (2.5%) were more influential in determining optimal harvest timing than initial planting density.

The S500 treatment offers management simplicity and enables earlier stand operability, making it suitable for landowners seeking reduced intervention and faster access to timber revenues. In contrast, the S1500 treatment demonstrates the highest long-term land expectation value (LEV) due to greater cumulative yield, albeit at the cost of increased establishment and tending expenses. The S1000 treatment emerges as a balanced compromise, providing viable thinning opportunities, solid diameter growth, and strong long-term economic performance.

Ultimately, the choice of initial spacing should align with the forest owner's objectives — whether the goal is to maximize long-term returns, generate earlier cash flow, or minimize management intensity. It is important to note, however, that the superiority of the S1500 regime is conditional. In an ideal context with no significant biotic or abiotic risks (such as storms, pests, or disease outbreaks), its productivity and profitability would justify the higher input costs. But under real-world risk scenarios, higher stand densities may increase vulnerability, reduce resilience, and complicate risk mitigation. Therefore, spacing regimes should not be chosen solely based on yield potential, but also on site-specific risk profiles, management capacity, and broader ecosystem objectives.

This study supports the notion that stand density is a powerful management lever, not only influencing biological growth patterns but also shaping the economic trajectory of forest investments. Future research could integrate market price dynamics, carbon valuation, and biodiversity considerations to broaden the assessment of optimal stand management strategies under climate-adaptive forestry.

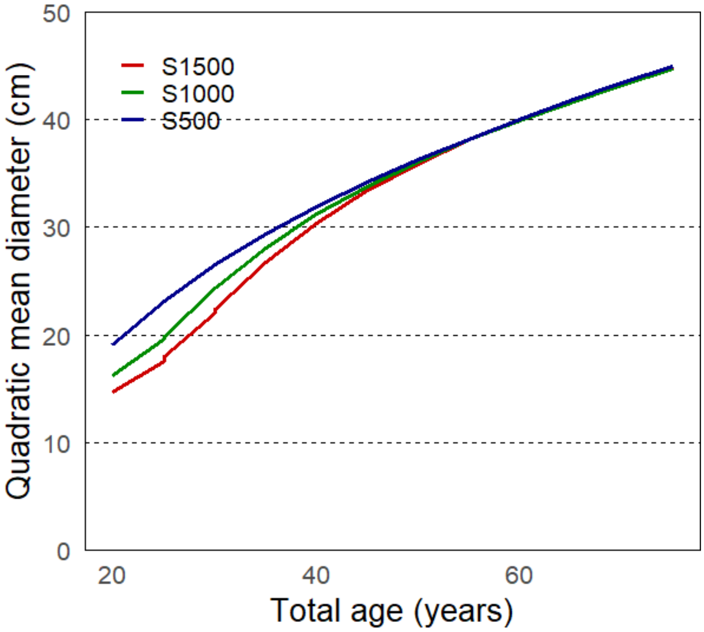


Figure 10. Quadratic mean diameter development compared to different spacing treatments over stand age.

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APPENDIX

Appendix 1.

Treatment	Estimated Mean (emmean)	Standard Error (SE)	Degrees of Freedom (df)	Lower CL	Upper CL	Group
500 E	11.6	0.582	28	10.4	12.8	a
1000 U	14.3	0.582	28	13.1	15.5	b
1000 E	15.8	0.582	28	14.6	17.0	b
1500 E	18.5	0.582	28	17.3	19.6	c

Source: Rstudio

Appendix 2.

Volume comparrsion of bigest 500 trees

Treat	emmean	SE	df	lower.CL	upper.CL	group
1000 U	72.8	5.43	2.43	53.1	92.6	a
1500 E	75.7	5.43	2.43	55.9	95.5	ab
1000 E	81.9	5.43	2.43	62.2	101.7	ab
500 E	90.2	5.43	2.43	70.4	110.0	b

Source: Rstudio

Appendix 3.

Volume comparrsion of bigest 500 - 1000 trees

Treat	emmean	SE	df	lower. CL	upper. CL	group
1000 U	45.2	2.05	20.1	40.9	49.5	a
1000 E	47.0	2.05	20.1	42.7	51.2	a
1500 E	49.4	2.05	20.1	45.2	53.7	a

Source: Rstudio

Appendix 4.

Average tree volumes in difrent size clases (0- 500, 500 – 1000 and 1000-1500.)

Treat	Tr Class	Vol 24 ha	Mean Vol	Vol Tukey	Tukey Pos
1000 E	0-500	81.94445	0.16388891	AB	81.94445
1000 E	500-1000	46.96403	0.09447391	A	120.00000
1000 U	0-500	72.83994	0.14567987	B	72.83994
1000 U	500-1000	45.19416	0.09204161	A	120.00000
1500 E	0-500	75.69968	0.15139935	AB	75.69968
1500 E	1000-1500	29.32164	0.06214497	-	29.32164
1500 E	500-1000	49.44438	0.09888876	A	120.00000
500 E	0-500	90.23252	0.18159970	A	90.23252

Source: Rstudio

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