Development and Productivity of Young Scots Pine Stands by Regulating Density

ANDRIUS KULIEŠIS, JONAS SALADIS AND ANDRIUS A. KULIEŠIS

Department of Forest Management, Lithuanian University of Agriculture Studentu 13, Akademija – Kaunas, LT - 53361 Lithuania

E-mail: *AndriusKuliesis@lvmi.lt*; *josalit@gmail.com*; *andrius_k@lvmi.lt*;

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Abstract

The key to the control of the productivity of Scots pine (*Pinus sylvestris* L.) is the regulation of stand density. The growth of two Scots pine stands of the forest type *Vaccinio-myrtillosa* has been observed in the course of 16 years. The initial age varied from 4 to 8 years, while the initial density was in the range of 5,400-8,100 trees/ha. Both stands are planted, one on former agricultural land and the second on former forest land. Ten plots with two replications of 5 treatments were established in each stand at the beginning of the experiment. Starting with 600 trees/ha, the initial density was increasing at each subsequent treatment with 500-1,000 trees/ha, ending with the control stand. The density was regulated to provide different conditions for competition during the time of the experiment. Each treatment was re-measured 4 to 8 times during the period of 13 to 16 years.

Growing of stands with 2,000-3,000 (4,000) trees per ha over the period of 7-19 years has a positive influence on the height growth of trees. The mean diameter increment of trees growing in the most intensively thinned stands (600 trees per ha) exceeds the mean diameter increment of trees in the control stand by 1.8-2.8 times. The ratio of the mean tree volume increment of intensively thinned stand to the control stand comprises 3.1-3.7 at the age of 17-24 years. Early and intensive thinning of pine stands resulted essentially decreased competition, increased growth and higher level of accumulated wood increment per stand. The study outlines the conditions enabling to achieve intensive growth of tree diameter and a higher level of yield.

Key words: forest stand density, diameter, height and volume increment, competition, yield level

Introduction

The most important indicator of potential forest site productivity is the height of trees at the reference age. There are various ways to achieve different yield level on the same forest site (Assmann and Franz 1963, Skovsgaard and Vanclay 2007). In any case, a higher yield level is a result of higher standard basal area (Assmann and Franz 1963, Hasenauer et al. 1994). Basal area differences can result from different number of stems per ha and the same mean diameter, or a different mean diameter of the same number of stems. Sterba (1987) and Hasenauer et al. (1994) investigated the relation of maximum number of trees and the yield level. Keeping a large number of trees is an effective way to achieve high yield level. However, a large number of trees is not compatible with high mean diameter value or high diameter increment value (Kuliešis 1989). One of the aims of this study is to investigate the influence of stand density on the tree diameter growth, mean diameter volume increment and total yield of stand.

Stand density, its well-timed regulation or sufficiently intensive self-thinning during its formation are among the most important factors for successful stand development and productivity at mature age. The dynamics of density is preconditioned by changing the requirements on the growing space under increasing dimensions of plants (Oliver and Larson 1996). The initial density is one of the most important factors since trees occupy free space and compete with other plants. However, the initial density, as a factor of successful reforestation (Malinauskas 1999, 2008, Salminen and Varmala 1993), should be further controlled depending on the purpose of stand growing. The initial density may predetermine the time of further density regulation, but it certainly cannot eliminate thinnings. To sustain optimal density and ensure high yield, permanent control of stand density is required (Kairiūkštis and Juodvalkis 1985, 2005). Most frequently, the weakest trees are removed from a stand in the current silvicultural practice. Lithuanian silvicultural regulations require leaving a certain number of pine trees after thinnings (Mikšys and Juodvalkis 2007). For example, in stands of 11 m height, it is required to leave about 2,000 trees/ha after thinnings. Foresters, selecting pine stands for repeated thinnings, very often face the situation when the number of trees is insufficient according to standards, though the stocking level indicates the necessity of thinning. Having an insufficient space, the remaining trees slow down their growth and development. This leads to a very small diameter increment of tended trees, although theoretically the diameter increment due to density regulation should be increased considerably (Kairiūkštis and Juodvalkis 2005). High self-thinning and mortality of trees at mature age indicate continuation of stand formation at the age, when it should be finished (Kuliešis et al. 2009).

One of the most important factors determining the diameter and volume increment is the competition among trees for growing space. Different indexes are used to evaluate competition: the correlation between the tree diameter increment during re-measurements (Kuliešis 1989), stand density (Reineke 1933) and relative density (Wilson 1946, Hasenauer et al. 1964, Castedo-Dorado et al. 2009). In this study, the ratio of the mean stand height and the area per tree has been applied for estimation of competition among trees in a stand.

The aim of the study is to investigate the influence of stand density, regulated with respect to the needs of plants for growing space, on the growth of diameter, height, volume of trees and the total productivity of pine stands. Seeking this aim, the influence of stand density on the growth of height, diameter of trees and on the mean diameter of stand at the same mean height will be tested. Results of experimental thinnings of different intensity will be compared with the results of thinnings as required by Lithuanian silvicultural regulations. The study will describe the conditions, under which a higher yield level of pine stands could be obtained, comparing the growth of modal pine stands of Lithuania according to the yield model by Kuliešis (1993) with the results obtained from this study.

Study object and method

This study was carried out in an object established in 1990–1992 (Kuliešis and Saladis 1998). It consists of two series of treatments on 20 plots. The area of each plot comprises 0.11–0.18 ha. Trial 201 was conducted in southeastern Lithuania (Valkininkai Forest Enterprise, Pirčiupiai forest distr., Block No 19) in a pine plantation established on former farmland (Table 1). Trial 206 was conducted in the western part of Lithuania (Jurbarkas Forest Enterprise, Mociškiai forest distr., Block No 29) in a reforested pine stand.

Table 1. Characteristics of experimental objects

Trial No	Land use category	Planting year	Planting distance, m	Beginning of experiment, years	Initial density, thous./ha at the beginning of experiment	Established plots	
						Number	Area, ha per plot
201	Arable	1982	0,5×2,0	1990	5–6	10	0,18
206	Clear felling area	1988	0,55×2,0	1992	8–8,5	10	0,11

The initial planting density of trials 201 and 206 was 10,000 and 9,100 trees/ha, respectively. Both plantations were established in areas of similar site conditions, corresponding to the normal drained poor forest site type (Nb). A temporary increased growth can be observed on the former arable land, after roots of trees penetrate the arable horizon.

The results of trial 201 cover the stand age from 8 to 24 years. For trial 206, the stand age is from 4 to 17 years, i.e. it corresponds to the main period of precommercial thinnings. Each treatment consists of two replications. In both trials five density treatments were established, creating different conditions for competition among trees. The conditions were estimated by applying the competition index (Formula 1)

$$CI = \frac{H}{Q} = \frac{H \cdot N}{10000} \quad (1)$$

where CI – competition index; H – mean height of trees, m; Q – site area per one tree, m^2; N – number of trees per 1 ha;

and $$Q = \frac{10000}{N} \quad (2)$$

The index used for estimation of the competition always equals to one when $H{\cdot}N$ = 10 000.

In both trials, control plots were used (treatment 1-2, Fig. 1), where no thinning was done, i.e. the competition between trees was not regulated. In treatment 3-4 the number of trees has been reduced by thinnings three times, leaving 3,000-4,400, 1,900-2,700 and 1,200-2,400 trees per ha, respectively. Stands in treatment 5-6 were thinned twice, the first time 2,000-2,400. and

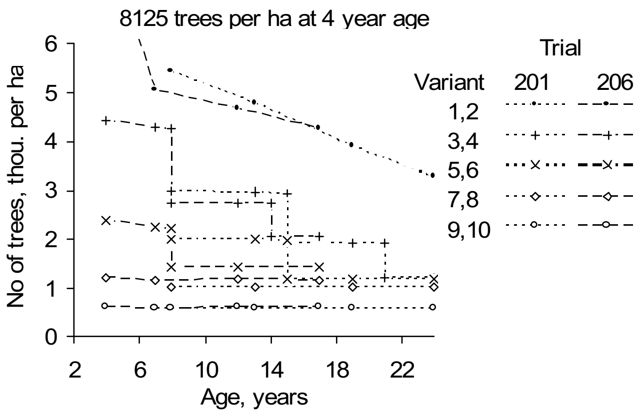

Figure 1. Changes and regulation of density in trials

the second – 1,200-1,400 trees per ha were left. Stands in treatments 7-10 were thinned only once – at the beginning of the experiment. Stands in treatment 7-8 were thinned down to 1,000–1,200 trees/ha, while in 9-10 – to 600 trees/ha.

The number of trees at the beginning of the experiment was changed in different treatments from 8,000 down to 600. The possible influence of selection of trees to be left in stand on their growth was estimated by comparing the mean height and mean diameter of all trees and 30 largest trees at the beginning of the experiment and 10-11 years later.

Stands of treatments 1-2, 7-8, 9-10 were measured four times, every 3–5 years. Stands of treatments 3-4, including measurement before and after cuttings, were measured eight times; while those in treatments 5-6 six times. Diameter at the breast height or the height of trees less than 1.3 m in height was measured for each tree. The height was measured for each tenth tree and for every fifth tree in the least density treatments.

The response of trees to the thinning was estimated comparing the growth of 30 largest trees of different treatments with the growth of trees in the control (not thinned), using method proposed by Horne et al. (1986). The volume increment was divided into two parts: base increment and response increment due to thinning. Base increment was determined by the volume increment of trees in the control stand. Response increment was determined as a difference of the increment in thinned stand and in the control stand.

Site indexes were estimated using the mean values of tree parameters: height (H) as an indicator of primary growth and diameter (D) as an indicator of secondary growth. To compare the mean height and mean diameter with the corresponding values in the yield models (Kuliešis 1993), site indexes were estimated according to height and diameter growth for given stand ages. The aforementioned indexes generally show prediction of height (H_{100}) and diameter (D_{100}) at the age of 100 years.

The growth of trees under conditions of different density was estimated according to the diameter increment and mean volume increment. The mean diameter increment was estimated according to the differences in mean diameter of the remaining trees at present and at the beginning of the study period. The volume increment over each time segment was estimated as the sum of volume change and the volumes of removed and dead trees. Stand productivity was estimated according to the gross volume increment, i.e. the volume of felled, dead and remaining trees.

The following method was applied to estimate the significance of differences of the mean stand characteristics in the different density treatments of investigated trials (Гмурман 1972):

$$\Delta X = \overline{X_1} - \overline{X_2} \tag{3}$$

The difference of the two mean values is estimated relying on statistics

$$t = \frac{\Delta X}{\sigma_{(\overline{X_1} - \overline{X_2})}} \tag{4}$$

where: ΔX – difference of the mean values of the compared treatments, $\overline{X_1}$, $\overline{X_2}$ – mean values of the first and second compared treatments, $\sigma_{(\overline{X_1} - \overline{X_2})}$ – standard deviation of the difference in the mean values

$$\sigma_{(\overline{X_1} - \overline{X_2})} = \sqrt{\frac{\sigma^2_{X_1}}{n_1} + \frac{\sigma^2_{X_2}}{n_2}} \tag{5}$$

where: $\sigma^2_{X_1}$, $\sigma^2_{X_2}$ – estimated variance of the first and the second mean value, n_1, n_2 – the number of measurements.

Differences between the two mean values are significant when:

$$t > t\alpha \tag{6}$$

$t\alpha$ – statistics of t value under probability α $t_{0,683} = 1$, $t =_{0,95} \approx 2{,}0$, (Cochran 1963, Fišas 1968).

In case the analysed characteristics of stand density treatments change within the limits of confidence interval, it is possible to state that differences of the analysed indexes of these treatments are statistically insignificant. On the contrary, when the compared values of characteristic occur outside the range of confidence interval of comparable treatments, it is possible to state that such values have statistically significant differences.

Results

Site conditions

Estimation of the site condition indexes was based on the mean height and diameter of 7–8 year-old and older stands. Variation of site indexes according to the height growth of trees (H_{100}) is of a random nature up to the age of 15 years. Sites of the unthinned control stands are characterized by the lowest height index. Up to the age of 15 years, H_{100} of stand 201, established on former farmland, are 1–3 m lower than those of stand 206, established on former cutting area. At later ages, height indexes on both sites become equal, or the stand on former farmland even outperforms the stand on former cutting area. Differences of height indexes of stands of the same age and different density do not exceed 1–2 m. A steady increase in the height index by 3-4 m is observed in stand 201 established on former farmland during the 15th–24th year of its growth. This can be explained by the influence of a more fertile arable soil layer. H_{100} of treatments 3-4 of both trials over the last 5 years are by one meter higher as compared with H_{100} of the other treatments.

The conditions of diameter growth in treatments of different density differ from the very beginning of the experiment (Fig. 2). The differences of diameter growth site index (D_{100}) increase with every year and become rather stable at the age 12 years reaching 21 cm difference between the treatments. Under the impact of each thinning, site index increases on average by 3 cm. A decrease in the index is usually observed 3–5 years after thinning. It comprises 2–3 cm, i.e. D_{100} returns to its initial value. Besides, the highest D_{100} in trial 201 is recorded at the age of 19 years, while in trial 206 at the age of 12 years.

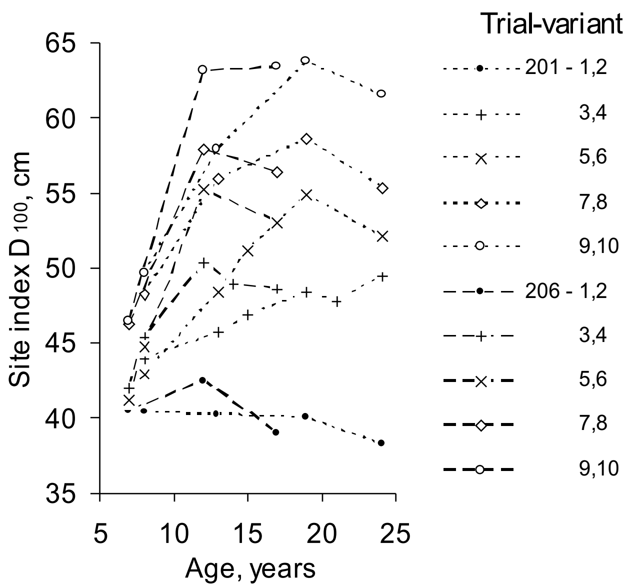

Figure 2. Site indices according to the diameter growth depending on stand age in trials 201 and 206

H_{100} vary within the range of 3–5 m and are weakly dependant on stand density. D_{100} are strongly dependant on stand density. The difference between D_{100} of the sparsest and densest stands comprises 24 cm at the end of the experiment.

Growth competition

Considering the end of stand formation, when the mean height of stand approaches 20–25 m and the density reaches 400–500 trees per 1 ha, competition index (CI) must inevitably approximate one. CI can increase during the whole period of stand formation in heavily thinned young stands gradually approaching one. In regularly and intensively thinned stands CI can be maintained close to one for the whole period, or it can even overcome one in young unthinned stands and then decrease for the rest time approaching one. It depends on stand improvement, its development strategy and type of formation of stand productivity.

Differences in the productivity of stands affected by controlled regulation of density and thinnings may to a large extent be explained by differences in tree competition (Fig. 3). CI of stands within the range of 5–11 m mean heights fluctuates from 2 to 2.2 if treated according to thinning standards. Significantly different values of CI were obtained in the experiment: 1.3 to 1.6 in stands where thinnings were of moderate intensity (treatment 3-4); 0.5 to1.1 in heavily thinned stands (treatment 7-8). CI of the control stand varies from 2.3 to 3.7, only slightly exceeding the CI the stand treated according to the current thinning standard.

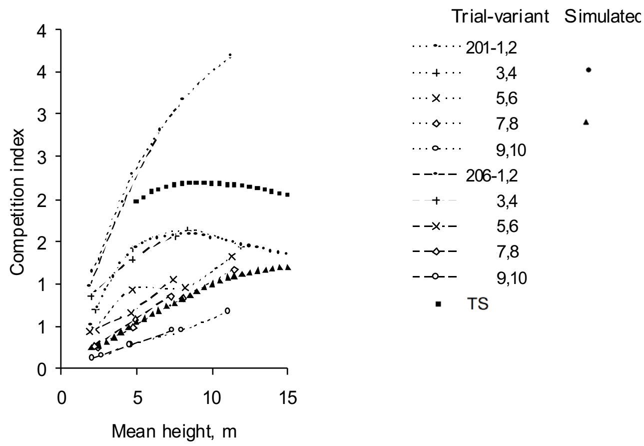

Figure 3. Comparison of competition indices in different density trials and thinning standards (TS) of pine stands

Influence of the stand density on the height of trees

Tree height dynamics was analised by comparing heights of trees of the same diameter (Fig. 4), heights of all trees and the 30 tallest trees (Fig. 5a) in treatments of different density at the beginning and at the end of the experiment. With some exceptions, the highest trees within the same diameter class were found in the densest control treatment (Fig. 4a)._With decreasing stand density, the heights of the same diameter trees in most cases decrease.

Over 10–11 years, the most favourable density for height growth was revealed. The greatest heights of the same diameter trees were ascertained in treatments 3-4 of both trials (Fig. 4b). Trees of the same diameter in this treatment surpassed the heights of trees of the control treatment by 0.2–1.0 m. When stand density

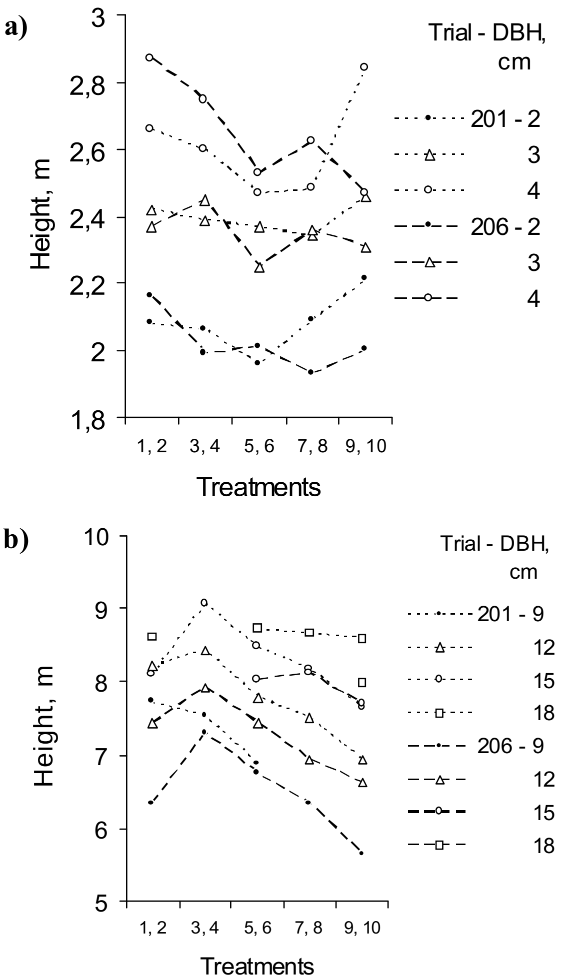

Figure 4. Mean tree height depending on tree diameter, stand density at the beginning of experiment (a) and 10-11 years later (b)

decreases, tree heights of different trials and different density treatments decrease on average by 0.3–0.6 m at each density level. Differences in tree heights among different treatments are statistically significant. It can be concluded that, at the density of 2,000 – 3,000 (4,000) pine trees/ha, the competition has a positive influence on the growth of tree height at the age of 7–19 years.

When selecting trees at the beginning of the experiment it was attempted to leave the largest trees, characterized by good form of the stem and crown. This can explain the increase in mean tree height as well as mean tree diameter of all trees with decreasing density at the beginning of the experiment (Fig. 5).

Differences in mean heights between different density treatments at the beginning of the experiment are statistically significant (t = 3.09 – 25.95). Comparing mean heights of the 30 tallest trees in different treatments it has been found, that the estimated differences at the beginning of the experiment are less significant than the differences of mean heights of all sample trees (Fig. 5a). Out of 20 compared pairs of the 30 tallest trees, the differences in mean heights among 7 pairs (t = 0.27 – 1.79) are statistically insignificant ($t_{0.95<1.96}$).

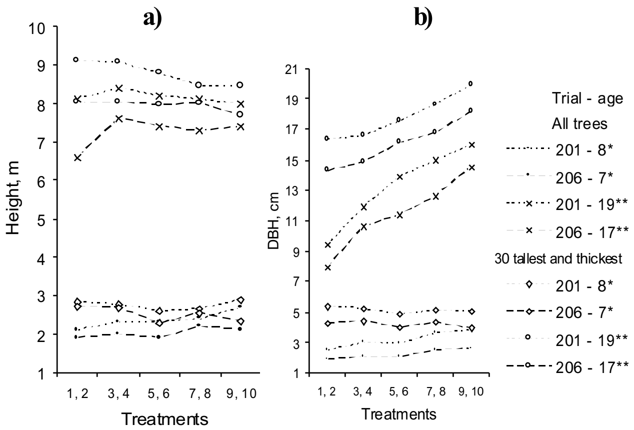

Figure 5. Comparison of mean height (a) of the 30 highest and all sample trees and mean diameter (b) of the 30 thickest and all measured trees in various density treatments at the beginning* of the experiment and 10-11 years later**

Five years later the significance of the differences in mean heights of all trees is recorded in some cases only. In the 19-year-old stands of trial 201, i.e. 11 years later, the greatest height of left trees (8.4 m) is found in treatments 3 and 4. It significantly differs (t = 2.77 – 2.79) from the mean stand height in treatments 7-8 and 9-10 (8.0– 8.1 m). These differences in the heights of all trees do not only remain, but also increase after next 5 years, at age 24 years. Differences of mean height of all trees in treatments 3 and 4 (11.9 m) and in other treatments at the age of 24 years comprise 0.6–0.8 m. This difference was statistically significant (t = 3.63 – 5.05). In trial 206, only the mean height (6.6 m) of all trees in the unthinned control treatment significantly (t = 3.6 – 3.94) differs from the mean heights of all the other treatments (7.3 – 7.6 m).

Ten years later, the greatest mean height of the 30 tallest trees in both trials was attained in treatments 1-2 and 3-4. Ten and fifteen years later differences in mean heights of the tallest trees among these treatments and all other treatments of trial 201 were statistically significant (t = 2.7 – 7.4). Mean heights of the 30 tallest trees in trial 206 gradually converged with increasing age in all treatments, except treatments 9-10. Mean heights of the tallest 30 trees of 9-10 treatments remained the smallest since the beginning of the experiment.

The most favourable conditions for the tallest trees height growth occur in the control (1, 2) and moderately thinned (3, 4) treatments (Fig. 5a). The 30 tallest trees of these treatments remained the highest amongst the other treatments during the whole time of the experiment. Mean height of all trees in the control (1, 2) treatment remains the smallest due to lots of small trees in this treatment.

Influence of stand density on the mean diameter and its increment

The mean diameter of all trees had a tendency to increase with decreasing density. At the beginning of the experiment, differences in mean diameters of all trees were statistically significant for 9 out of 10 pairs in different treatments of trial 201 (t = 2.57 – 25.57). In trial 206, significant differences in mean diameters of all trees (t = 4.35 – 9.07) were estimated between 7-8; 9-10 and the rest treatments, i.e. among 6 out of 10 pairs. Differences in mean diameters of all trees, estimated at the beginning of the experiment, became even more distinct 10 years later, being significant in18 out of 20 compared pairs (t = 2.15 – 12.72) (Fig. 5b).

In the beginning, the mean diameters of the 30 thickest trees had a tendency to decrease with decreasing density (Fig. 5b). The differences are statistically significant (t =2.05 – 6.22) for 13 out of 20 compared pairs in both trials. This shows that, leaving the lesser number of trees for further growth, some of the thickest trees have been removed in order to attain even distribution in stand. Ten years later, the relationship essentially changed (Fig. 5b). At the beginning of the experiment, mean diameters of the 30 thickest trees in the most spacious treatments 9-10 were 0.3 cm lower than those in the control treatments 1 and 2. Five years later they became larger by 1.2–2.0 cm, 10 years later by 3.6–3.9 cm, while 15 years later by 4.9 cm. Diameter of the 30 thickest trees increased considerably more in the treatments of lower density despite lower initial mean diameter. This can be attributed to a more intensive competition for growing space under the conditions of higher density, which influences decreasing growth not only of thinner, but also of the thicker trees.

The mean diameter increment increases with age, attains maximum and decreases in both trials and all thinning treatments (Fig. 6). Maximum mean diameter increment was recorded in both trials at almost the same time, at the age of 12–13 years in all density treatments, except treatments 9-10 and 5-6 of trial 201 (here at the age of 13-19 years). The timing of the highest mean diameter increment coincides with that the highest ratio of mean diameter to height. The maximum of the annual mean diameter increment ranges from 0.62 cm in the control to 1.17 cm in the lowest density treatment of trial 201, and from 0.73 cm in the control to 1.4 cm in the lowest density treatment of trial 206. Maximal increment values in the sparsest stands are 1.9 times higher than in the control stand. Comparison of the mean diameter increment values of all trees (Fig. 6) and the mean diameter of 30 thickest trees (Fig. 5b) in stands of various density show that diameter growth losses due to growth in high density conditions cannot be compensated by the means of later decreased density.

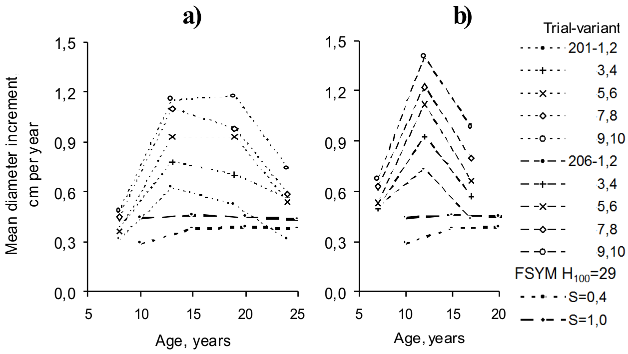

Figure 6. Mean diameter increment depending on age and stand density in trials 201 (a) and 206 (b) and their comparison with forest stand yield model of Lithuania (FSYM)under different stocking level (S)

Volume growth and its response to stand density

The mean annual volume increment per ha increases with age and initial density (Fig. 7). An intensifying volume increment in density treatments 7-8 of trial 201 was estimated at the age of 24 years, exceeding the increment of treatments 5–6 and approaching the

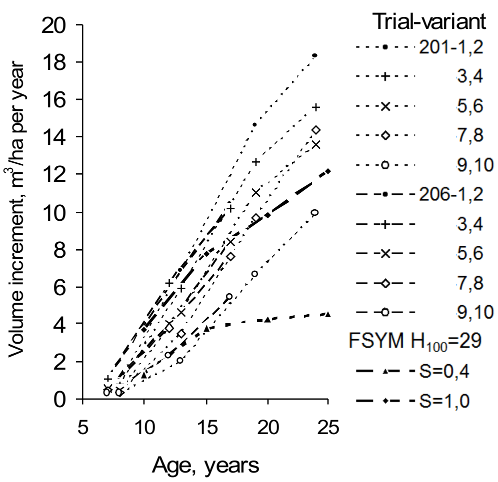

Figure 7. Mean annual volume increment depending on age and stand density in trials 201 and 206 and their comparison with forest stand yield model of Lithuania (FSYM) under different stocking level (S)

increment of treatments 3-4. The volume increment of density treatments 5 to 8 in trial 206 is very close.

The growth efficiency of trees at different densities was estimated using the ratio of the mean tree volume increment of different density stands and mean tree volume increment of the control stand at the appropriate age. The ratio of the mean tree volume growth increases with increasing stand age and with decreasing stand density. This ratio reaches maximum at the age of 19–24 years. In density treatments 7-8 of trial 201, the mean tree volume increment at the age of 19–24 years (density 1,017 trees/ha) is by 2.5 times higher than in the control stand; in treatments 9-10 (density 568 trees/ha) it is 3.1 times higher. Taking into account the latter treatments, it is probable that gross volume increment in these treatments will equalize. This will probably happen 10-15 years later, if only the process of self-thinning in the control stands will be of a similar intensity as till now, while the ratio of the mean tree volume increment of the sparsest stand and the control stand will not undergo significant changes.

A total of 30 thickest trees per treatment were used for estimating the response of tree volume increment to thinnings (Table 2). The sample of the thickest trees, used in the experiment represents on average from 83 trees/ha in trial 201 to 136 trees/ha in trial 206. These make up 15-23 % of all trees in treatments 9-10.

every 5 years and finally there was left 15 % of trees more than in treatments 7, 8. It increased the growth up to 15-25 %.

Total productivity and stand density

The highest total productivity was observed in the control stands of trial 201 at the age of 24 years (221 m^3/ha) and in the stands of trial 206 at the age of 17 years (87 m^3/ha). Total productivity of density treatment 3-4 in trial 201 makes up 88%, while in trial 206 it amounts to 99% of the control stand (Fig. 8). Total productivity in both trials of treatments 5-6 makes up 74–75% of the control. This result was predetermined by comparatively similar density of trials 201 and 206 at the age of 4–13 years. Stands in treatments 7-8 attained 68-70%, while in 9-10 treatments they reached only 45-47% of the control productivity. The most valuable feature of the growing regime of treatments 7-10 is the greatest response of the growth to thinning and the highest growth efficiency of mean trees. Maintaining these features for a long time is a prerequisite for a high yield of large size wood in future stand.

The share of increment accumulated in a stand changes depending on the timing and intensity of thinnings. Almost whole increment is accumulated in intensively thinned stands at the age of 4-8 years, density treatments 7 to 10. Gradually and later thinned stands (treatments 3 to 6) accumulated 76–91% of the volume increment in trial 201 and 90–98% in trial 206. Self-thinning in the control stands is very weak and almost all volume increment of 98–99% is accumulated in the stand. The control stand of trial 201 has even attained the stocking level of 1.42. At such stocking level, stand becomes highly susceptible to adverse factors.

Table 2. Response of the 30 thickest trees volume increment to the thinning of stands during 8-24 years

Treatment	Trials																			
	201												206							
	Age of stand, years																			
	8-13				13-19				19-24				7-12				12-17			
	total trees per ha	30 thickest trees per treatment: an. increment, m^3	an. response, m^3	an. response, %	total trees per ha	30 thickest trees per treatment: an. increment, m^3	an. response, m^3	an. response, %	total trees per ha	30 thickest trees per treatment: an. increment, m^3	an. response, m^3	an. response, %	total trees per ha	30 thickest trees per treatment: an. increment, m^3	an. response, m^3	an. response, %	total trees per ha	30 thickest trees per treatment: an. increment, m^3	an. response, m^3	an. response, %
1,2, control	4756	0.153	0.0	0	3904	0.342	0.0	0	3255	0.511	0.0	0	4647	0.138	0.0	0	4259	0.254	0.0	0
3,4	2960	0.155	0.002	1	1924	0.357	0.015	4	1212	0.566	0.055	10	2744	0.150	0.012	8	2051	0.272	0.018	7
5,6	1989	0.150	-0.003	-2	1175	0.404	0.062	15	1167	0.634	0.123	19	1432	0.160	0.022	14	1413	0.338	0.084	25
7,8	1022	0.182	0.029	16	1022	0.425	0.083	20	1017	0.661	0.150	23	1178	0.182	0.044	24	1164	0.355	0.101	28
9,10	568	0.180	0.027	15	568	0.502	0.160	32	568	0.769	0.258	34	594	0.187	0.049	26	591	0.425	0.171	40

Moderately intensive thinnings every 5 years (treatments 3, 4) allowed increasing volume growth in the first ten years only by 4-8%.

Heavy thinnings done once at the beginning of the experiment, (leaving six hundred stems per ha (9, 10 treatment)), increased growth by 32-40% after 10-15 years. In treatment (7, 8) with twice as many trees left, the response increment reached 23-28 %. In treatments 5.6, the number of trees was reduced gradually

The total productivity of the most intensively thinned stands differs considerably from the productivity of the control treatment (Fig. 8). With increasing stand age, differences in productivity, as compared to the control, decrease. The heavier the stands are thinned, the faster their productivity approaches the control stand. In comparison to the control, differences in productivity of the most sparse stand of trial 201 (9-10 treatments) decreased from 72 to 53% over 11 years. In treatments 3-4, the difference decreased only from 15 to 12% over the same period. These differences are caused by a different response of tree growth to the thinning intensity and frequency.

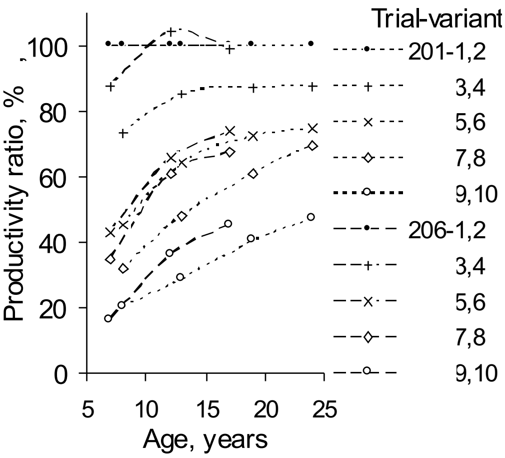

Figure 8. Comparison of the total productivity of different density stands with the productivity of the control stand (productivity ratio)

Comparison of main growth parameters of experimental and modal stands

Parameters of experimental stands of the different density were compared with the parameters of modal stands, described by the stand yield model (Kulie□is 1993). The dynamics of mean tree height in both trials is very close (Fig. 9a). It approximates the height dynamics of stands with H_{100} = 27–30 m. Mean heights of both trials slightly vary over time, from the growth corresponding to H_{100} = 27 m at the age of 15 years to H_{100} = 30 at the age of 24 years.

The dynamics of the mean diameter of stands in the control treatment corresponds to diameter growth of stands with average 0.7 stocking level on sites with H_{100} = 29 m (Fig. 9b). The dynamics of all other density treatments is different; therefore it is necessary to have dynamic models of the mean diameter for all density treatments.

The mean diameter increment values of modal Lithuanian pine stands with 1.0 stocking level and growing on analogous sites are close to increment

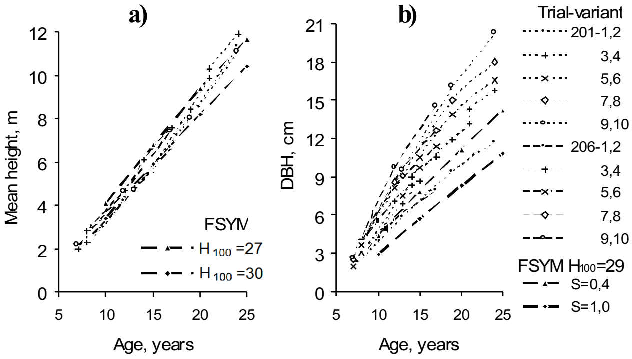

Figure 9. Dynamics of mean tree height (a) and mean tree diameter (b) in trials 201 and 206 and their comparison with forest stand yield model of Lithuania (FSYM)) under different stocking level (S)

values in the control stands (Fig. 6). The mean diameter increment trajectories of all other stand density treatments deviate essentially from the modal stands.

The volume increment of modal stands growing in similar conditions (H_{100} = 29, stocking level 0.4–1.0) according to forest yield model is similar only at the age up to 15 years (Fig. 7). Later the curve of the volume increment depending on age for experimental stands is steeper, which shows more intensive growth in comparison to the growth of modal stands.

The results of the last comparison have been obtained by analysing volume growth intensity, expressed as a percentage of volume increment in experimental and modal stands (Fig. 10). The maximal growth intensity has been recorded in stands of 7-13 years age in both trials. Growth intensity decreases with increasing age of a stand. Growth intensity of experimental stands increases when the stocking level of stands decreases up to some limit, that is particular for each age. For modal pine stands, a slight decrease of the growth intensity was estimated (Kuliešis, 1993), when the stocking level decreases.

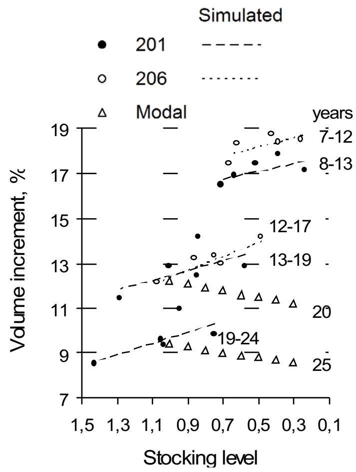

Figure 10. Dependance of growth intensity on stand age and stocking level in experimental and modal stands

Influence of improvement cuttings on productivity of experimental versus modal stands

In silvicultural practice, thinning of pure pine stands begins when they exceed a certain allowable number of trees or stocking level under determined mean stand height. A certain defined number of trees or a critical stocking level should be maintained in the stand after cuttings (Mikšys and Juodvalkis 2007). One of the most important stand productivity indexes is the accumulated growing stock volume, expressed by the number of trees, relative stocking level, mean diameter and height.

We have compared mean diameters of pine stands of different densities with mean diameters of stands of the same height (Fig. 11) left after improvement cuttings. According to thinning standards, the mean height of 5–11 m corresponds to the mean tree diameter of 6.1–10.6 cm, i.e. the diameter and height ratio of the remaining trees varies within the range of 1.22–0.96. This ratio is slightly higher in untended control stands. The ratio in moderately intensively thinned stands (treatments 3-4) ranges from 1.6 to 1.36, and in heavily thinned stands (treatments 7-8) it reaches 2.0 to 1.64.

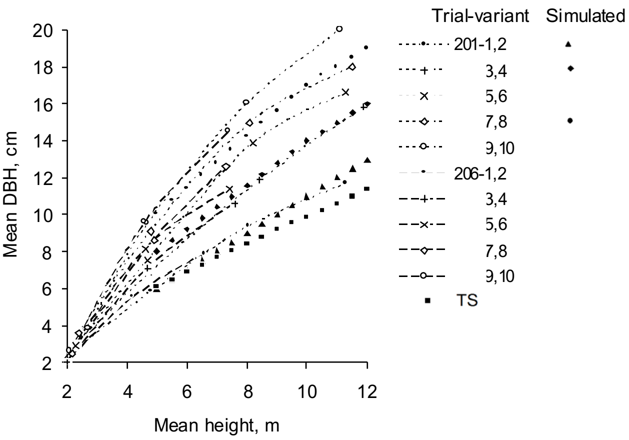

Figure 11. Comparison of mean diameter at mean height in different density trials and thinning standard of pine standards (TS)

Having left 1,210 trees/ha after moderately intensive thinnings with frequency 6-7 years (at age 8 years left 2,998 trees, 15 years – 1,924 trees, 21 years – 1,212 trees, trial 201, treatments 3-4), the stands at the age of 24 years with mean height of 11.9 m attain the mean diameter of 15.8 cm, relative stocking level of 0.94 and accumulate per stand 75 % of the volume increment. Stands thinned one time at the age of 8 years up to 1,020 trees density per ha (201 trial, 7-8 treatments) at the age of 24 years such stands with mean height of 11.5 m attain the mean diameter of 18.0 cm, relative stocking level 1.04 and accumulate per stand 97 % of the volume increment. Extremely intensive and early thinnings, long period growth without disturbances in the stands of 7-8 treatments resulted in higher diameter increment and higher volume accumulation per stand as compared with stands of 3-4 treatment. In both cases early regulation of stand density allows in the best way to use intensive growth period for forming stands from vigorous and vital future trees.

Discussion

Forest stand density is amongst the most important parameters in predetermining the yield level of the stand (Sterba 1987, Hasenauer et al. 1994). Tree height and especially diameter growth are under the influence of stand density (Oliver and Larson 1996, Mitchel et al. 1983, Salminen and Varmala 1993, Kuliešis 1989, Kuliešis and Saladis 1998, Kairiūkštis and Juodvalkis 2005). The results of our study cover the relationship between tree height, diameter growth and total productivity under the influence of different density pine stands during 4-24 years of age.

The dependence of tree height on different initial density is less important for final productivity of stand and this relationship is expressed less definitely (Тимофеев и др. 1961, Hamilton 1981, Harrington 1983, Юодвалкис 1988, Kerr 1996, Malinauskas 2008). In the forest steppe zone of Ukraine, an increase in height with decreasing initial density has been observed (Гаврилов 1961, Шинкаренко et al. 1981). Assmann (1964) (after Hamilton 1981) also suggested that higher intensities of thinning have a stimulating influence on the height growth. Hamilton (1981) concluded that the highest height increment was found in the unthinned control plots, but that different thinning intensities had no significant effect on height growth. Kerr (1996) determined that the lightest regime of crown thinning produced the tallest trees; and the heaviest treatment produced the lowest trees. Taking into account that the height growth has a priority in respect to the diameter growth (Oliver and Larson 1996), it is most likely, that due to reduced space and increased competition, the diameter increment initially decreases most remarkably. At the initial stages of increasing competition, the height increment remains stable (Kuliešis and Saladis 1998).

Long term studies for Douglas – fir stands (Harrington et all 1983) showed that immediately after thinning trees faced a thinning shock that generated a reduction of the height growth. From 15 to 25 years following thinning, height growth was positively related to growing space with the best growth at wider spacing. The results of Harrington et al. (1983) study explain various possible reactions to height growth depending on thinning intensity, duration after thinning and competition level between trees for the moment of estimation.

The results of our study have reliably shown that the greatest height is attained in moderately intensively thinned pine stands (treatments 3-4), i.e. with a reasonable competition among trees. Mean heights of trees in the dense control stands are lower than in moderately thinned stands due to especially tough competition and high numbers of short trees. However, these of the control stands are higher than of heavily thinned stands, considering both all trees in the stand and the tallest trees only.

Growing stock volume of a given stand height is often referred to as the yield level (Skovsgaard and Vanclay 2007). The yield level is usually expressed by the standard value of maximum basal area or growing stock volume at the appropriate height. Comparing basal area or growing stock volume of an individual stand with its standard value, a relative stocking index of stand is obtained. Such a system of stocking level estimation is applicable in usual forestry practice for majority of stands. Depending on climate, soil, provenance, method of stand establishment and treatment, and duration of rotation, the actual yield level can remarkably exceed the usual standard level. A higher yield level can be achieved in two main ways: growing higher number of trees of usual diameter at breast height or growing a usual number of trees with higher diameter at breast height (Hamilton 1981, Hasenauer et al. 1994, Skovsgaard and Vanclay 2007). Maintaining a larger number of trees per area without severe increase of competition between trees is possible only in some restricted cases: on slopes, using trees of genotype with typical narrow crown, on special sites, allowing growing trees resistant to damages of wind, insects and so on. Usual increasing number of trees always will induce increased competition, leading to suppressed growth and instability of stand.

Regulation of stand density by thinnings is oriented towards increasing growth intensity of the remaining trees. There are two strategies: 1) to keep a larger number of trees as long time as possible and to remove trees weakened by competitions or 2) to remove a part of trees before they start competing with other trees. The first strategy allows using the growing space maximally, but not growing energy at early stage. Such thinnings in pine stands usually start at 20 years age or later, when the period of maximum tree growth has passed. The best time for intensive growth is missed for all as well as for largest trees and they never will reach such a diameter that could be obtained in free growing conditions without competition. Such strategy is acceptable for growing stands of average productivity and average rotation period. The second strategy of stand formation allows to maximally using the growth energy, which is a precondition for a higher level of yield. Differences in growth intensity of modal pine stands of Lithuania (the first strategy) and our experiment (the second strategy) are predetermined by different growing history of these stands especially during the period of intensive growth. Experimental stands of low density or low stocking level have vital, trees of large diameter due to sufficient growing space during the intensive growth period. Thinning of modal pine stands in the silvicultural practice of Lithuania is more focused on growing an excessive number of trees in a stand (Mikšys and Juodvalkis 2007). Thus, the competition index of thinned stands in the period of the most intensive growth, when the mean tree height is 5–11m, exceeds 2.0 and occupies an interim position between unthinned control and moderately thinned stands. The current silvicultural practice leads to the situation when the prevailing part of trees is weakened by competition and has slow diameter growth.

The mean diameter of freely growing trees increases mainly due to intensive growth of the tree. In this case, the ratio of the mean diameter increment of freely growing trees to that of the trees growing under high competition in the control stands always overcomes the corresponding ratio of the mean diameters of the same stands. These differences are a result of more intensive growth of trees on a more spacious area. For example, the mean diameter increment ratio of stands 9, 10 to control at 19-24 years of age is equal to 0.74/0.31=2.39, when the corresponding ratio of the mean diameters is equal to 20.2/11.7=1.73.

Modal pine stands of high stocking level as well as low stocking level consist of trees more or less weakened by competition. The period of intensive growth was insufficiently used by remaining trees in both cases. Increase in the mean diameter of low-stocked modal stands is not only a result of the growth, but also by intensive self-thinning of small size diameter, suppressed trees. The ratio of the mean diameter increment of highly-stocked stands to low-stocked modal stands is lower than the mean diameter ratio of the same stands. It is a result of a stable, yet decreasing growth intensity when the stocking level of modal stands decreases. For example, for modal pine stands of the same site and age, as experimental stands, the ratio of the mean diameter increment is equal to 0.41/0.36=1.14 and the ratio of the mean diameters – 14.2/10.8=1.31. The analyzed ratios of modal stands always are smaller and closer to 1.0 compared with the corresponding ratios of stands purposefully oriented to intensive growth.

High response of the tree diameter and volume growth to early and intensive thinning and accelerated increase of the mean trees diameter are the main prerequisites for reaching a higher level of the yield at the same forest site, characterized by the stable height growth.

Conclusions

1. Pine stands growing on infertile sites of normal humidity, characterized by site index 29 m, attain the maximum of the mean diameter increment at the age of 12–13 years. In the year of its maximum and later, the mean diameter increment of heavily thinned stands (down to 568 trees/ha) is higher than the mean diameter increment of the control stand by 1.8–2.8 times. At the end of experiment, the mean diameter growth exceeds the growth in the control by 1.7-1.8.

2. Competition among trees has a positive influence on height growth at the density of 2,000–3,000 (4,000) trees/ha in 7–19 year old stands. The tree height at the same diameters surpassed the tree height in stands with 600 trees per ha by 22 %. It also exceeded the height of the most lightly thinned stands, (4,000-4,400 trees per ha) by 11%.

3. The volume increment per tree increases with decreasing density of stand and increasing age up to 19–24 years. The mean tree volume increment in the most spacious treatment is 3.1–3.7 times higher than the mean increment in the unthinned control stand.

4. As a response to thinnings, the growth of thickest trees during 4-24 years increases from 4-8 % in case of moderately intensive thinnings performed every 5 years up to 32-40 % in case of intensive thinnings, when the number of left in stand trees aged 4-8 years decreases up to 568-591 per ha.

5. Total productivity of regulated stands of different density treatments comprises 45–85% of the control stand productivity at the age of 17–24. The lowest, but at the same time the most quickly approaching control stand productivity, is the productivity of the most heavily thinned stands.

6. High response of the tree diameter growth and volume increment to the early, intensive and optimal frequency thinnings are the main prerequisites for development of stand by the way of the higher level of the yield.

References

Assmann, E. and Franz, F. 1963. Varlanfige Fichten – Ertragstutel fur Bayern/ Inst. Ertragskundle.- Munchen, 104 pp.

Castedo-Dorado, F., Crecente-Campo, F., Alvarez-Alvarez, P., and Barrio-Anta, M. 2009. Development of a stand density management diagram for radiata pine stands including assessment of stand stability. *Forestry* 82(1): 1–16.

Ńochran, W. G. 1963**.** Sampling techniques. New York, London, John Willey and Sons, 413 pp.

Fišas, M., 1968. Tikimybių teorija ir matematinė statistika [Theory of probability and mathematical statistics]. Vilnius, *Mintis,* 551 pp.

Hamilton, G. J. 1981. The effect of high intensity thinning on yield. *Forestry* 54:1-15.

Harrington, C. A. and Reukema, D. L. 1983. Initial shock and long – term stand development, following thinning in a Douglas – fir plantation. *Forest science* 29:33-46.

Hasenauer, H., Burkhart, H. E. and Sterba, H., 1994. Variation in potential volume yield of Loblolly pine plantations. *Forest science* 40(1): 162-176.

Horne, R., Robinson, G. and Gwalter, J. 1986. Response increment: a method to analyze thinning response in even – aged forests. *Forest science* 32 (1): 243 -253.

Kairiūkštis, L. and Juodvalkis, A. 1985. Etaloniniai medynai ir jų formavimas [Standard stands and their formation]. Vilnius: *Mokslas,* 244 pp. (In Lithuanian)

Kairiūkštis, L. and Malinauskas, A. 2001. The influence of the initial density on spruce (Picea abies Karsten) wood quality. *Baltic Forestry* 7(2): 8-17.

Kairiūkštis, L. and Juodvalkis, A. 2005. The theoretical fundamentals of forming of the most productive stands. *Baltic Forestry* 11(2): 38-50.

Kerr, G. 1996. The effects of heavy or free growth thinning an oak (Quercus petraea and Quercus robur). *Forestry* 69: 303-317.

Kuliešis, A. 1989. Medynų našumas ir jo panaudojimas [Yield of forest stands and its use]. Vilnius. 141 pp. (In Lithuanian)

Kuliešis, A. 1993. Lietuvos medynų prieaugio ir jo panaudojimo normatyvai [Forest yield models and tables in Lithuania]. "*Girios aidas"*, 383 pp.

Kuliešis, A. and Saladis, J. 1998. The effect of early thinning on the growth of pine and spruce stands. *Baltic Forestry* 1: 8-16.

Malinauskas, A. 1999. The influence of the initial density and site conditions on Scots pine growth and wood quality. *Baltic Forestry* 2: 8-19.

Malinauskas, A. 2008. Miško želdinių pradinis tankumas [Initial density of forest plantations]. Kaunas, *Lututė*, 229 pp. (In Lithuanian)

Mikšys, V. and Juodvalkis, A. 2007. Rekomendacijų medynų ugdymo projektavimo bei vykdymo normatyvų tikslinimui parengimas [Preparation of the recommendations for planning and performing of stands thinnings]. Baigiamosios ataskaitos rankra□tis, Girionys, Lietuvos miškų institutas, 43 pp. (In Lithuanian)

Oliver, C.D. and Larson, B.C. 1996. Forest stand dynamics, update edition. John Wiley and Sons, Inc., 520 pp.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. *Journal of Agricultural research* 46: 627-638.

Salminen, H. and Varmale, M. 1993. Influence of initial spacing and planting design on the development of young Scots pine (*Pinus sylvestris* L.) stand. *Silva Fennica* 27(1): 21-28.

Skovsgaard, J. P. and Vanclay, J. K. 2007. Forest site productivity: a review of the evolution of dendrometric concepts for even – aged stands. *Forestry* 2008 81 (1) : 13-31. Forestry advance access originally published online on October 24, 2007.

Sterba, H. 1987. Estimating potential density from thinning experioments and inventory data. *Forest science* 33 (4): 1022-1034.
Wilson, F.G. 1946. Numerical expression of stocking in terms of height. *Journal of Forestry* 44: 758-761.
Гаврилов, Б.И. 1963. Лесные плантации быстрого прироста [Fast growing forest plantations]. *Лесной журнал* 1969 4: 14-16. (In Russian)
Гмурман, В. Е. 1972. Теория вероятностей и математическая статистика. Москва, Высшая школа, 386 сс.
Шинкаренко, И.Б., Говорова, Т.Т., Головчанский, И.Н. и др. 1981. Разработка рациональных режимов выращивания искусственных сосновых плантаций [Investigations of efficient regimes of growing artificial pine plantations]. Киев, *Лесоводство и агролесомелиорация,* вып. 59: 3-8. (In Russian)
Юодвалкис, А. 1988. Особенности роста культур сосны различной первоначальной густоты [The growth of Scots pine (*Pinus sylvestris* L.) plantations of the different initial density]. Lietuvos miškų ūkio MTI darbų rinkinys, T. 28. V. *Mokslas*, p. 55-67. (In Russian)

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РАЗВИТИЕ И ПРОДУКТИВНОСТЬ СОСНОВЫХ ДРЕВОСТОЕВ, ВЫРАЩИВАЕМЫХ В УСЛОВИЯХ РЕГУЛИРУЕМОЙ ГУСТОТЫ

А. Кулешис, Й. Саладис, А.А. Кулешис

Резюме

Основным мероприятием по регулированию продуктивности сосновых древостоев является регулирование их густоты. В течение 16 лет изучалось формирование и рост двух сосновых древостоев, растущих в лесах *Vaccinio-myrtillosa* типа, с первоначальной густотой 5.4-8.1 тыс. ед./га. Исследование проводилось, начиная с возраста 4-8 лет. Оба насаждения созданы искусственным путем, один на бывшей пашне, второй – на лесосеке. Десять проб (пять вариантов по два повторения) было заложено в каждом насаждении. Изучалось пять вариантов с различной первоначальной густотой от 0.6 тыс. ед./га до густоты контрольных насаждений с интервалом 0.5-1.0 тыс.ед./га. Густота насаждений регулировалась с целью получения различных конкурентных условий за все время исследования. Каждый вариант был обмерен от 4 до 8 раз.

Густота деревьев от 2 до 3 (4) тыс. ед./га в возрасте от 7 до 19 лет положительно способствует росту деревьев в высоту. Средний прирост по диаметру деревьев, растущих наиболее редко (0.6 тыс. га), превышает средний прирост по диаметру контрольного насаждения в 1.8-2.8 раза. Отношение объемного прироста среднего дерева наиболее разреженного и контрольного насаждений в возрасте 17-24 лет составляет 3.1-3.7 раза. Интенсивные и ранние изреживания сосновых насаждений существенно снижающие конкуренцию между деревьями после смыкания крон, позволяют максимально использовать энергию роста в молодом возрасте, что является предусловием достижения древостоем более высокого уровня продуктивности.

Ключевые слова: густота, рост по диаметру, высоте и запасу, конкуренция, уровень продуктивности древостоя