Appropriate experimental design and Pre-commercial thinning regime in Norway spruce Stands on former agriculture lands in Latvia

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Abstract

Recent decades Latvian land usage has change and lot of unused agricultural lands has been reforested. These areas show difference by increased growth from typical forest land, because of this trait stands need different silvicultural treatments, implementation time and intensity. Norway spruce (*Picea abies*) is one of the main species afforested agricultural lands, because of it growth and wood quality properties. Experimental plots were established in south east Latvia, because this region has large proportion of abandoned agricultural land afforested.

One of first important silvicultural practice for managing stand development is pre-commercial thinning (PCT). It allows to alter future stands characteristics by choosing what trees will be left for future forest. PCT allows changing species composition, density and tree quality left after implementation that has direct effect on future growth.

Main objective for thesis was to distinguish appropriate long-term experimental design for assessing effect of different intensity PCT on growth of future stand as well model economical outcome for each treatment.

Randomized complete block design was chosen as appropriate experimental design. Four PCT-treatments were established. The treatments were 1) even distribution PCT retaining 500 trees ha^{-1}, 2) even distribution PCT retaining 1000 trees ha^{-1} favoring even spatial distribution between trees, 3) PCT retaining the 1000 trees ha^{-1} with the largest dbh and 4) even distribution PCT with density defined from density of the plot with the lowest density before PCT (1500 trees ha^{-1}). Economical outcome was modeled with heureca using five different scenarios that differed in number of thinnings (2,1,0) that were applied during rotation. Treatment 1500 trees ha^{-1} showed best economical results. It showed by 17.6% (Stand 1.) and 12% (Stand 2.) larger max NPV+LEV than closest treatment. Treatments with lower density didn't give significant gain of lowering rotation age as well decreased economical return.

Key words: management regime, heureka, randomized complete block design, density, economical rotation age, land expectation value.

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1 Introduction

1.1 Background

Territory of Latvia is 6.46 million ha large, from that 51% is forest land. Compared to 1923 forest land area has increased by 28% (State Forest Service, 2018). After independence gain in Latvia agriculture sector got into standstill, because of the destruction of the previous system (Liepiņš 2013). During agrarian reform 36.6% agricultural land and 42% of forest land become property of private owners (Daugaviete et al., 2017). After the restitution, the agriculture sector started to developed slowly and at beginning only the most fertile sites were used (Liepiņš 2013). Other agriculture lands started to reforest slowly with trees or stayed as grasslands because of strong competition from ground-vegetation. Forest land area in Latvia is still increasing, because of artificial and natural reforestation of unusable agriculture land (State Forest Service, 2018). One option for unmanaged agricultural lands was to establish forest and very common tree species was *Picea abies*. Large areas throughout Latvia were reestablished with forest.

Afforestation is establishment of forest on sites that was not previously land covered with forest. Afforestation in abandoned agriculture lands have many purposes as rational land usage, pollution decrease in environment, landscape diversification and increased recreational values. Afforested areas can be registered as plantation forests – area afforested for specific purpose. For afforested areas improved genetic material should be used, because of faster growing rate and tree quality. From 1999-2015 afforested agricultural land with improved planting material were 32357 ha, from that 9502ha were plantation forest (Daugaviete et al., 2017). In the period from 2014-2020, there is available state and EU funding for afforestation of abandoned former agricultural lands. In 2016, 4000 ha were afforested and 2700 ha was afforested as plantation forests (Figure 1). Main tree species for afforestation are silver birch, Norway spruce, Scots pine and grey alder (Figure 2.).

The goal of afforestation, including regeneration, pre-commercial thinning (PCT) and commercial thinning, is to provide wood resources for the country, maintain natural ecological balance and improve recreational and aesthetic qualities of the forest (State Forest Service, 2018).

Norway spruce is a good option, because it produces acceptable quality timber while planted in low density. Norway spruce growth in fertile agriculture soil is high and the rotation age can be relatively short because maximum mean annual increment is reached at a relatively young age (Uotila 2014).
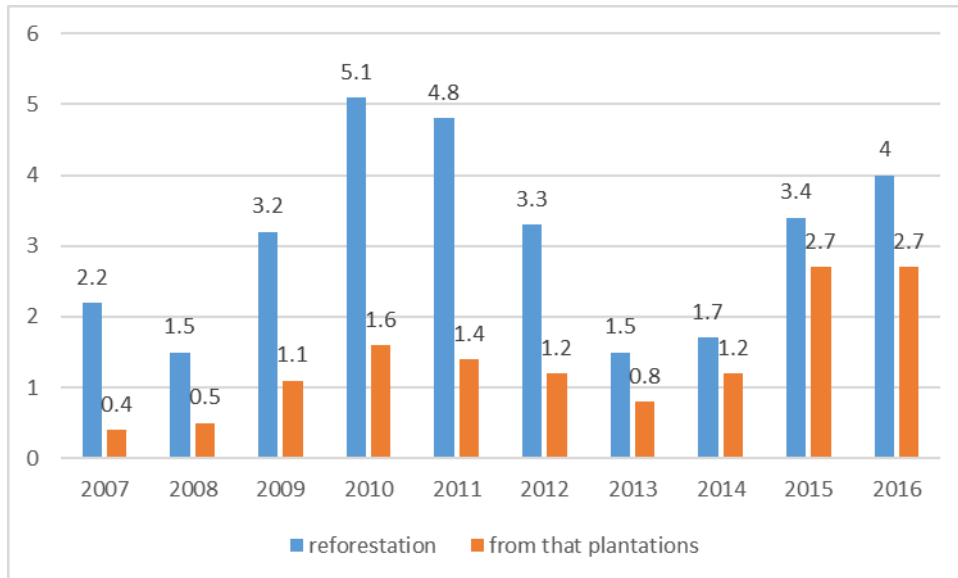
Figure 1. Number of tree seedlings used for forest regeneration and reforestation (thous.) (State Forest Service, 2018).
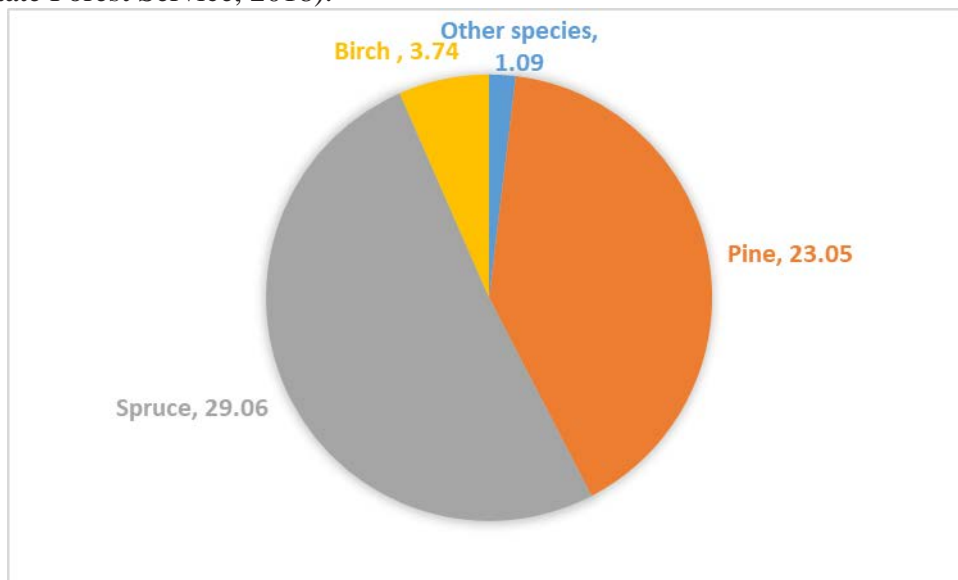
Figure 2. Reforestation of abandoned agriculture land in 2007.-2016. (ha) (State Forest Service, 2018.).

1.2 Aim of the study

Afforested areas with Norway spruce show different growth than in forest land. To appropriately manage Norway spruce on former agriculture land, forest managers need to understand growth pattern and how different silvicultural practices affect growth. The aim of this study was to establish long-term pre-commercial thinning experiments, where data about growth will be collected, depending on different pre-commercial thinning intensities. From collected data growth for future Norway spruce stand on former agriculture land will be modeled.

1.3 Pre-commercial thinning

Norway spruce growth is high on fertile soils, resulting in short economical rotation-time and high timber yield. Soil preparation in fertile soils usually are more expensive for establishing stand well. Stands usually need to be tended in order to optimize stands structure

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because of unwanted non-crop species even though they are well established (Uotila, Saksa 2014).

Research has been done to estimate growth of forest on former agricultural land since 1995. Research shows that stand up to age of 20 years shows higher growth in every aspect. Later in rotation growth evens out compared to forest land (Daugaviete et al., 2017).

The possibilities for influencing stand structure is generally greatest when stands are young (Fahlvik et al., 2015). For maximization of Norway spruce growth in early stage it is important to minimize competition around future crop trees by removing unwanted vegetation with pre-commercial thinning. Non-target species should be removed as early as a height of 1m (Uotila, Saksa 2014).

The main purpose of PCT is to regulate species mixture favoring the main commercial species as well lowering the number of stems per ha in order to decrease competition. PCT allows to distribute resources which are needed for growing more evenly (Ulvcrona 2014; Weiskittel et al., 2009). PCT results in increased wind throw resistance, wood uniformity, nutrient accessibility, resistance to pests and changes understory structure and development. PCT have a long-term positive impact on the economy of the stand (Weiskittel et al., 2009; Lazdins et al., 2013). PCT also gives the possibility to control volume distribution between diameter classes. Unthinned stands or stands with low thinning intensity will have larger total volume, but part of this volume cannot be used in the future, because of natural mortality or large proportion of the trees will be too small to have a commercial value (Fahlvik 2005). PCT done at the right time allows stand to reach necessary dimensions for commercial usage 10-20 years earlier (Lazdins et al., 2013).

The most common PCT strategies includes timing and density after PCT and timing is often determined from stand height. For Norway spruce and Scots pine, the most common practice is to do PCT when tree height is about 2-3m high and retain 1500-3500 trees ha^{-1} after PCT. When target species are conifers other broad leave trees are left only in gaps and in case when target species trees are severely damaged and needs to be replaced.

Uotila and Saksa (2014) mention that PCT is the most common practice in Nordic countries for young stand management. When stands reaches 3-4 m, stand density should be 1600-1800 stems per ha for Norway spruce. Early cleaning of stand makes later PCT easier, but doesn't mean that late PCT can be skipped.

Silvicultural practice in Germany contains tending and pre-commercial thinning in Norway spruce stands up to 12 m height (Mäkinen and Hein 2006). Swedish silvicultural practice consists of PCT when tree height is 2-4 m tall and adjustment of species composition that is determined by owner. Naturally regenerated seedlings can be retained together with planted seedling and constitute components of the future stand (Holmström et al., 2016). PCT practice in Latvia consist of manual cutting with brush saw before a stand reaches height of 6 m. After PCT, remaining tree minimum and critical number are set by Regulations of Cabinet of Ministers No. 935 and depends of stand height (Lazdins et al., 2013).

1.4 Long term sample plot establishment

Permanent long-term sample plot is needed for assessing changes that have happened in forest during some time period and measurements could be repeated (Allen 1993).

Most researches uses permanent plots that are established and measured at the beginning of experiment and remeasured after previously set time period. This type of experiments isn't favored from administration perspective, because they are expensive and takes up a lot of time before intended results are reached. Permanent plots provide information with superior accuracy and otherwise unobtainable in other experimental designs. Real growth models can be obtained for the period of time that observation had been done, compared to artificially made where growth models are constructed from single measurements at different stages of stand

development. Records of stand development from permanent plots over extended period can be used for compering estimates and their accuracy. Permanent plots can provide information of stand development and treatment effects on it, as well stands mortality and received damaged throughout rotation that otherwise isn't obtainable from other type of plots (Curtis et al.,2005).

Research experiments design should be planed so it would be possible to obtain high quality data as well possible to interpret them easily. Long term experiment should have timeless design so it would give information about rising questions in future. Experiments should be designed with fewer basic treatments and include reference plots, replicates and plot size should be defined so it would fulfill intended requirements for obtaining high quality data.

Experiments should have administration that guarantees continuity of it, as well have future plan for plots, data archive that are accessible and interpretable (Andersson 2007).

Long term experiments are connected with fact that it is very expensive, not only taking direct cost of establishing experiment, but as well taking account cost of time needed for data collection. Taking account amount of data and importance of it, then it is still most cost effective method of research (Körschens 2006).

For establishment of permanent sample plots, a system for how to locate plots in the area need to be decided. Plots can be located random, restricted random or systematically. Quite often, random sampling is done in forestry research, because it eliminates systematic errors which may occur in systematic sampling. The downside is that randomized sample plots could be establish in places where it doesn't represent stand correctly. Systematic sampling covers the area more evenly and gives better coverage (Allen 1993).

At early age basal area and volume variation is highly nonlinear to different spacing and it can be explained with differences in stem numbers. When stand gets older competition have more effect on growth of individual trees in close spacing, than in stands with wider spacing (Gizachew et al., 2012). Site condition varies, so to decrease effect of site variation on data, treatment plot spacing should be as small as possible (Holmström et al., 2016).

1.5 Randomized complete block design

In silvicultural experiments, treatments are usually replicated at a given location or locations in accordance with some specified experimental design. This provides an estimate of experimental error and allows statistical analysis of results at that location.

They are often found valuable for purposes other than the study for which they were installed, and for purposes not anticipated by the person who installed them.

A first step in any sampling scheme is to define the population about which conclusions are to be made, in terms of such associated characteristics as physical location, site quality, stand origin, age class, species composition, management treatment, and freedom from destructive agents (Curtis et al.,2005).

Design of long term PCT-experiment depends on specific factor what need to be addressed, like density of remaining trees, different spacing patterns, timing of PCT as well selection of trees that needs to be removed or retained (Ulvcrona 2014). Timing refers usually to the height that crop-trees has reached at the time of PCT. Form of PCT describes what kind of trees are removed, like "wolf trees" or prioritizing specific tree species or trees with specific characteristics (Fahlvik 2005). For quantifying changes after PCT, stem number, basal area, diameter at breast height and total stem volume per unit can be monitored (Ulvcrona 2014). Basis for inference can be formed from randomization (Oehlert 2010).

In published PCT-experiments, experimental designs consisted of e.g. completely random replicated arrangement (Weiskittel et al., 2009), Latin square design (Gizachew et al., 2012), but the most common design was randomized complete block design (Uotila, Saksa 2014; Holmström et al., 2016; Gizachew et al., 2012; Lindgren, Sullivan 2013; Ulvcrona, Ahnlund 2011; Honggang 2012; Ligné 2004).

Main reason for using randomization is because it reduces the confounding effect of site-variation. Blocking is a method to reduce the effect of site variation. Blocking means that the experimental area is divided in blocks that are in some sense homogeneous. Within a block, there should be as little variation in site characteristics as possible. Randomized complete block design (RCB) is the most common blocking design (Oehlert 2010).

Plots are basic observation units, that are usually delineated area where treatments would be applied. Plots can consist of number of subplots arranged systematically or randomly within chosen area or stand. Plots can be any shape but usually are used square or circular shape, that minimizes plots edge length as well needed buffer zone to deal with edge effect. Circular plots are usually used for smaller plots, because it gets difficult to set plot edge for larger plots, especially when there is dense vegetation or steep slope. Rectangular shape allows easily set accurate borders and corners as well determine their location.

Plot size depends of research objectives, site conditions, research length and amount of available finances and establishment costs. Plot numbers affect variability connected with smaller plots, increasing plot number can decrease variability (Curtis et al.,2005). Decreasing plot size increases variability. Excessively small plots will increase variable values in density and volume, as well will give biased and inaccurate estimates of mortality and damage (Curtis et al.,2005).

Plot size and shape varies considerably between studies. Square plots were the most represented (Weiskittel et al., 2009; Simard et al., 2004; Ligné 2004; La Sala 2006). Plots with rectangular shape were also common (Ulvcrona et al., 2014; Honggang 2012) and circular plots (Pothier 2002; Zhang et al., 2006). Plot size also differed between experiments, staring from 0,0064 ha (Ligné 2004) up to 0,12 ha (Chase et al., 2016), but mostly in between (Weiskittel et al., 2009; Chase et al., 2016; Ulvcrona, Ahnlund 2011; Honggang 2012; Ulvcrona et al., 2014; La Sala 2006; Persson et al., 1995). Buffer zones around the plots reduce the effect of different treatments on edge trees and it was almost always used, but the size varied between experiments from around 5 m (Weiskittel et al., 2009; Ulvcrona et al., 2014; Ligné 2004; Honggang 2012) up to 10 m (La Sala 2006; Persson et al., 1995) and more (Simard et al., 2004; Chase et al., 2016).

Choosing plot size need to consider stand conditions at the end of experiment, rather than at the initial conditions. Not large enough buffer will give underestimates of differences connected with treatment. Buffers have larger effect on smaller plots, because of the ratio of edge to total area of plots that are larger for smaller plots (Curtis et al.,2005).

1.6 Spacing

Spacing has an important role in the growth of individual trees and establishing costs. Control of spacing density allows to effectively manage growing stock. Tree density are controlled with planting, PCT and commercial thinning intensity. Decreasing density decrease planting costs, because fewer seedlings need to be planted and individual tree-size will be larger because of reduced competition. First commercial thinning are more profitable in lower density stands compared to dense stands because of larger diameter of trees. Taking account of these aspects, modern silviculture tends to decrease planting density. Planting density between 1300-2500 trees ha^{-1} are seen as normal planting density, whereas young stands with less than 1000 trees ha^{-1} are considered as wide spacing (Mäkinen, Hein 2006).

Norway spruce occupies successfully space released from removed trees because of it growing characteristics with long crown and its shade tolerance as well dominant trees may occupy resources that are available after suppressed trees are removed (Mäkinen, Hein 2006). Mean diameter growth increases by increasing spacing between trees, but dominant height is relatively little affected by density (Gizachew et al., 2012). Rapid growth of remaining trees may negatively affect timber quality. In young stands, rapid growth rate has positive effect on

branch diameter as well as stem-taper, so the most valuable log will have lower quality (Mäkinen, Hein 2006).

Branch size and knottiness affect strength and stiffness of the stems so PCT should be done at time and intensity so that good branch control could be done. At regions with a high risk of wind and snow damaged, timing of PCT should be done with regard not only to wood quality and volume growth, but also to maintain stand stability (Moore et al., 2009).

Tree slenderness is an important parameter when evaluating the risk of wind and snow damage. For tree densities below 1600 trees ha^{-1}, stability of trees is considered to be acceptable.

Planted seedling spacing pattern may have a significant effect on tree growth. However, in a spacing experiment with lodgepole pine, Brand (2013) showed little difference in growth and quality parameters between quadratic spacing and rectangular spacing.

Silvicultural treatments that are delayed probably has the largest effect in young stands development, because of decreased individual tree growth, lower wind and snow damage resistance (Mäkinen, Hein 2006).

2. Methods and materials

2.1 Study site

The experimental sites were located in South East Latvia near the city Ludza, stand Nr. 1. (56°29´N, 28°02´E), stand Nr. 2. (56°20´N, 28°06´E).

The height of selected stands were 4-6 m, they were 13 years-old and in need of first pre-commercial thinning. Sites with homogeneous site conditions were chosen, so plots would have as equal as possible growing conditions. Pre-commercial thinning was done in autumn after vegetation period. All study sites were regenerated with 2000 seedlings/ha with spacing of 1,6×3 meters.
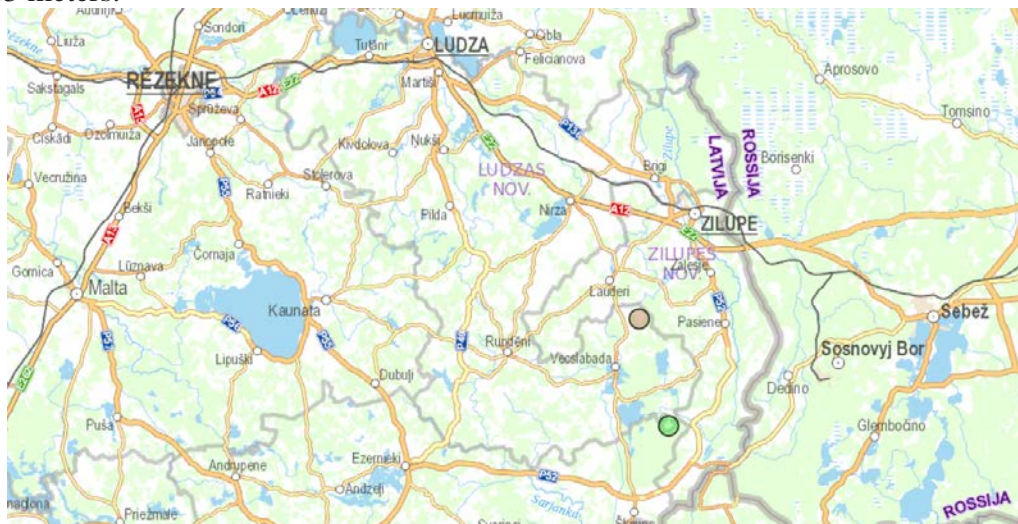
Figure 3. Site location in Latvia.

2.2 Experimental design

Randomized complete block design was used as experimental design. The area was divided in four similar parts, in each part square block were establish (50×50m). Each block consisted of four plots. Each plot size was 20×20 m with 2.5 m buffer zone where the same PCT-treatment was done. For simplifying data collection, each plot was divided in four 10×10 m square subplots. Treatments were randomly selected for each block. Each plot corner was marked with poles.
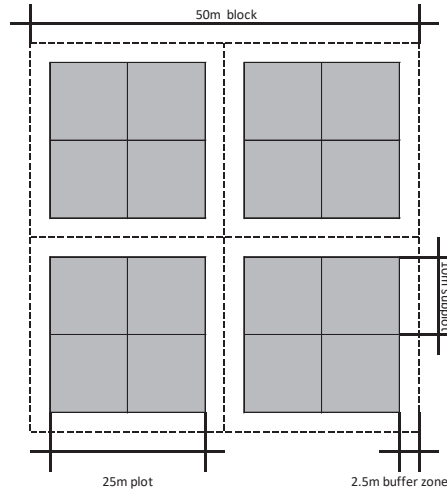
Picture 1. Scheme of randomized complete block design

2.3 Treatments

Four PCT-treatments were established. The treatments were 1) even distribution PCT retaining 500 trees ha^{-1}, 2) even distribution PCT retaining 1000 trees ha^{-1} favoring even spatial distribution between trees, 3) PCT retaining the 1000 trees ha^{-1} with the largest dbh and 4) even distribution PCT with density defined from density of the plot with the lowest density before PCT (1500 trees ha^{-1}). The experiment was repeated in 2 sites, in total 32 square plots were established with total area of 2 ha.

Criteria for selecting removable tree were the same for all plots:
- "Wolf tree" removal, dominant trees that were of poor quality, suppressing surrounding potential good quality trees.
- Even spacing distance between retained trees with spacing depending on thinning intensity.
- Removal of all non-target species from sample plots.
- Favoring undamaged trees.
- In case of similar opportunities, favor tree with best quality.
- Treatment criteria are selected to favor growth of dbh
- Stems to be left were primarily selected among dominant and co-dominant trees.
- Even spacing with a minimum distance of 1 m between stems after PCT.

2.4 Measurements and data processing

After treatment all trees were measured in height (m) and dbh (mm) and permanently numbered with aluminum tags. Tags first number refers to plot number, second number refers to tree number in plot.

Quadratic mean diameter (dg), basal area (Ba), basal area weighted mean height (Hgv) and standard deviation SD was calculated for each plot:

$$dg = 100 * \sqrt{\frac{4G}{\pi N}} \tag{1}$$

where G is sum of basal areas of trees (m^2 ha^{-1}) at breast height, and N is number of trees per hectare. Multiplication by 100 is done to convert from m to cm.

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

where d is diameter and divided by 40000 is done to convert from cm^2 to m^2.

$$hgv = \frac{\sum_{i=1}^{n} g_i h_i}{\sum_{i=1}^{n} g_i} \qquad (3)$$

Where n is number of tree objects, g_i basal area at brest height for tree object i, h_i height for tree object i.

$$Sd = \sqrt{\frac{\sum(x-\bar{x})^2}{(n-1)}} \qquad (4)$$

where x is sample mean of observations, n is the sample size.

For volume estimation each tree volume was estimated using SOA-function (Andersson 1954) and Brandels (Brandel 1990) function depending on tree diameter.

For trees below 4 cm it is with the SOA-function (Andersson 1954):
$$V_{SOA} = (0.22 + 0.1086 * dbh^2 + 0.01712 * dbh^2 * h + 0.008905 * dbh * h^2)/1000 \quad (5)$$
where dbh is diameter at breast height and h is tree height.

For trees with diameter above 6 cm it is with Brandel function (Brandel 1990):
$$V_{Brandel} = (10^{-1.02039} * dbh^{2.00128} * (dbh + 20)^{-0.47473} + h^{2.87138} * (h - 1.3)^{-1.61803})/$$
$$1000 \qquad (6)$$

For trees between 4 and 6 cm it is from both functions in proportion of how close the diameter is to either 4 or 6 cm:
$$V_{Combined} = IF(dbh < 4\ V_{SOA}, IF(AND(dbh \geq 4, dbh \leq 6), (6 - dbh + 0.00001)/$$
$$2 * V_{SOA} + (1 - (6 - dbh + 0.00001)/2) * V_{Brandel}, V_{Brandel})) \qquad (7)$$

2.5 Heureka simulation depending on management regime

The Heureka Forestry Decision Support System were used to estimate differences between treatments during rotation where StandWise simulation were used (Wikström et al., 2011).

Full rotation was simulated for each treatment. The beginning of the simulations was at stand age of 13 years (period 0) and the period length was 5 years.

Thinning intensities was 30% for first thinnings and 25% for second thinnings, treatments with density of 1500 trees ha^{-1} was simulated with two thinnings, 1000 trees ha^{-1} with one thinning, 500 trees ha^{-1} was simulated without thinnings. In addition, the treatment 1000 even was also simulated without thinning. For decreasing the risk of wind throw, all thinnings were done before stand reached a dominant height of 20 m. First thinning was done when stand reach basal area of 25 m^2/ha and second at 27 m^2/ha

For financial valuation, a common method is to use net present value (NPV), it allows to discount all costs and incomes to a specific time (rotation period.). It allows to look at future revenue at present value minus future costs at present value (James et al., 2017).

$$NPV = \sum_{t=1}^{T} \left(\frac{CF_t}{(1+i)^t} \right) - C_0$$

Where C_0 initial investment, T time horizon in the same units as t, the time period, CF cash flow and i interest rate.

Land expectation value (LEV) represents NPV of even aged stand from point of regeneration with an infinite amount of rotation periods. LEV allows to compare different stand management methods with different rotation periods, because it show investment in infinite time line, while NPV stops with one rotation (Bettinger et al., 2009).

$$LEV = \frac{NPV(1+i)^R}{(1+i)^R - 1}$$

Where R is rotation length (years), i interest rate and NPV net present value of the first

rotation.

NPV was calculated using 2.5% interest rate. For economical calculations regeneration costs and pre-commercial thinning cost were set as 12000 Skr. Optimal rotation age was estimated by calculating LEV and NPV for each period and using third degree polynomial function maximum value, age and value were calculated. For target diameter estimation, a second degree polynomial function was used to calculate the age when target diameter was reached.

NPV+ LEV means that NPV for first generation stared at age of 13 with LEV added as an income at the end of the rotation.

3   Results

Statistically significant difference was found for basal area and volume that decreased proportionally to number of trees ha^{-1} (Table 1;2). Statistically insignificant difference for volume and basal area was found for treatments density of 1000 trees ha^{-1} uneven and even spacing. Average height and dg at Stand 1 varied statistically insignificant between plots, same situation is in Stand 2 (Table 1;2).

Table 1. Average parameters for treatments from Stand 1. A different letter beside the figure denotes significant difference (p<0.05).

| Spatial distribution	Trees ha^{-1}	Ba (m2/ha)	Dg (cm)	Hgv (m)	Volume (m3/ha)	Standard deviation
Even	1500	6.09 (a)	7.2 (a)	5.41 (a)	20.0 (a)	1.42 (a)
Uneven	1000	4.69 (b)	7.7 (a)	5.38 (a)	15.2 (b)	1.25 (a)
Even	1000	4.27 (b)	7.3 (a)	5.34 (a)	14.0 (b)	1.31 (a)
Even	500	2.25 (c)	7.6 (a)	5.31 (a)	7.22 (c)	1.09 (a)

Table 2. Average parameters for treatments from Stand 2. A different letter beside the figure denotes significant difference (p<0.05).

Spatial distribution	Trees ha^{-1}	Ba (m^2/ha)	Dg (cm)	Hgv (m)	Volume (m^3/ha)	Standard deviation
Even	1500	7.56 (a)	8.0 (a)	5.96 (a)	26.3 (a)	1.50 (a)
Uneven	1000	4.70 (b)	7.7 (a)	5.68 (a)	17.9 (b)	1.56 (a)
Even	1000	5.26 (b)	8.1 (a)	5.79 (a)	18.0 (b)	1.79 (a)
Even	500	2.72 (c)	8.3 (a)	6.03 (a)	9.55 (c)	1.50 (a)

Simulated volume development was highest in unthinned 1000 trees ha^{-1} in both stands (Figure 4 and 5). Treatments 1000 even and uneven showed similar volume development in both stands. Lowest volume development in both stands shows treatment with 500 trees ha^{-1}. Stand 2 had first thinning one period earlier than in Stand 1 (Figures 4 and 5).
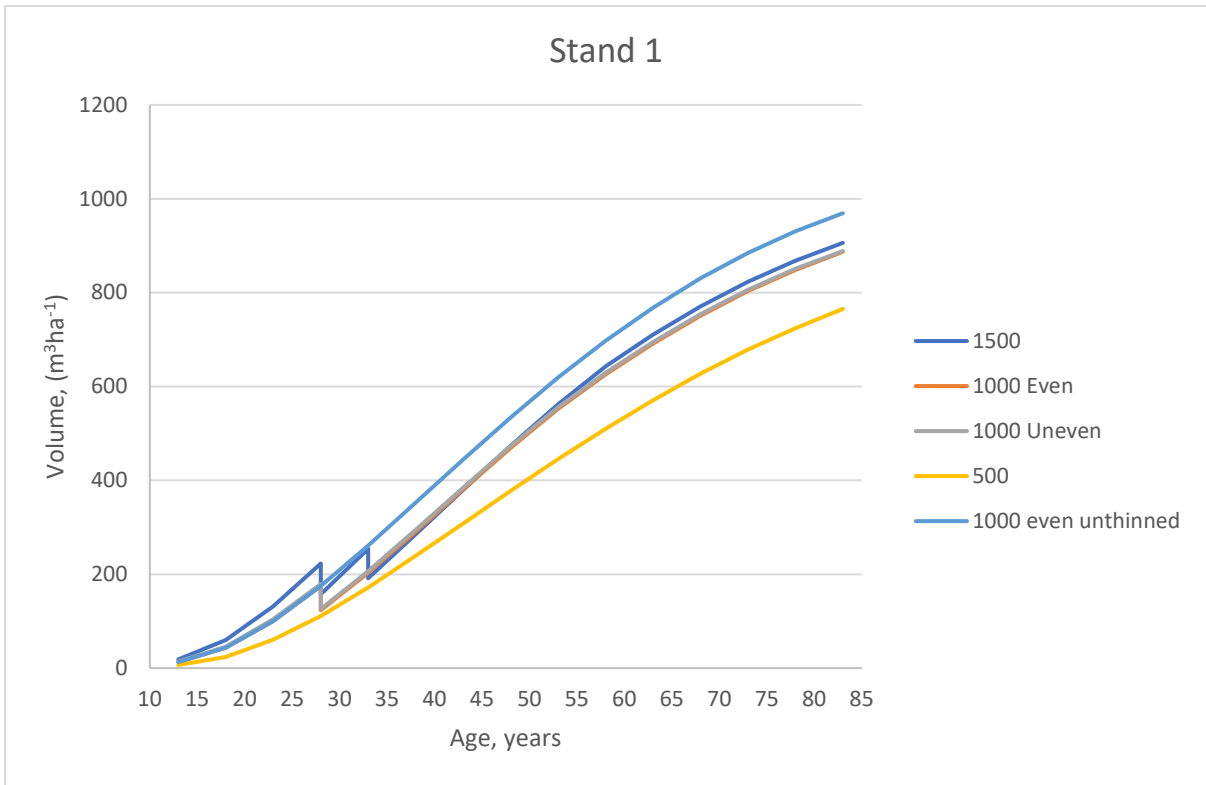
**Figure 4.** Volume development depending on treatment for Stand 1.
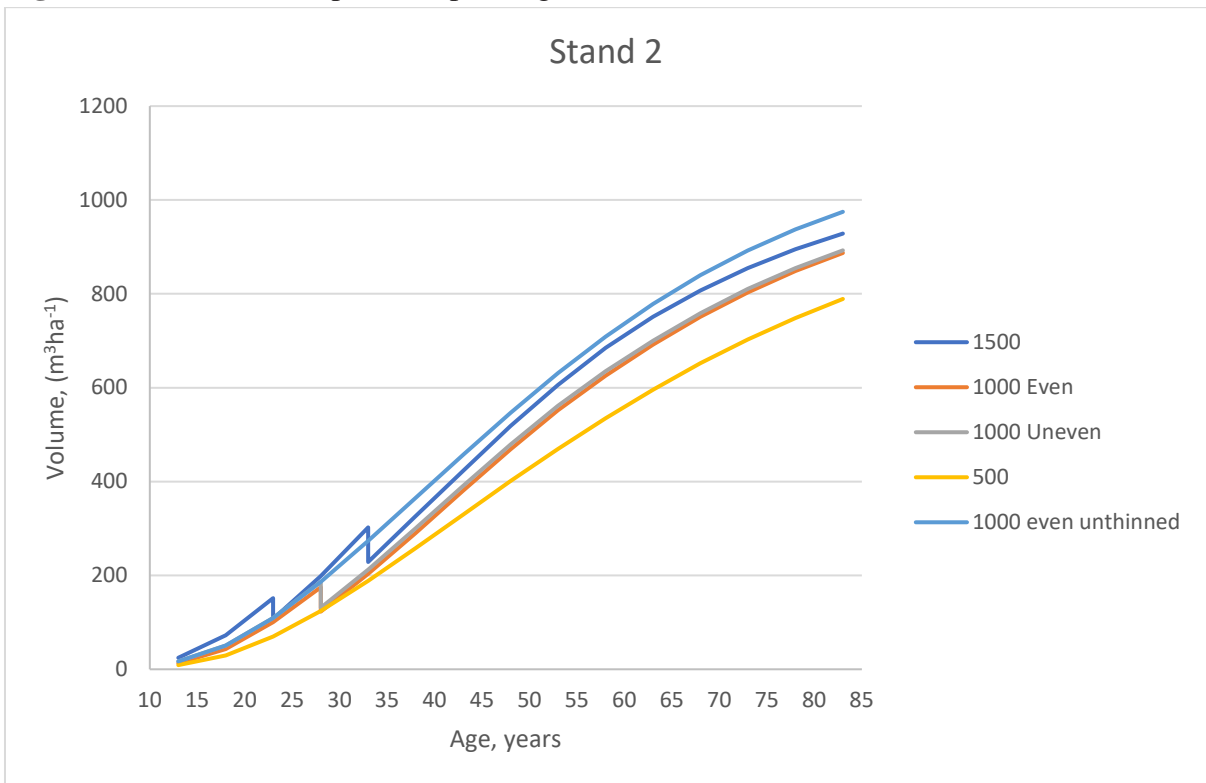
Figure 5. Volume development depending on treatment for Stand 2.

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Economical rotation age was calculated for each treatment. Lowest economical rotation age at Stand 1 showed two treatments the same rotation age (55.5 years), 1000 trees ha^{-1} and 1000 uneven. In stand 2 treatment with 1500 trees ha^{-1} showed lowest optimal rotation age – 53.4. In total, between treatments, optimal rotation age differed little (stand 1 0.1 - 2.2 years; stand 2 1.4-2.8 years). Largest difference was visible at maximum NPV+LEV. Largest economical return showed stand with treatment 1500 trees ha^{-1}. It showed 11.8% (Stand 1.) and 9.2% (Stand 2.) larger value than next closest treatment. Lowest economical return showed treatment with 500 trees ha^{-1}, it showed 49% (Stand 1.) and 47% (Stand 2.) lower return than treatment with 1500 trees ha^{-1}. Treatments with 1000 trees ha^{-1} showed similar economical returns for treatments with density of 1000 trees ha^{-1}, except for stand 2, where treatment 1000 even unthinned had larger economical return (≈6%) than other treatments with same density (Table 3.).
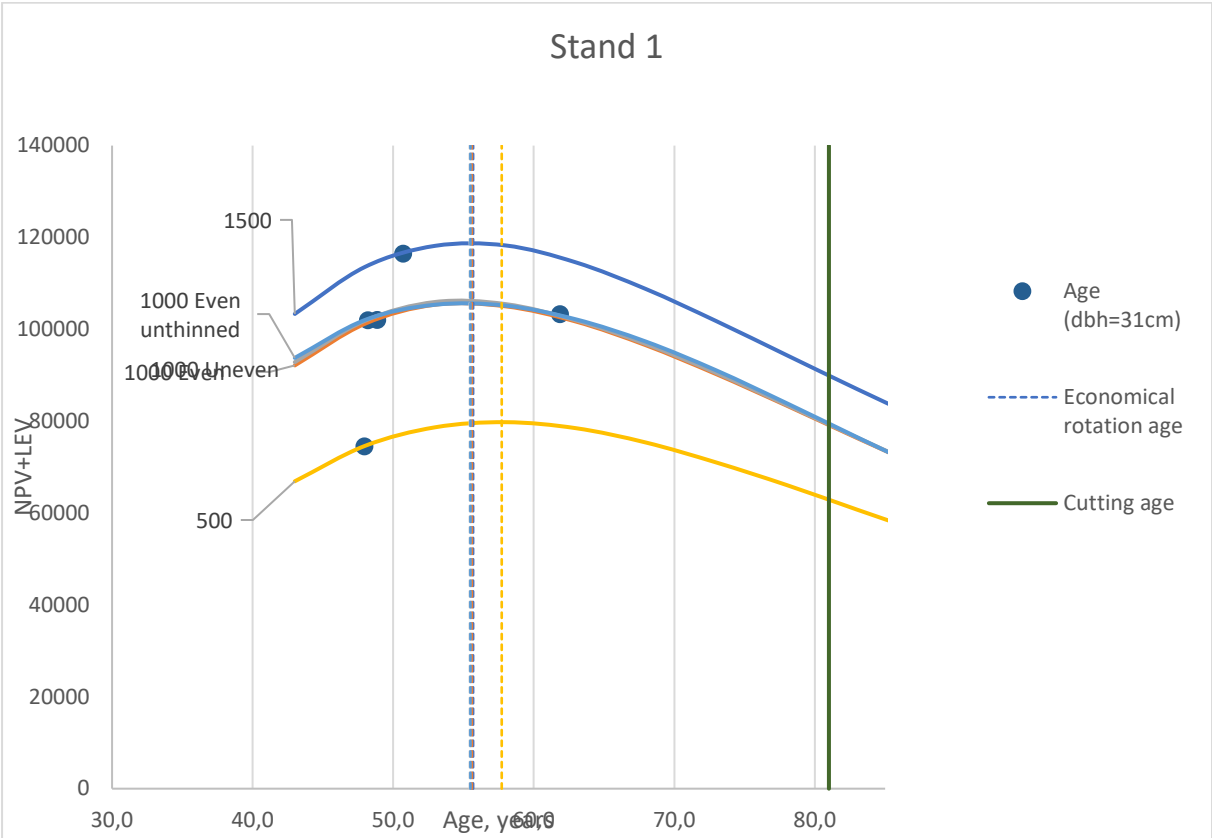
Figure 6. Estimated max NPV+LEV, economical return when cutting diameter is reached.
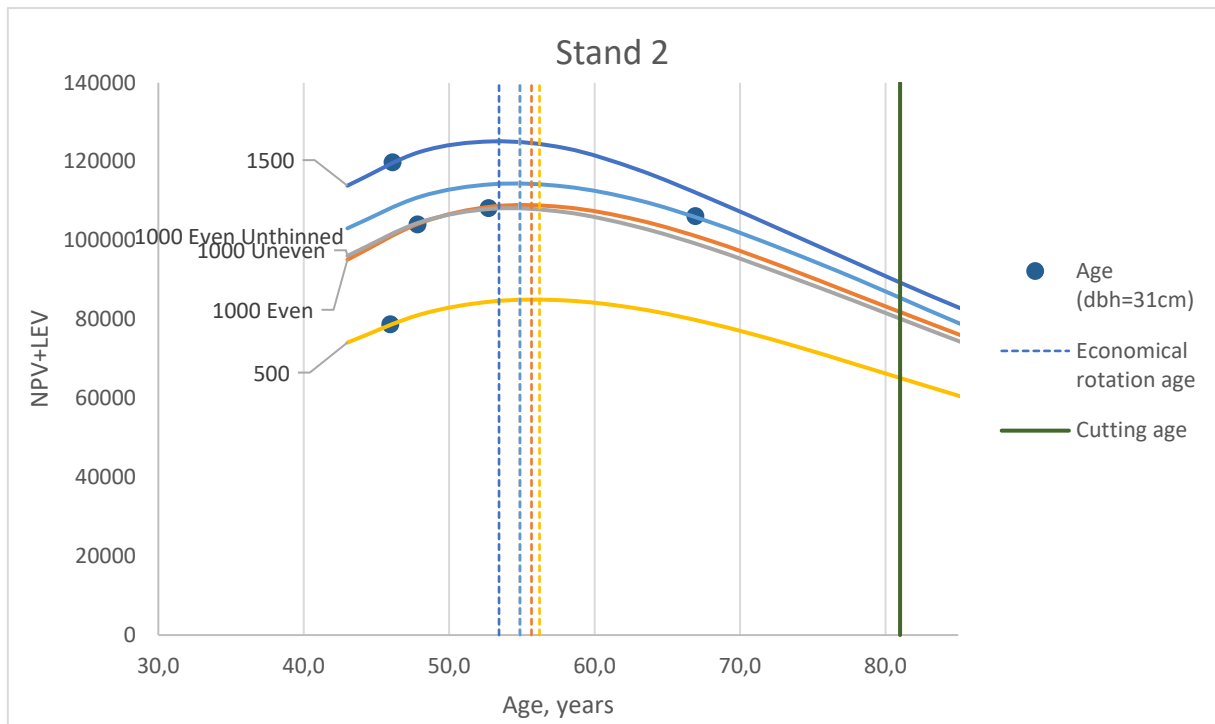
Figure 7. Estimated max NPV+LEV, economical return when cutting diameter is reached.

Table 3. Economical return depending of treatment (rounded up to closest 500)

Treatment	Age	Max NPV+LEV(SEK)	Age (dbh=31cm)	NPV+LEV(SEK)	Difference, %	NPV+LEV (Age=81)	Difference, %
Stand 1 1500	55.7	118500	50.7	116500	1.7	90000	24.5
Stand 1 1000 Even	55.6	105500	48.9	102000	3.3	79000	25.3
Stand 1 1000 Uneven	55.5	106000	48.2	102000	3.8	79000	25.6
Stand 1 - 500	57.7	79500	47.9	74500	6.6	63000	21.4
Stand 1 1000 Even Unthinned	55.5	105500	61.9	103500	2.2	79500	24.9
Stand 2 - 1500	53.4	125000	46.1	120000	4.0	89000	28.9
Stand 2 - 1000 Even	55.7	109000	52.7	108000	0.6	81500	25.1
Stand 2 - 1000 Uneven	54.8	108000	47.8	104000	3.5	80000	26.1
Stand 2 - 500	56.2	85000	46.0	79000	7.3	65000	23.5
Stand 2 1000 Even Unthinned	54.9	114500	66.9	106000	7.1	85000	25.5

Cutting diameter is reached from 3-10.2 years earlier than optimal rotation depending on treatment, except treatments without thinning. When model reaches cutting diameter, economical return differs from 1.7-7.3% depending on treatment and stand, compared to max NPV+LEV. Modeled NPV+LEV at cutting age showed lower values by 21.4-28.9% difference depending from treatment and stand compared to Max NPV+LEV (Table 3).
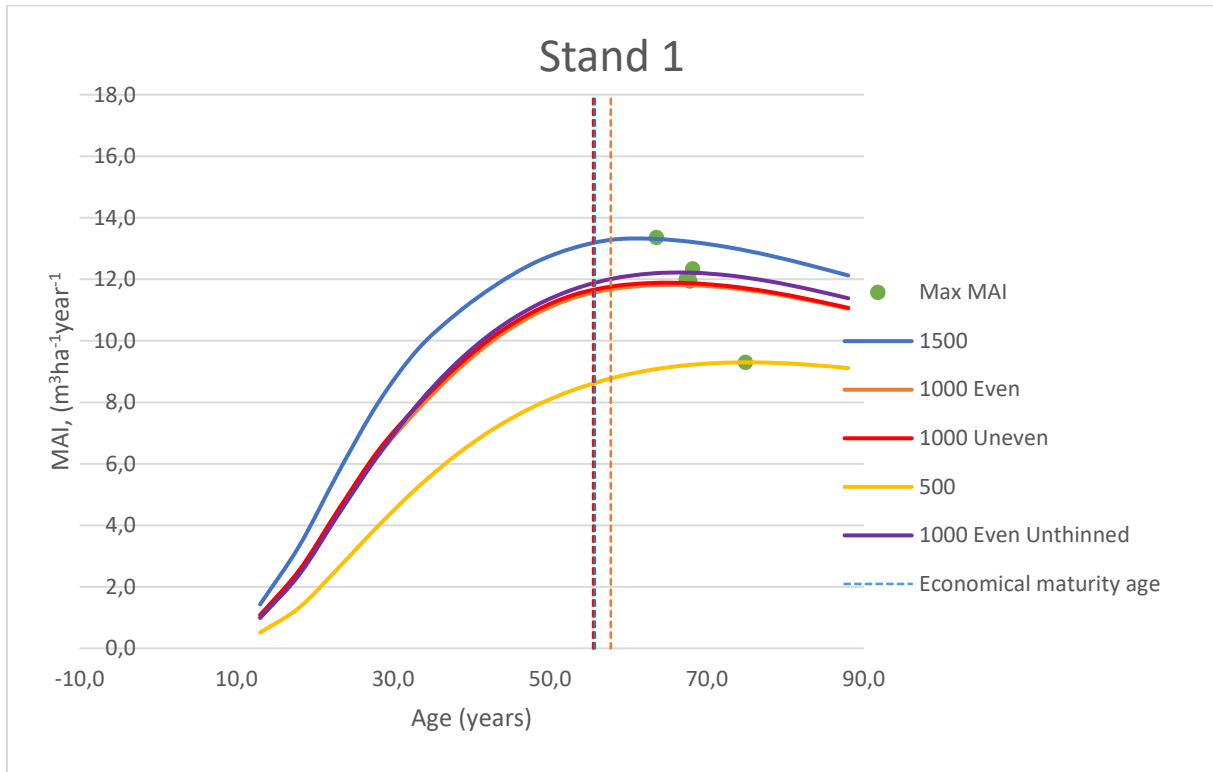
Figure 8. MAI development depending on treatment.
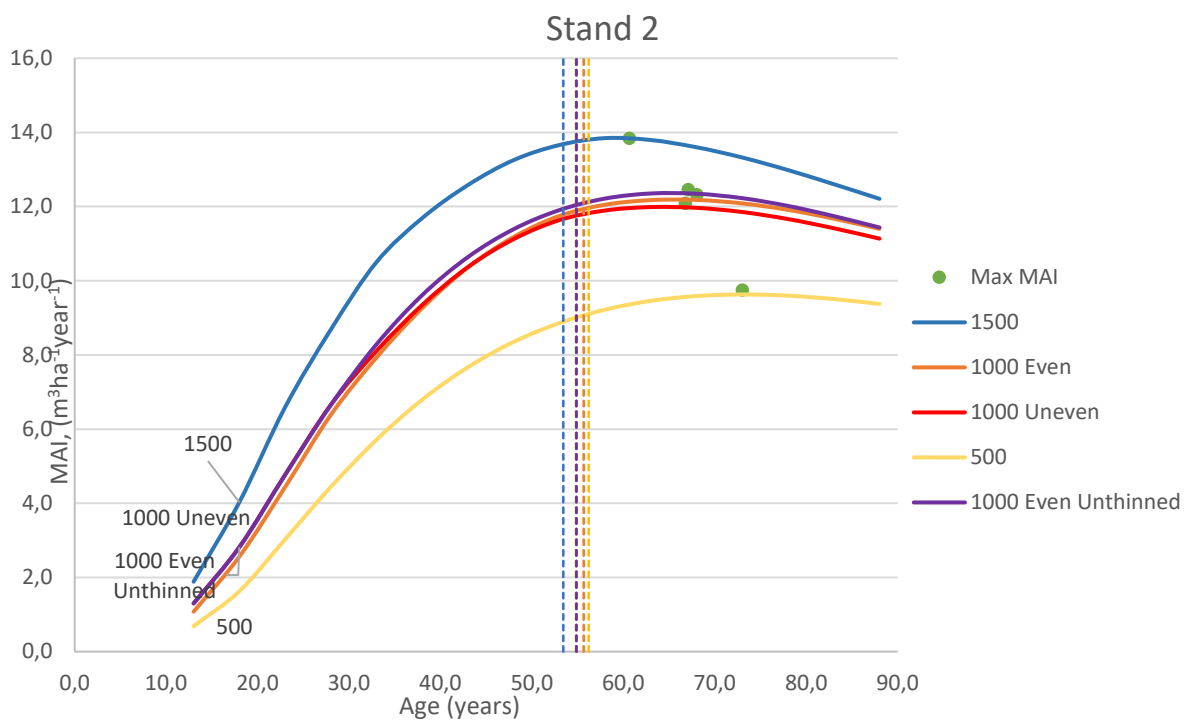
Figure 9. MAI development depending on treatment.

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Table 4. Mean annual increment.

Treatment	Economical rotation age (years)	Age$_{MAImax}$ (years)	MAI$_{max}$ (m^{3}ha^{-1}year^{-1})
Stand 1-1500	55.7	63.5	13.4
Stand 1-1000 Even	55.6	67.8	11.9
Stand 1-1000 Uneven	55.5	67.3	12.0
Stand 1 - 500	57.7	74.9	9.3
Stand 1-1000 Even unthinned	55.5	68.2	12.3
Stand 2 - 1500	53.4	60.6	13.8
Stand 2 - 1000 Even	55.7	68.0	12.3
Stand 2-1000 Uneven	54.8	66.8	12.1
Stand 2-500	56.2	73.0	9.8
Stand 2-1000 Even unthinned	54.9	67.1	12.5

Stand one and two show similar trends between treatments (Fig. 8 and 9). Both stands maximum MAI reaches at age of 63.5 (stand 1) and 60.6 (stand 2) in the same treatment (1500). Treatments with 1000 trees ha^{-1} shows similar trends in maximum MAI that is from 11.9-12.3 m^{3}ha^{-1}year^{-1}, but age when maximum MAI is reached differs between 63.5-74.9 years (stand 1). Stand 2 reaches faster maximum MAI age, and higher MAI comparing similar treatments. Different growth condition effect on growth is visible in stand 2 between treatments 1000 even and 1000 uneven where largest trees were left, in theory if plots had similar growing conditions treatment 1000 uneven should have produced higher MAI and faster. Lowest MAI is for treatments with 500 trees ha^{-1} as well reaches it later than other treatments. Economical rotation age is reached 7.2-17.2 years earlier than point where maximum MAI is reached, depending from treatment (Table 4.).
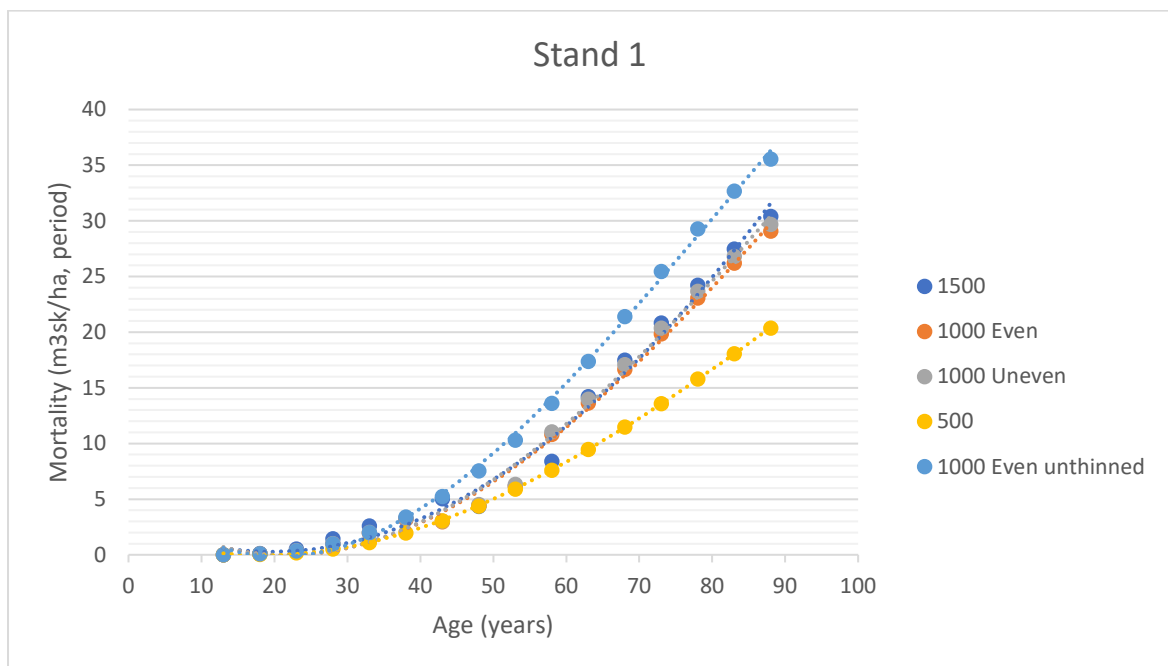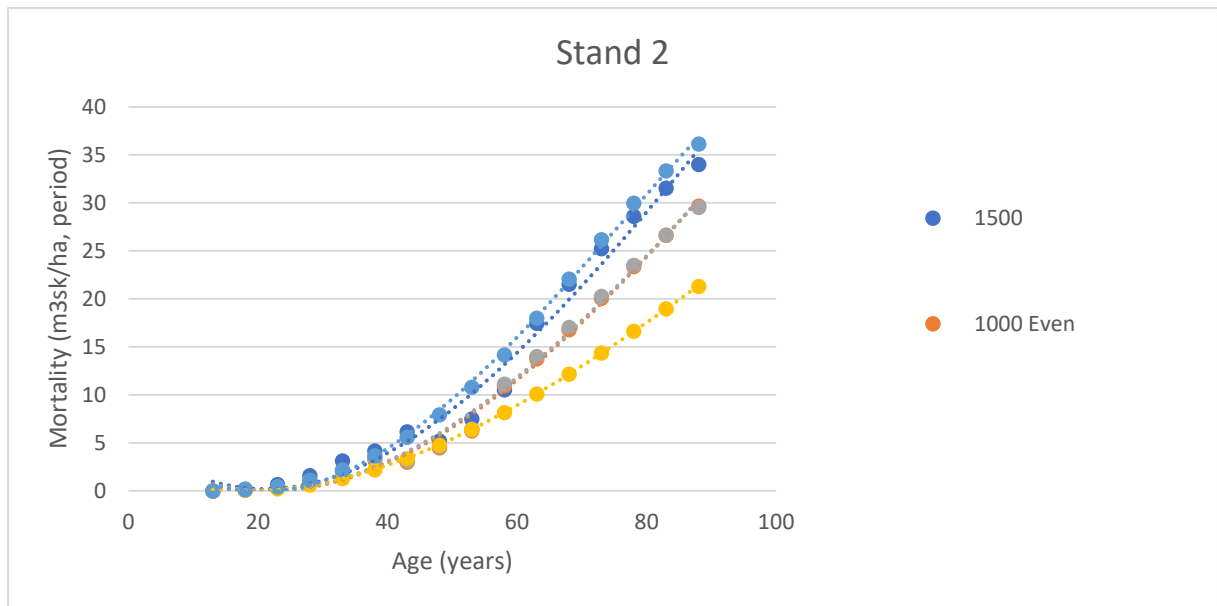

**Figure 10.** Mortality depending on treatment

Figure 11. Mortality depending on treatment

Mortality rate increases with age and denser stands. Lowest mortality rate shows plots with treatment 500 trees ha^{-1}. Highest mortality rate shows treatment 1000 trees ha^{-1} with even spacing and without thinning, as well treatment with 1500 trees [-1]ha (Fig. 10 and 11). Looking at point when stands reaches economical maturity age, mortality rate was similar between thinned treatments with difference of few m^3 (Table 5.).

Table 5. Total mortality at economical rotation age.

Treatment	Economical rotation age (years)	Total mortality (m^{3}ha^{-1})
Stand 1 1500	55.7	28.1
Stand 1 1000 Even	55.6	25.8
stand 1 1000 Uneven	55.5	26.2
Stand 1 - 500	57.7	24.3
Stand 1 1000 Even unthinned	55.5	36.7
Stand 2 - 1500	53.4	29.4
Stand 2 - 1000 Even	55.7	26.3
Stand 2 - 1000 Uneven	54.8	25.4
Stand 2 - 500	56.2	24.1
Stand 2 1000 Even unthinned	54.9	37.2

Diameter development is similar for thinned stands. Greatest diameter development shows stand with lowest tree density. Unthinned treatment with density of 1000 trees ha^{-1} shows lowest diameter development. It can be explained with higher density of trees throughout rotation and higher competition between trees, compared to other treatments with lowered tree density after thinning or already low initial tree density (Fig. 12 and 13).
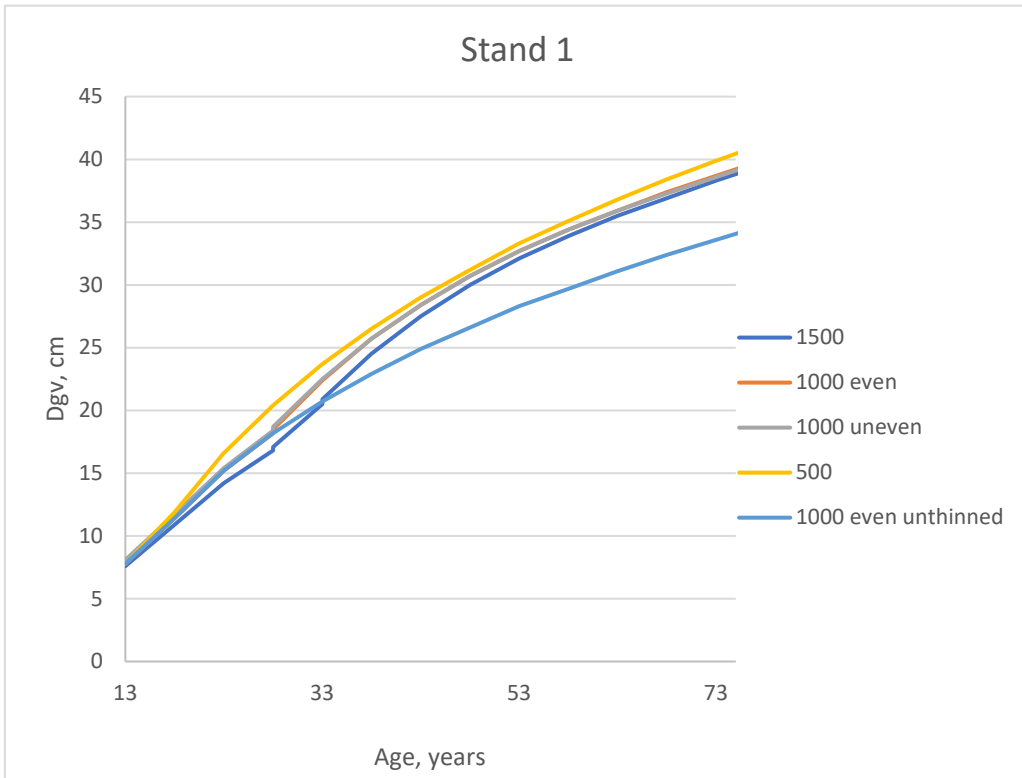
Figure 12. Weighted mean diameter development
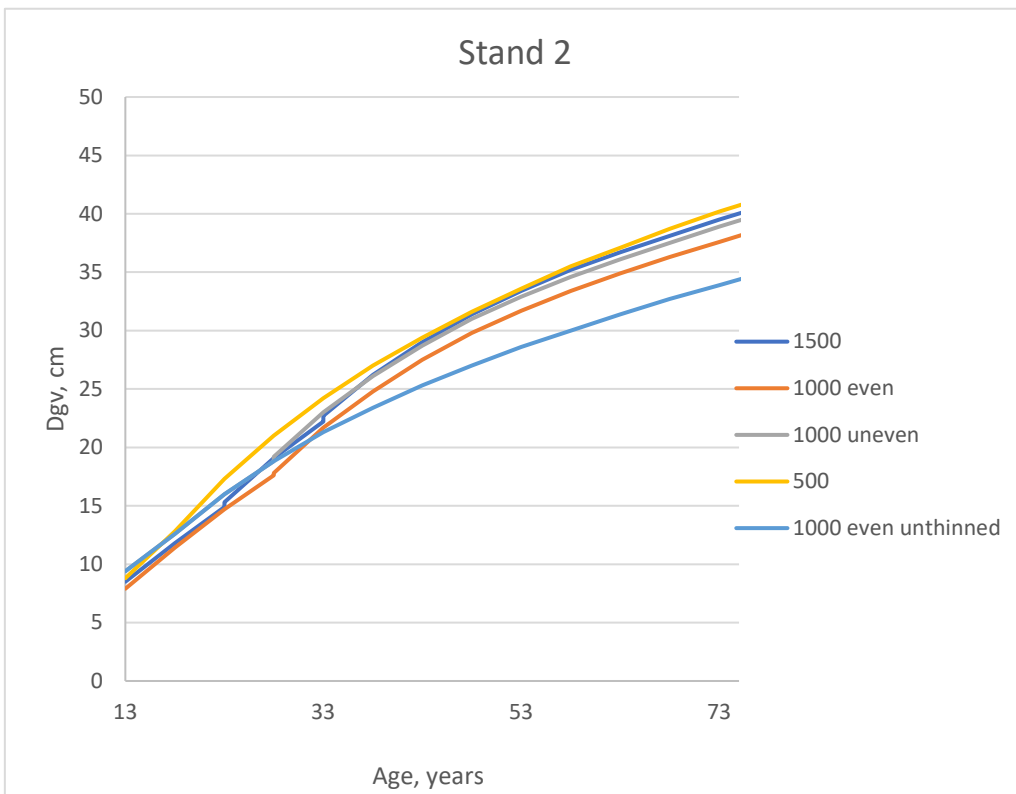
Figure 13. Weighted mean diameter development

4 Discussion

PCT treatments

Treatment 1500 trees ha^{-1} showed best economical results. It showed by 17.6% (Stand 1.) and 12% (Stand 2.) larger max NPV+LEV than closest treatment with density 1000 trees ha^{-1}, that is considerable amount. Difference is made because of extra second thinning compared to single or no thinning in other treatments as well larger harvested volume in first thinning.

Treatment 1000 trees ha^{-1} uneven was chosen to increase average size of retained trees that would give better stand development as well better economics in future. During PCT, if all the smallest diameter trees are taken out without considering spacing, makes PCT easier and faster for workers. During thinning only larger diameter class trees are left to choose between, so during thinning operator doesn't have to cut smaller diameter class trees that haven't reached merchantable size, so increasing profitability.

Treatment 500 trees ha^{-1} were used to avoid future thinning and related damages to stand as well reduce risk of wind-throw. This low density could be used for reaching necessary cutting diameter earlier than other treatment that way shortening rotation period and improving economics. Cutting diameter was reached faster compared to other treatments, but only by 0.2-6.8 years (Table 7.). Considering economics max NPV+LEV was reached later than at other treatments and it was by 46.9% (Stand 1.) and 45.2% (Stand 2.) lower compared to best treatment. This can be explained because of low density of trees that produces less volume as well no incomes from thinning. Considering low gain in cutting age this treatment isn't perspective. Other problems with wood quality could be observed in future.

Need to consider treatment with PCT thinning when only unwanted tree species are removed, this way increase harvestable volume during first thinning. PCT would be done to remove broadleaf tree species growing in-between planted rows or in small empty spots where spruce has died for different reasons. Reasoning for that would be low planting density at the beginning (2000 trees ha^{-1}), that allows to reach parameters for thinning faster as well with considerably low mortality. Comparing to treatment with density 1500 trees ha^{-1} economical gains could be insignificant. Gains in harvestable volume could be reduces by increased cost in thinning, also average tree diameter would be smaller and trees would be more susceptible to wind. Lowering planting density to 1600-1800 trees ha^{-1} would allow to save money during regeneration as well during PCT where only unwanted tree species would be removed and during first thinning there would be lower harvesting costs. Lowering planting density have other risks as mortality in which case large empty spots in stand could develop.

Considering timing when PCT was done, need to take account that initial stand density was low, about 2000 trees ha^{-1} and average height was between 5-6m. Fahlvik et al., 2015 mentions that typical PCT for pine and spruce is done when stand reaches 2-3m and recommended stand density after PCT is 1500-3500 trees ha^{-1}. If thinning would have been done earlier at recommended height stand development wouldn't differ because of low initial stand density that allows for trees to grow under low competition until they have reached substantial height.

Comparing the two treatments with 1000 trees ha^{-1} (uneven and even spacing), uneven spacing should have larger average tree size compared to even spacing, because selection was done by tree size before spacing, but the average diameter, height as well standard deviation differences between treatments were statistically insignificant. Strategy to retain largest trees didn't change significantly stand structure because of stands homogeneity, maybe in future there will be more visible differences.

Spatial evenness

Most of the studies are done considering density effect on growth without taking account spatial position of trees. Studies about spatial positions looks at planting patterns like square, rectangular or triangular. Gil (2014) looks at spatial effect in Scots pine and concluded that triangular spacing better effect on tree diameter growth. Brand (2013) looked at lodgepole pine response to five different planting rectangularities (1 x 4 m, 1.33 x 3m, 1.46 x 1.46 x 4 m, 2 x 2 m and 0.8 x 5 m). He concluded that rectangularities with spacing 1.33 x 3m, 0.8 x 5 m produced largest volume, other aspects were as well affected, like largest branch that was for rectangularitie 0.8 x 5m, but straightness didn't show significant difference between rectanguralities. Considering this study even spacing isn't that significant aspect that would affect growth. This aspect can be used to plant stands in a way that machinery could be operated in stand without cutting trees necessary for roads as well decrease damage from machinery. Norway spruce has long crown as well tolerant to shade so it can occupy easily growing space (Mäkinen and Hein 2006), so it shouldn't be affected substantially by uneven spatial positioning.

Rotation age

Defining rotation age need to look not only at optimal and biological rotation age, but also on restrictions by Law. In Latvia if reforested land isn't plantation, but forest land, restrictions applies for cutting age and cutting diameter, stand can be harvested if it reaches one of defined restrictions. Cutting age is different between tree species and site index class, for spruce cutting age (81) is the same in all site index class. Stand can be harvested before cutting age if dominant tree species first story trees average dbh reaches defined dbh by law (Table 6.) (Law on Forests, 2018).

Table 6. Final felling dbh from trees species and site index (Law on Forests, 2018)

Dominant tree species	Site index			
	Ia	I	II	III
	dbh (cm)			
Pine	39	35	31	27
Spruce	31	29	29	27
Birch	31	27	25	22

Site index for both sites were Ia so at dbh of 31cm stands could be harvested. Each treatment reaches this mark at different age. In both stands treatments with 500 trees/ha reaches this mark sooner 47.9, 45.9 years (Stand 1, Stand 2). Treatments without thinning took 13.9, 20.9 years (Stand 1, Stand 2) longer to reach necessary diameter. Between thinned stands and treatments age differed little, 0.3-2.8 years (Stand 1), 0.2-6.8 years (Stand 2) (Table 7.).

If target diameter is used for determining cutting age and compared to economical rotation age, lost value between treatments varies from 1.7-6.6% (Stand 1) and 0.6-7.3%(Stand 2) (Table 3).

Table 7. Age when cutting diameter is reached.

Treatment	Age, (years)
Stand 1 1500	50.7
Stand 1 1000 Even	49.5
stand 1 1000 Uneven	48.0
Stand 1 - 500	47.9
Stand 1 1000 Even unthinned	63.4
Stand 2 - 1500	46.1
Stand 2 - 1000 Even	52.7
Stand 2 1000 Uneven	47.1
Stand 2 - 500	46.0
Stand 2 1000 Even Unthinned	61.4

Considering worries that economical maturity age would be reached before stand could be legally harvested only applies if stands are harvested when legal cutting age is reached. If stands are harvested considering when cutting dbh is reached than it in all treatments, except unthinned treatment, reaches cutting dbh before max NPV+LEV is reached (Table 3.)

Comparing cutting age with economical rotation age it is visible that difference is 21.4-28.9% in value depending from stand and treatment (Table 3.). Today's restrictions for cutting age is economically unreasonable for regenerated stands in agriculture land or anywhere else where stands are regenerated artificially with superior planting material.

Growing conditions in specific region varies a lot and have large effect on spruce growth on former agriculture land. Relief is very specific with hills and dens heavy soil, lows in between hills whit excessive water. During stand selection overlooked many stands and were chosen only those with the best increment and survival. Increment differences were very visible between stands. Considering results, need to take account that not all stands will produce modeled growth. For better understanding of growth on former agricultural lands, evaluation on effect of soil conditions should be taken in account. Forest management would differ from those stands with best growth conditions affecting rotation age.

Thinning regime

Figure 14. Model for thinning in pure spruce stands on fertile soil types. (LVM, 2008) Green area – zone where thinning is necessary, yellow area – optimal basal area, red area – critical basal area.

Considering material for thinning timing taken from Joint Stock Company "Latvia's State Forests" (LVM), modeled stands reaches basal area for first thinning about 5 years earlier and second thinning about 20 years earlier. Model showed stand reaches in most treatments during period 5 as well period 4, that is 12-20 years earlier than in LVM model. LVM model used for fertile soil types in forest land isn't proper for estimating thinning timing for spruce regenerated in former agricultural land.

Considering ways how to improve economics of treatments need to look at postpone thinning in stand, because in case where two thinning were done, second thinning was done in next period or 2 periods later than first thinning (treatment with density of 1500 trees ha^{-1}). Postpone thinning could increase economical return because of larger dimension trees and harvested volume, but on the other hand it would decrease stand stability, because stand height would be over 20 meters. In treatment where only one thinning is planned, postpone thinning could increase incomes, but doing first thinning close before when stand height is almost 20 meters, will have effect on stand stability. Thinking about postpone thinning, risks should be taken account and evaluated if forest owner is willing to take these kind of risks.

Optimal timing for first thinning should be at point when majority of trees have reached commercial dimensions, but before point at which trees start to die from natural mortality (competition) as well considering wind throw risks (Cao et al., 2006).

Choosing thinning type need to consider interest rate, at low interest rate (1%) thinning from below can be used, thinning from both diameter ends can be used in dense stands or thinning in low density stands with interest rate of 3%. For increasing economical return at begging of rotation not only postpone thinning could be considered, but also thinning from both diameter ends or from above, but all these actions will have effect on optimal rotation age as well final stand (Cao et al., 2006).

Thinning from above isn't usual practice in Latvia. Thinning from above could increase logging cost, because it may require marking trees, as well additional damage to retained trees. Key factor for rotation length and thinning regime are site conditions and initial stand density (Cao et al., 2006).

5. Conclusions

Most appropriate experimental design for long term experiments were randomized complete block design with buffer zone.

Considering restrictions set by law for harvesting stand economical rotation age is reached earlier than cutting age, but cutting diameter is reached earlier than economical rotation age, that allows not to worry about restriction of law that wouldn't allow to harvest stand at optimal time.

Study showed that after PCT left density of 1500 trees ha^{-1} showed best economical results. It showed by 17.6% (Stand 1.) and 12% (Stand 2.) larger max NPV+LEV than closest treatment with density 1000 trees ha^{-1}, that is considerable amount. Difference is made because of extra second thinning compared to single or no thinning in other treatments as well larger harvested volume in first thinning. Treatments with same density, but different spacing criteria showed insignificant difference in growth and economical parameters, that can be explained with initial stand homogeneity.

Economical rotation age is reached 7.2-17.2 years earlier than maximum MAI is reached depending on treatment.

Treatment with density 500 trees ha-1 reached cutting diameter earlier (0.2-6.8 years), but max NPV+LEV was reached later than at other treatments and it was by 46.9% (Stand 1.) and 45.2% (Stand 2.) lower compared to best treatment.

Evaluating all treatments optimal density after PCT were 1500 trees ha-1 with two thinnings during rotation. PCT intensity was low considering that initial planting density were 2000 trees ha^{-1}.

PCT treatment are important not only for improving stand development and stucture, but as well to lower costs during first thinning, that way increasing profitability.

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