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THE INFLUENCE OF STEM DENSITY ON THE PRODUCTIVITY AND QUALITY OF SPRUCE (*PICEA ABIES* [L.] KARST.) WOOD IN A SHORT ROTATION PLANTATION IN THE BOREAL ZONE OF NORTH-WEST RUSSIA

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Abstract: *In the boreal zone of North-West Russia, a number of experimental short-rotation pulpwood spruce plantations have already reached the age for clear felling, so that currently it is possible to draw conclusions about the effect of different stand density management regimes on the qualitative and quantitative characteristics of spruce wood. The aim of the project was to evaluate the effect of planting density and thinning on the productivity of a short-rotation spruce plantation and the quality of the produced spruce wood. Three variants of stand planting densities in two replications were investigated (1,000, 2,000, 4,000 trees ha^{-1}). On the replicated sample plots, thinning was carried out. Wood volume, wood density, and wood macro- and microstructure were evaluated and compared in accordance with planting density and thinning intensity. The best growth and stem biomass parameters were observed in the variant with the initial planting density of 2,000 trees ha^{-1} and the density of 1,065 trees ha^{-1} after thinning at the age of 25 aimed at retaining the best trees. The density of the spruce wood was mostly influenced by the macro- and microstructure of the early wood zone. The thinning of a stand led to a decrease in the average number of early wood cells in annual layers, with a simultaneous increase in cell wall thickness. The densest wood was formed in the variant with the initial density of 4,000 trees ha^{-1} and the final density of 1,050 trees ha^{-1} after thinning at the age of 25.*

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1. Introduction

Artificial forest stands with a short-rotation period, or forest plantations, are stands created and grown to obtain wood with predetermined parameters to be used by a particular enterprise. Based on advanced industrial technologies, wood is grown in large quantities on such plantations within considerably shorter periods of time as compared with forests of natural origin with a full-rotation period [3], [11], [30], [32, 33]. Globally, forest plantations are associated with the cultivation of fast-growing, highly productive and highly demanded forest tree species; in such plantations, the increase in growing stock is many times greater than that in natural forest stands [8], [30, 31]. The most important factor that makes it possible to increase forest plantation growing stock and improve wood quality is the use of appropriate silvicultural systems and activities [33, 34].

The optimal density of a growing forest stand is such that the number of trees per unit area will ensure the existence of a closed canopy during the entire growing period and the maximum use of both solar energy by the surface of leaves and soil fertility, by the root systems [8]. To determine the optimal density of forest plantations, foresters have long begun to create experimental forest stands [28]. European spruce (*Picea abies* (L.) Karst.) is one of the most important forest species in Central and Northern Europe due to its high ecological plasticity and economic versatility [5], [25]. For this reason, studies of spruce forest plantations are relevant to the science and practice of forestry.

Different authors provide different and often contradictory data and recommendations on the density and planting patterns of trees used in the creation of plantations and in artificial reforestation [1], [29], [35]. A number of authors have noted that in Western Russia, the natural tree loss in thickened spruce plantations is higher as compared with that in natural forest stands [23], [33]. Overdensity of spruce stands strongly affects the diameter of trees. While the difference in height between thinned (5 thousand trees) and dense (11 thousand trees) spruce stands was 19% (the average height of the former was used as a control line), the difference in diameter was 36%. As the planting density of spruce stands grows, the sum of the basal areas of the trunks increases, as well as the density and mortality of the trees. However, it does not have a noticeable effect on the height, diameter, and productivity of spruce trees; moreover, these parameters have a tendency to level out. Over time, the tree numbers and the average diameters even out in spruce stands of different initial densities, so that the differences in these characteristics, which at first are enormous in size, become less pronounced or completely disappear [33].

In a number of studies on the effect of spruce stand density on the height and diameter of trees at different age stages, different results were obtained, depending on soil and climatic conditions, for different parts of Europe [2], [19], [30], [32], [38], [41].

For the conditions of Central and Northern Europe, the results of studies on the regulation of spruce stand density have shown that the optimal thinning regimes and the plantation turnover period depended on the quality of the site and the initial characteristics of the stand [29], [34]. During the first thinning, the optimal approach depended on the initial density. The harvesting of trees with smaller and larger trunk diameters turned out to be the most appropriate for the initially dense forest stands. For the second and subsequent thinnings, the felling of larger trees yielded better results in terms of growing stock accumulation [6].

In Northern Europe, studies of the methods for spruce stand thinning have shown that systematic thinning resulted in the least increase in timber volume. It is noted that semi-systematic thinning most likely did not lead to a significant increase in tree mortality and loss of the final growing stock by the time a stand reached the felling age [20]. More recent studies have shown that as spruce stand density decreases, there is a much stronger reduction in volume increments than previously demonstrated in Fennoscandia [13], [24].

In some studies in European countries, it has been noted that thinning of different intensities and frequencies in spruce plantations does not always lead to the same amount of profit. Obviously, growing stock and financial return contradict each other; the former is maximized when large trees are cut down, and the latter, when small trees are frequently cut down [18], [25].

In the case of targeted forest cultivation, along with the inventory volume parameters of a stand as a whole, it is necessary to take into account its qualitative productivity, i.e. the commercial structure of the stand and the technical properties of timber [6]. Knowledge about such characteristics of wood structure as density, late wood width, and cell wall thickness substantially improves our understanding of the qualitative characteristics of wood [27]. A number of studies [9], [14, 15] have demonstrated that in spruce, the formation of late wood and wood density is under strict genetic control, which is confirmed by a high value of the heritability coefficient. But the density of spruce wood can also change under the influence of silvicultural activities. Only a limited number of studies have addressed this issue [1], [23], [27], and information on the effect of silvicultural activities on the density and content of late wood in annual rings is contradictory. Studies carried out in the European North of Russia have demonstrated that in spruce forests, the content of late wood and wood density did not decrease as a result of thinning [37].

Changes in the anatomical structure and density of wood also depend on the age of the plantation in which the forestry activities are carried out and on their intensity. In some cases, in spruce forests with the same content of late wood, wood density can differ [16]. The relationship between wood density and the width of annual rings is not always evident. Such parameters as cell wall thickness, tracheid length, late zone porosity, and wood volumetric and surface porosity have a stronger influence on wood density [21].

Several studies have reported a significant effect of stand density and tree diameter class on wood density [17], [32], [39, 40]. In the European boreal zone, studies of the thinning influence on spruce stands produced different results in terms of qualitative and quantitative wood properties. A study carried out in uneven-aged spruce stands showed that the differences in wood density and anatomical structure depended on the spatial distribution of the trees [26]. Thinning experiments in high-yield spruce plantations (*Picea abies* (L.) Karst.) in Southern Sweden have shown that the silvicultural regime consisting of several thinnings did not affect the average basic wood density. With more intensive thinning, spruce wood density decreased. In general, the thinning of spruce stands reduced the content of early wood in the annual increment [22]. According to the results of two long-term experiments carried out in Central Finland, the influence of different thinning regimes and fertilization on growth and wood density of spruce (*Picea abies* (L.) Karst.) was negligible; however, the radial growth of individual trees increased significantly [16].

The success of forestry efforts and the achievement of the intended outcomes in terms of wood quality and quantity are pre-determined by the initial and final stand density. The optimal density can be achieved with the help of silvicultural activities. As a rule, ignoring the importance of planting density leads to a decrease in stand productivity.

The aim of the research was to study the effect of stand density regimes and silvicultural activities on stand productivity and wood quality in short-rotation spruce plantations. It should be noted that in Northwest Russia, a number of experimental short-rotation pulpwood spruce plantations have already reached the felling age. Based on the results of long-term experiments, it is now possible to draw conclusions about the effect of silvicultural activities and different stand densities on the qualitative and quantitative characteristics of spruce wood. For plantations with short rotation period, it is necessary to predict the performance of the raw material at different rates of density and types of maintenance. Therefore, the results will be of interest for plantation management in boreal countries to choose the most scientifically based optimal regime of planting density and further management for accelerating the production of woody biomass.

2. Materials and Methods

2.1. Study Object

The study was carried out in an experimental spruce stand established in 1976. The stand is located in the Gatchinsky District of the Leningrad Region, in the boreal zone of North-West Russia (59.296631 N, 30.161518 E). The climate of the study area is Atlantic-continental. Sea air masses cause relatively mild winters with frequent thaws and moderately warm, sometimes cool summers. The average January temperature is –8°C, in July, +17°C. Annual precipitation is 650-700 mm.

The site is a former drained hayfield with a slight change in the relief. In the elevated part of the site, soils are soddy, medium podzolic, sandy loam on loams; in the middle part of the site, moist humus-peaty, medium podzolic on loams or sands; and in the lower part of the site, moist humus peat on loam.

The soil was cultivated with a PLO-400 forest reclamation plow, which created 30–35 cm high layers and 35–40 cm deep furrows. Standard three-year-old seedlings of *Picea abies* (L.) Karst. were planted. The following planting densities were used:

- 1,000 trees ha^{-1}, 3.2 m spacing;
- 2,000 trees ha^{-1}, 1.6 m spacing;
- 4,000 trees ha^{-1}, 0.8 m spacing.

Each experiment with spruce density included two replications and each of the sample plots had an area of 0.2 ha. In total, the objects of the study were 5 sample plots. No silvicultural activities were carried out on the 1,000 trees ha^{-1} plot; that was the control plot in relation to the plots with higher densities, and it was not planned to carry out any additional thinning on it.

On the replications of the plots with the planting densities of 2,000 trees ha^{-1} and 4,000 trees ha^{-1}, thinning was carried out at the age of 25. Thinning was done evenly over the area by hand with chain saws, with priority given to removing retarded trees. As a result, the planting density was reduced by 50% to 1,000 and 2,000 trees ha^{-1} accordingly.

Data on the tree growth dynamics in the experimental plots are presented in Table 1.

Table 1

Spruce growth parameters in the experimental plots: average diameter, D; average height, H; average tree volume, V; and yield, Y

At the age of 15				At the age of 43				
Initial stand density [trees ha^{-1}]	D [cm]	H [m]	V [m^3]	Final stand density [trees ha^{-1}]	D [cm]	H [m]	V [m^3]	Y [m^3 ha^{-1}]
1,000	3.5	2.8	0.0023	948	22.5	19.2	0.427	405
2,000	3.1	2.5	0.0016	1,253	18.8	18.7	0.311	390
2,000*	3.1	2.5	0.0016	1,065	22.8	20.8	0.466	496
4,000	3.4	2.9	0.0023	1,535	17.2	19.2	0.247	380
4,000*	3.4	2.9	0.0023	1,050	19.3	19.8	0.308	323

Note: * Thinning was carried out at the age of 25

2.2. Applied Methods and Equipment

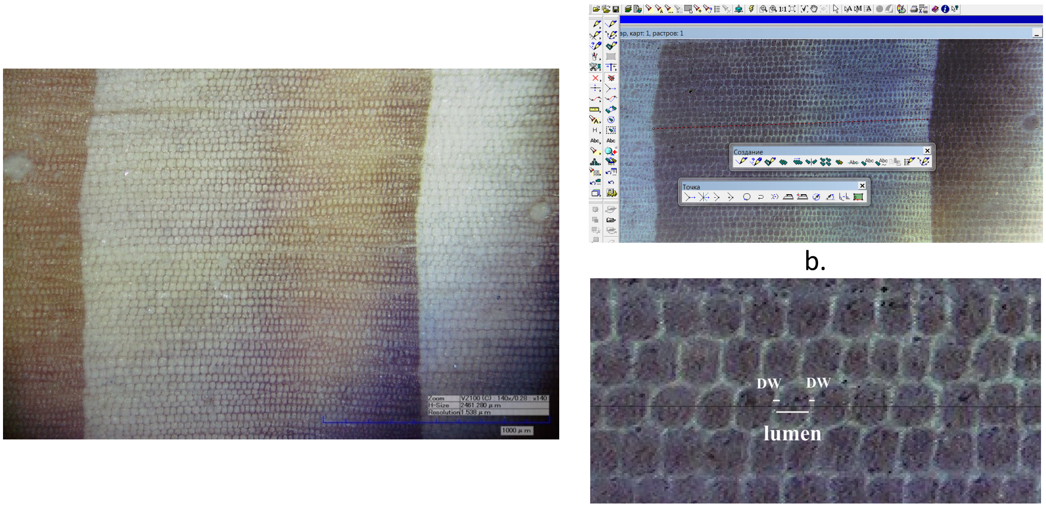
During the study period (until the stand reached 43 years of age), experimental plots were surveyed, and the remaining viable individuals were counted to estimate plant survival rate. During the surveys, the following parameters were measured: height, in 60 to 100 individuals from each plot; and diameter at a height of 1.3 m from the root neck, in 450 to 4,500 individuals in different years. Measurement of plantation taxation parameters was carried out with Haglöf tree calipers and Suunto altimeters. Subsequently, using the measured stand heights, graphs were obtained that most accurately described the dynamics of tree growth, and equations were calculated on the basis of which the average heights (H_{graph}) were determined. The volume of wood was calculated based on the measured trunk diameters according to the average tree heights.

In each sub-plot, 800 cores were taken from trees of each diameter class at the height of 1.3 m from the soil level using a Pressler age drill [27].

The density of wood is an integral indicator of its quality, because it affects the physical-mechanical and mass parameters. Wood density was estimated using the method of the maximum moisture recommended for small samples [27]. Stem biomass was calculated as the ratio of the wood trunk volume to the wood density.

Wood density is influenced both by macrostructural elements, such as early wood zone, late wood zone, and microstructural elements at the level of xylem cell structure. Therefore, wood at the macro and micro levels was investigated. The annual layer width and the late and early wood width were measured for the entire lifespan of a tree with an accuracy of ± 0.01 mm using a high-resolution scanner [4], [10]. These measurements were taken for all of the wood samples obtained.

To study the anatomical microstructure of the xylem, a Leica DVM5000 digital electron microscope was used; its design allows the study of objects in reflected and lateral light (Figure 1a).



a. c.

Fig. 1. *a. Digitized image of a fragment of the xylem in a prepared spruce wood sample; b. Measurement of the anatomical structure of the xylem in a sample; c. Measurement of double cell wall thickness (DW) and xylem lumen*

Based on the previously proposed methodology [37], the parameters of every tenth cell in the early and late wood zones were measured, and with a smaller number of cells, in no fewer than three cells (Figure 1b). The two outermost cells on each side of the early and late wood zones were not measured, because those could belong to the transition zones between these structural elements [4], [37].

To speed up the measurements and to improve accuracy, the thickness of the double cell wall was measured on each side of the lumen along the line. Subsequently, the thickness of a single cell wall was calculated as a quarter of the obtained value (Figure 1c).

All statistical analyses were done in Statistica 10, STATGRAPHICS Centurion XVI and Microsoft Excel.

The statistical analysis of the forest stand taxation indicators was carried out using MS Excel 2017 and Statistica 8.0 [7], [12]. The following statistical parameters were calculated: mean, mean error, and standard deviation. To test the significance of the tree stand diameter differences between individual plots, we used Student's *t*-test and the variance analysis.

The results were assessed using ANOVA, correlation analysis, and Fisher's *F*-test. Factor analysis was used to study the relationship between various wood microstructure indicators. Factor loadings were also calculated, with an *R* coefficient of more than 0.7 being accepted as an indicator of a strong correlation [7], [12].

3. Results

3.1. Growth Indicators of Spruce Stands with Various Densities

Over the entire observation period, the highest number of planted trees survived only in the site with an initial density of 1,000 trees ha^{-1} (Figure 2a). On the plot with the initial density of 2,000 trees ha^{-1} (without thinning during the entire observation period), the density decreased by 40% (to 1,253 trees ha^{-1}) over the last 20 years. In the plot with 4000 trees ha^{-1}, under the same conditions the density decreased by 60% (to 1,535 trees ha^{-1}), and trees with the diameters of 8-12 cm were lost for natural reasons. Thus, we observed the natural thinning of tree numbers in the artificial stands under study.

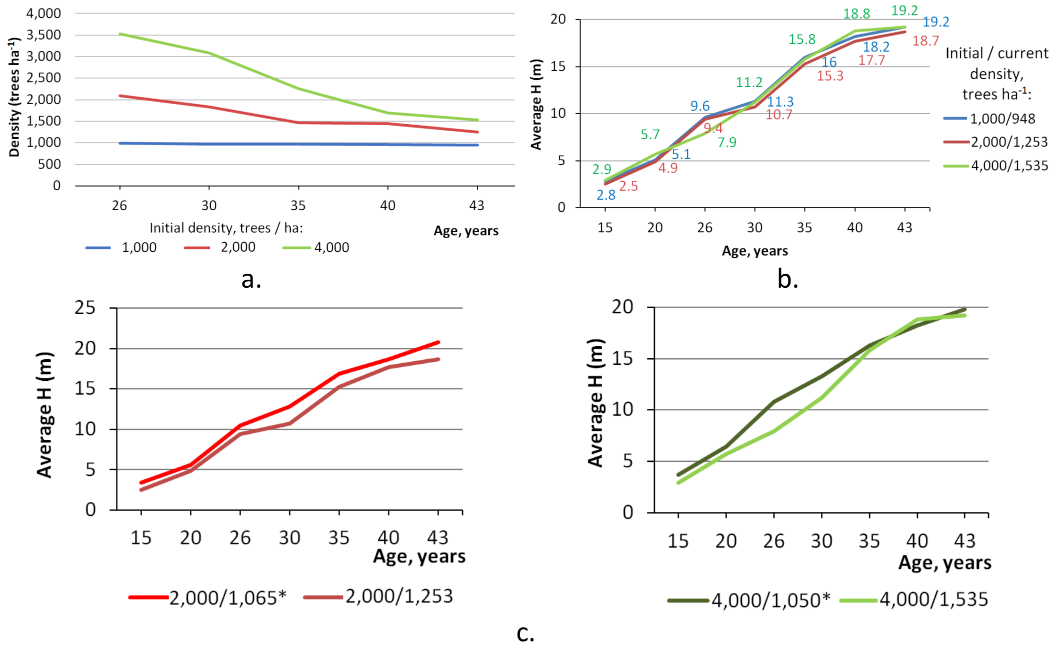
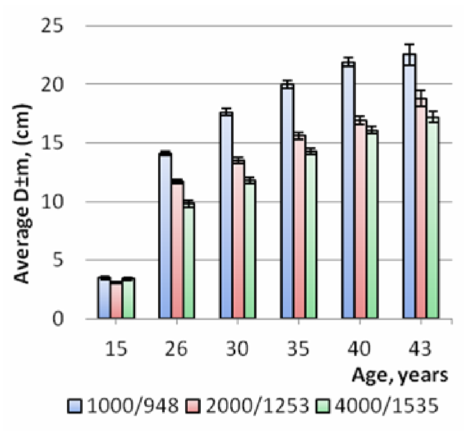


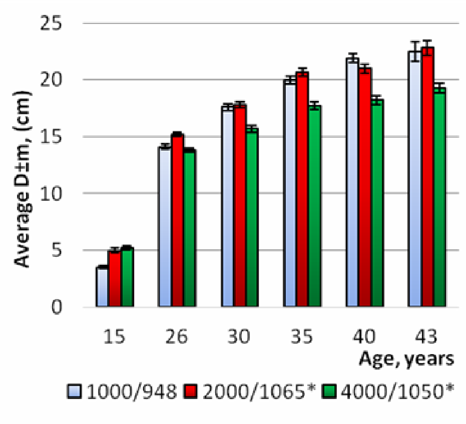
Fig. 2. a. *Natural thinning of the spruce plantations; b. Height growth in spruce stands with different densities. The numbers on the graph correspond to the average height of spruce stands with different initial and current densities; c. Height growth of the thinned spruce stands. Thinning at the age of 25 is marked with an asterisk (*)*

The dynamics of tree height growth has shown that the average height of stands without thinning was within the measurement error of 5% (Figure 2b). Natural thinning in the stands with different densities resulted in the formation of closely related average stand heights from the age of 30. This is due to the differentiation of trees in the course of spruce growth and stand formation.

The visual analysis of the height growth curves (Figure 2c) for the sub-plots thinned at the age of 25 did not show any increase in the average height of the spruce stands.



a.



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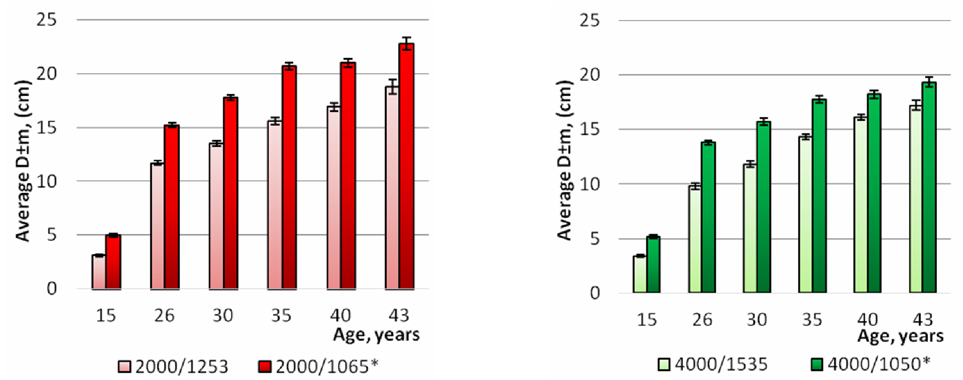


c.

Fig. 3. a. *Spruce stand diameter growth depending on stand density; b. Spruce stand diameter growth depending on thinning intensity. Thinning at the age of 25 is marked with an asterisk (*); c. Changes in the stem diameters of unthinned and thinned spruce stands. Thinning at the age of 25 is marked with an asterisk (*)*

The results have shown that the average diameter of the stand was more strongly dependent on the current number of trees. In the unthinned stands, the average stand diameter was negatively related to the initial stand density: the lower the density, the larger the diameter. The variance analysis carried out for the plots with different planting densities has shown that their mean diameters differed at a significance level of $p<0.05$ (Figure 3a).

The reduction of the original density of 2,000 trees ha^{-1} by removal of 50% of trees (to 1,065 trees ha^{-1}) resulted in an increase in the mean stand diameter at the age of 43. At the time of the last observation, the average stand diameter was comparable to that of the stand with the planting density of 1,000 trees ha^{-1} (Figure 3b).

The effect of thinning carried out at the age of 25 on the average stand diameter is demonstrated in Figure 3c, with significant differences at the 0.05 level. By the age of 43, on the sub-plot with 2,000/1,065 trees ha^{-1}, the average diameter was 18% higher compared to the experiment with 2,000/1253 trees ha^{-1}; and in the experiment with 4,000/1,050 trees ha^{-1}, 10% higher compared to the experiment with 4,000/1,535 trees ha^{-1}.

3.2. Anatomical Structure and Density of Spruce Wood in Stands with Different Planting Densities

External structural changes in spruce plantations could not but affect the anatomical structure of the wood. The analysis of the data given in Table 2 shows that in the sample plots with different planting densities and thinning intensities, the wood has different densities. This trend varies slightly depending on the stand density, as well as on the stem diameter class. At the same time, the analysis of the influence of thinning at the age of 25 on wood density in the experimental sub-plots has shown significant differences with unthinned plots ($t_{1.99} = 2.44$; $p = 0.017$).

Table 2

Average basic wood density [kg m^{-3}] of 43-year-old spruce stands

Initial/final planting density [trees ha^{-1}]	Density per diameter class [cm]							
	8	12	16	20	24	28	32	36
1,000/948	–	369.4	402.8	376.7	411.4	383.7	382.3	412.0
2,000/1,253	394.7	395.5	375.0	364.1	396.2	388.9	383.1	–
2,000/1,065*	–	395.1	393.0	377.0	390.8	388.8	402.5	393.0
4,000/1,535	397.3	401.9	394.9	380.0	393.5	397.4	383.1	–
4,000/1,050*	410.0	428.0	392.4	414.4	399.7	398.6	410.1	–

Note: * Thinning was carried out at the age of 25

Spruce wood density depends on the structure of the xylem elements. The relationship between the macrostructural elements of the xylem structure and the wood density has different degrees of correlation by Pierson. The results obtained (Table 3) show that in different plots, the wood density was statistically significantly correlated with the late wood width. It should be noted that the share of the late wood was 10-20% of the annual ring width. In a number of cases, there was a statistically significant relationship between the wood density and either the width of the early wood zone or the width of the annual layer. Thinning did not result in considerable changes in the xylem macrostructure parameters. Differences in the variation of the average wood density on the experimental plots are related not only to external influences, but also to intraspecific competitive relations between the trees. The highest average density of spruce wood was observed in the sections with the highest initial planting density. The highest annual layer and early wood width is observed on the sections with lower initial densities. Therefore, to study the effect of thinning, the xylem was then analyzed at the microstructural level.

Table 3

Relationship between the initial planting density and the Spruce density (kg m^{-3}) of late wood, early wood, and annual layer

Initial/final planting density [trees ha^{-1}]	Structural elements of the xylem		Mean	Std. dev.	R^2
1,000/948	Width [mm]	Late wood	0.363	0.142	0.594
		Early wood	3.982	0.980	0.045
		Annual layer	4.344	1.065	0.120
	Density [kg m^{-3}]		389.6	26.116	1.000
2,000/1,253	Width [mm]	Late wood	0.414	0.107	0.160
		Early wood	3.945	0.948	0.231
		Annual layer	4.359	1.055	0.224
	Density [kg m^{-3}]		383.9	12.535	1.000
2,000/1,065*	Width [mm]	Late wood	0.383	0.114	0.632
		Early wood	3.425	1.358	0.595
		Annual layer	3.808	1.447	0.609
	Density [kg m^{-3}]		391.1	8.297	1.000
4,000/1,535	Width [mm]	Late wood	0.337	0.079	-0.903
		Early wood	2.978	1.254	0.338
		Annual layer	3.315	1.199	0.294
	Density [kg m^{-3}]		392.6	9.719	1.000
4,000/1,050*	Width [mm]	Late wood	0.398	0.098	-0.269
		Early wood	3.245	0.709	-0.171
		Annual layer	3.643	0.788	-0.187
	Density [kg m^{-3}]		407.6	21.678	1.000

Note: * Thinning was carried out at the age of 25; coefficients in bold are statistically significant at *p*-values < 0.05

The study of the wood microstructure (Table 4) shows that the average quantitative data differ according to the planting density. Thinning caused a decrease in the average number of early wood cells with a simultaneous increase in the cell wall thickness. Thinning had no effect on the quantitative characteristics of the late wood cells; however, it led to an increase in the average cell wall thickness of the late xylem (3.31 μm) in the experiment with 4,000/1,050 trees ha^{-1}, which contributed to the formation of the densest wood in comparison with other variants.

Table 4

Anatomical characteristics of wood by stand density

Initial/final planting density [trees ha^{-1}]	Average number of cells in the annual layer		Average cell wall thickness [µm]	
	Late wood	Early wood	Late wood	Early wood
1,000/948	19	109	2.65	2.23
2,000/1,253	17	100	2.60	1.90
2,000/1,065*	19	65	2.34	2.09
4,000/1,535	20	66	2.85	2.40
4,000/1,050*	20	54	3.31	2.81

Note: * Thinning was carried out at the age of 25

The analysis of the data on the anatomical wood structure has shown the need to take into account the entire complex of the xylem elements that affect the wood density in the variants with different densities (Table 5). The factor analysis has revealed that the early wood width and the number of cells, as well as the width of the annual rings, made the strongest negative effect on the wood density in all the plots. The contribution of other structural elements of the xylem to the spruce wood density was not statistically significant.

Table 5

Contribution of xylem anatomical structure elements to spruce wood density in sub-plots with different stand densities

Anatomic elements of xylem		Initial/final planting density [trees ha^{-1}]				
		1,000/948	2,000/1,253	2,000/1,065*	4,000/1,535	4,000/1,050*
Average number of cells in the annual layer	Late wood	-0.132	0.309	-0.834	0.031	-0.775
	Early wood	-0.936	-0.929	-0.912	-0.975	-0.864
Average cell wall thickness [µm]	Late wood	-0.136	0.138	-0.103	0.231	-0.363
	Early wood	0.178	0.357	-0.176	-0.241	-0.488
Width [mm]	Late wood	-0.153	0.242	-0.869	0.026	-0.839
	Early wood	-0.980	-0.966	-0.916	-0.973	-0.913
Annual layer width [mm]		-0.989	-0.935	-0.950	-0.974	-0.948
Total variance		2.997	3.053	4.528	3.345	4.248
Share of the total variance		0.333	0.339	0.503	0.372	0.472

Note: * Thinning was carried out at the age of 25; coefficients in bold are statistically significant at *p*-values < 0.05

The growing stock and the wood density ultimately affected the yield of stem biomass, which is the main quantitative element of a forest plantation (Table 6). In the unthinned plots, the largest amount of stem wood was formed in the plot with the lowest initial and final density (1,000/948 trees ha^{-1}). Among the thinned stands, the largest amount of stem wood was recorded in the plot with 2,000/1,065 trees ha^{-1}.

Table 6

Statistical parameters of spruce stem biomass in the sub-plots with different stem densities

Initial/final planting density [trees ha^{-1}]	Stem biomass [thousand kg ha^{-1}]	Skewness	Kurtosis
1,000/948	158,581	0.328	-2.249
2,000/1,253	150,656	1.314	1.530
2,000/1,065*	182,964	0.496	-1.180
4,000/1,535	148,203	0.363	-1.637
4,000/1,050*	130,876	1.088	0.014

Note: * Thinning was carried out at the age of 25

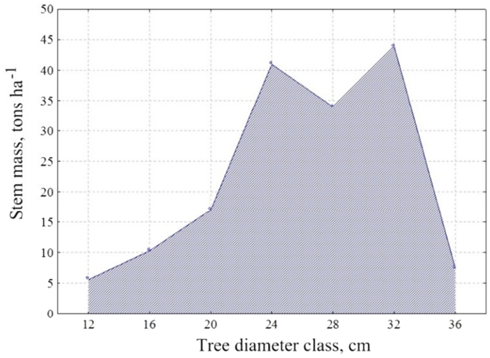
The ranking of the stem biomass provides biological meaning to the processes of spruce stand formation. In plots with different tree densities, it is possible to reliably record in which size categories of spruce trees the quantitative indicators of wood are more important. The positive skewness and negative kurtosis of the wood biomass distribution curve (Figure 4) indicate that the biomass is accumulated in the middle- and large-diameter classes. In the sub-plots with positive skewness and kurtosis (2,000/1,253 and 4,000/1,050), stem biomass is accumulated mainly in the larger-diameter classes.

4. Discussion

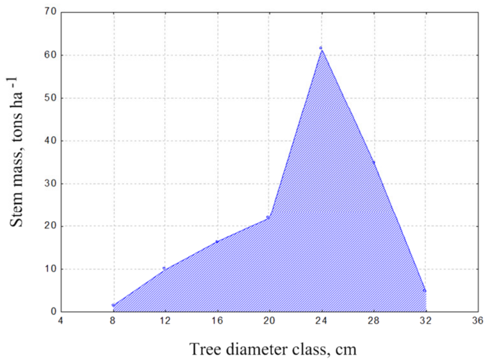
Globally, growth rate variations on forest plantations range from 7 to 30 m^3 ha^{-1} yr^{-1} [11]. In our experiment, the average annual growth rate of a spruce plantation was 10 m^3 ha^{-1} yr^{-1} at best. In Northern Iran, 50-year-old *Picea abies* plantations had growing stock of 290 m^3 ha^{-1}, while in our study the growing stock of the 43-year-old plantation was 320-470 m^3 ha^{-1} [36]. However, the values of other quantitative characteristics of the Iranian plantations were higher: the diameter was 37.3 cm against 17.2-22.8 cm in the plantations under study; and the height was 24.2 m against 18.7-20.8 m demonstrated by our study.

In Latvia, a forest plantation with the initial planting density of 3,300 trees ha^{-1} was created [18]. By the age of 50, the density had decreased naturally down to 400 trees ha^{-1}. The average stand diameter was 35 cm, the average height, 25 m, and the yield ranged from 194 to 422 m^3 ha^{-1}.

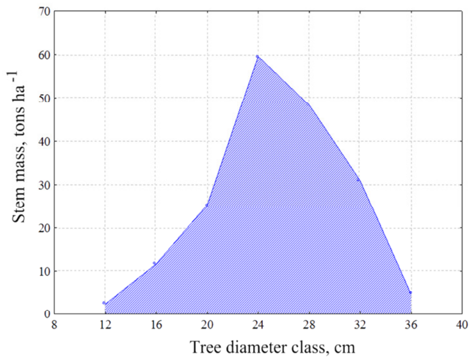
At the stage of tree stand differentiation, a high initial stand density results in low diameter, height and standing volumes, as well as reduced tree growth and development. As a result of natural thinning, the differences in stand density start to level out, and after 40 years they begin to disappear; however, the residual effects persist, particularly in unthinned tree stands. In our study, thinning optimized the stand density and all the inventory parameters of the stands.



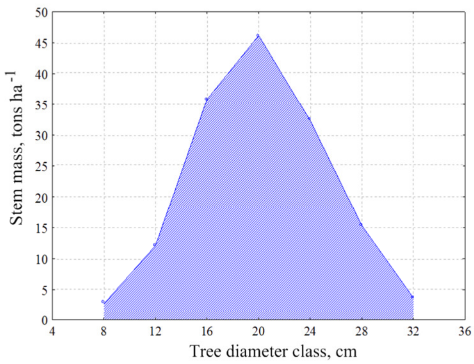
a) Initial / final density was 1,000/948 trees ha^{-1}



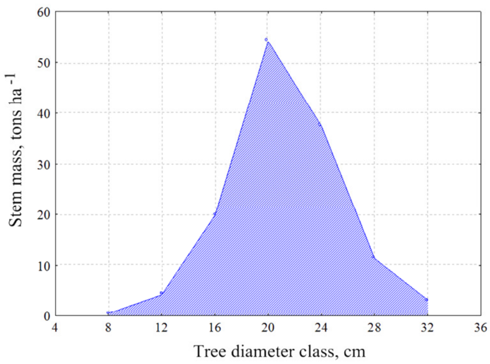
b) Initial / final density was 2,000/1,253 trees ha^{-1}



c) Initial / final density was 2,000/1,065* trees ha^{-1}



d) Initial / final density was 4,000/1,535 trees ha^{-1}



e) Initial / final density was 4,000/1,050* trees ha^{-1}

Fig. 4. *Distribution of wood biomass by tree diameter classes at experimental sites. Thinning at the age of 25 is marked with an asterisk (*)*

It should be noted that the wood densities on the experimental plots were similar and in some cases even higher than the average reference data for the study region [8]. Summarizing the results of our study, it should be emphasized that an optimal choice of stand density can ultimately maximize the stem biomass. The results obtained show that the optimal density for the accumulation of the largest amount of stem biomass is in the range of 1,000-2,000 trees ha^{-1}. On the plots where thinning was made in a timely manner, tree distribution by diameter class was close to normal. The largest amount of biomass was accumulated in medium-size and large-diameter trunks.

In general, the results obtained show that the density of the stand significantly affects the nature of the relationship between the density of wood and its macrostructure.

Understanding the processes of xylem formation makes it possible to predict the composition of wood raw materials and their suitability for the needs of an end user. In the thinned plots, the average values of the early wood cell wall thickness were higher than in the plots without thinning. The results of the study have demonstrated that in spruce plantations, the share of early xylem in the total wood increment was 80-90%. Consequently, most of the trunk wood consisted of cellulose, because this structural element is formed by conductive fibers of early wood [14], [37]. In general, the results obtained show that a significant volume and mass of stem wood suitable for cellulose production and other industrial purposes are accumulated in the experimental plots. According to the inventory characteristics of the 43 year-old stands under study, they were comparable to mature spruce stands (85-100 year-old); wood density characteristics were similar to the average for the study region (380-400 kg m^{-3}) [8], [27]. Future studies should address the component composition of spruce wood, estimate the cellulose yield, and assess wood fiber quality by conducting test chemical pulping.

5. Conclusions

The research has shown that by the age of 43, the best linear, volumetric and mass indicators of wood were observed in the plots with the initial density of 2,000 trees ha^{-1} with thinning carried out at the age of 25 to the stem density of 1,065 trees ha^{-1}.

The densest wood was formed in the spruce stand with the initial density of 4,000 trees ha^{-1} and thinning at the age of 25 to the density of 1,050 trees ha^{-1}.

By the age of 43, the major contribution to the density of spruce wood was made by the early wood xylem elements.

In accordance with the above, the quality of spruce wood produced on short-rotation forest plantations depends on the initial planting density and its timely regulation.

In the boreal zone of North-West Russia, short-rotation spruce plantations for pulpwood production can ensure resources of raw materials within significantly shorter periods of time. In terms of the qualitative and quantitative characteristics, the spruce wood of the forest stands studied was comparable to that of mature tree stands.

Author Contributions

The manuscript was written through the contributions of all authors. The authors have declared that no competing interests exist. All authors have given their approval for the final version of the manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Blouin, D., Beaulieu, J., Daoust, G. et al., 1994. Wood quality of Norway spruce grown in plantations in Quebec. In: Journal of Wood and Fiber Science, vol. 26(3), pp. 342-353.
2. Cao, T., Hyytiäinen, K., Tahvonen, O. et al., 2006. Effects of initial stand states on optimal thinning and rotation of *Picea abies* stands. In: Scandinavian Journal of Forest Research, vol. 21(5), pp. 388-398. DOI: 10.1080/02827580600951915.
3. Carle, J., Duval, A., Ashfordc, S., 2020. The future of planted forests. In: International Forestry Review, vol. 22(1), pp. 65-80. DOI: 10.1505/146554820829523970.
4. Carlquist, S., 1988. Comparative wood anatomy. Springer Verlag, Berlin, Germany.
5. Caudullo, G., Tinner, W., de Rigo, D., 2016. *Picea abies* in Europe: distribution, habitat, usage and threats. In: European Atlas of Forest Tree Species, Publ. Off EU, Luxembourg, pp. 114-116.
6. Coordes, R., 2012. Influence of planting density and rotation age on the profitability of timber production for Norway spruce in Central Europe. In: European Journal of Forest Research, vol. 132, pp. 297-311. DOI: 10.1007/s10342-012-0675-9.
7. Corpuz, O.S., Corpuz, A.S., 2012. Forestry Statistics and Research Methods, Lambert Academic Publishing.
8. Danilov, D., 2018. Qualitative and quantitative indicators of coniferous in boreal zone after care for a forest. In: Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives. World Sustainability Series, Leal Filho, W., Pociovălișteanu, D., Borges de Brito, P. et al. (Eds). Springer, Cham, Switzerland, pp: 555-565. DOI: 10.1007/978-3-319-73028-8_28.
9. Danilov, D., Janusz, S., 2019. Macrostructure and density of pine and spruce wood on fallow lands on north-west of Russia. In: Proceedings of 25th Annual International Scientific Conference ”Research for Rural Development 2019”, Jelgava, Latvia, May 15-17, 2019, pp. 31-37. DOI: 10.22616/rrd.25.2019.005.
10. Fabijanska, A., Danek, M., Barniak, J. et al., 2017. A comparative study of image enhancement methods in tree-ring analysis. In: Computers and Electronics in Agriculture, vol. 140, pp. 279-289. DOI: 10.1007/978-3-319-47274-4_8.
11. Freer-Smith, P., Muys, B., Bozzano, M. et al., 2019. Plantation forests in Europe: challenges and opportunities. In: From Science to Policy, vol. 9, Hetemäki, L. (Ed.), European Forest Institute, 52 p. DOI: 10.36333/fs09.
12. Gardener, M., 2017. Statistics for Ecologists Using R and Excel. Pelagic Publishing, United Kingdom.
13. Gizachew, B., Brunner, A., 2011. Density-growth relationships in

thinned and unthinned Norway spruce and Scots pine stands in Norway. In: Scandinavian Journal of Forest Research, vol. 26(6), pp. 543-554. DOI: 10.1080/02827581.2011.611477.

14. Ikonen, V.-P., Peltola, H., Wilhelmsson, L. et al., 2008. Modelling the distribution of wood properties along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) as affected by silvicultural management. In: Forest Ecology and Management, vol. 256(6), pp. 1356-1371. DOI: 10.1016/j.foreco.2008.06.039.
15. Jyske, T., Kaakinen, S., Nilsson, U. et al., 2009. Effects of timing and intensity of thinning on wood structure and chemistry in Norway spruce. In: Holzforschung, vol. 64(1), pp. 81-91. DOI: 10.1515/hf.2010.013.
16. Jyske, T., Mäkinen, H., Saranpaa, P., 2006. Wood density of Norway spruce: Responses to timing and intensity of first commercial thinning and fertilization. In: Forest Ecology and Management, vol. 237(1), pp. 513-521. DOI: 10.1016/j.foreco.2006.09.083.
17. Jyske, T., Mäkinen, H., Saranpaa, P., 2011. Wood density in Norway spruce: Changes with thinning intensity and tree age. In: Canadian Journal of Forest Research, vol. 35(7), pp. 1767-1778. DOI: 10.1139/x05-118.
18. Katrevičs, J., Džeriņa, B., Neimane, U. et al., 2018. Production and profitability of low density Norway spruce (*Picea abies* (L.) Karst.) plantation at 50 years of age: case study from eastern Latvia. In: Agronnomy Research, vol. 16(1), pp. 113-121. DOI: 10.15159/AR.18.014.
19. Mäkinen, H., Isomäk,i A., 2004. Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. In: Forest Ecolology and Management, vol. 201(2-3), pp. 295-309. DOI: 10.1016/j.foreco.2004.07.017.
20. Mäkinen, H., Isomäki, A., Hongisto, T., 2006. Effect of half-systematic and systematic thinning on the increment of Scots pine and Norway spruce in Finland. In: Forestry, vol. 79(1), pp. 103-121. DOI: 10.1093/forestry/cpi061.
21. Mäkinen, H., Jaakkola, T., Piispanen, R. et al., 2007. Predicting wood and tracheid properties of Norway spruce. In: Forest Ecology and Management, vol. 241(1-3), pp. 175-188. DOI: 10.1016/j.foreco.2007.01.017.
22. Pape, R., 1999. Effects of thinning regime on the wood properties and stem quality of *Picea abies*. In: Scandinavian Journal of Forest Research, vol. 14(1), pp. 38-50. DOI: 10.1080/02827589908540807.
23. Pekkoev, A.N., 2016. Wood quality of spruce crops under intensive growing [In Russian with English summary]. In: Russian Forestry Journal, vol. 1(349), pp. 89-99.
24. Peltola, H., Kilpeläinen, A., Sauvala, K. et al., 2007. Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. In: Silva Fennica, vol. 41(3), pp. 489-505. DOI: 10.14214/sf.285.
25. Petri, P., 2019. Spruce forest stands in a stationary state. In: Journal of Forest Research, vol. 30(5), pp. 1-12. DOI: 10.1007/s11676-019-00971-4.

26. Piispanen, P., Heinonen, J., Valkonen, S. et al., 2014. Wood density of Norway spruce in uneven-aged stands. In: Canadian Journal of Forest Research, vol. 44(2), pp. 136-144. DOI: 10.1139/cjfr-2013-0201.
27. Poluboyarinov, O.I., 1976. Plotnost' drevesiny (Density of wood) [in Russian], Izd. Lesnaya promyshlennost', Moscow, Russian Federation.
28. Pretzsch, H., 2009. Forest dynamics, growth and yield: From measurement to model. Springer-Verlag Berlin Heidelberg, Germany.
29. Pretzsch, H., 2020. Density and growth of forest stands revisited. Effect of the temporal scale of observation, site quality, and thinning. In: Forest Ecology and Management, vol. 460, pp. 1-14. DOI: 10.1016/j.foreco.2020.117879.
30. Sebastian, H., Herbstritt, S., Kohnle, U., 2008. The European stem number experiment in Norway spruce (*Picea abies* [L.] Karst.): Effect of crop tree thinning on growth, timber assortment and economic results. In: Allgemeine Forst und Jagdzeitung, vol. 179(10), pp. 192-201.
31. Sedjo, R., 1999. The potential of high-yield plantation forestry for meeting timber needs. In: New Forests, vol. 17(1), pp. 339-359. DOI: 10.1023/A:1006563420947.
32. Seeling, U., 2001. Transformation of plantation forests — expected wood properties of Norway spruce (*Picea abies* (L.) Karst.) within the period of stand stabilisation. In: Forest Ecology and Management, vol. 151(1), pp. 195-210. DOI: 10.1016/S0378-1127(00)00708-8.
33. Shutov, I.V., Markova, I.A., Omelyanenko, A.Ya. et al., 2007. Plantacionnoe lesovodstvo (Industrial tree plantations as the objects of forestry) [In Russian], St. Petersburg State Polytechnical University, Russian Federation.
34. Spiecker, H., 2000. Growth of Norway spruce (*Picea abies* [L.] Karst.) under changing environmental conditions in Europe. In: Spruce Monocultures in Central Europe – Problems and Prospects, Klimo. E., Hager, H., Kulhavý, J. (Eds.). EFI Proceedings, Finland, pp. 11-26.
35. Strengbom, J., Dahlberg, A., Marek Larsson, A.M. et al., 2011. Introducing intensively managed spruce plantations in Swedish forest landscapes will impair biodiversity decline. In: Forests, vol. 2(4), pp. 610-630. DOI: 10.3390/f2030610.
36. Tavankar, F., Bodaghi, A.I., 2013. Evaluation of survival and growth of coniferous species plantation in Hyrcanian forests, North of Iran. In: International Journal of Agronomy and Plant Production, vol. 4(3), pp. 530-536.
37. Vaganov, E.A., Hughes, M.K., Shashkin, A.V., 2006. Growth dynamics of conifer tree rings: images of past and future environments. Ecological Studies. Springer, Berlin-Heidelberg, Germany.
38. Van Der Maaten-Theunissen, M., Boden, S., Van Der Maaten, E., 2012. Wood density variations of Norway spruce (*Picea abies* (L.) Karst.) under contrasting climate conditions in southwestern Germany. In: Annals of Forest Research, vol. 56(1), pp. 91-103. DOI: 10.15287/afr.2013.46.

39. Wilhelmsson, L., Arlinger, J., Spångberg, K. et al., 2002. Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. In: Scandinavian Journal of Forest Research, vol. 17(4), pp. 330-350. DOI: 10.1080/02827580260138080.
40. Zaytsev, D.A., Danilov, D.A., Navalihin, S.V., 2019. Wood density of pine and spruce stands according to trees diameter distribution after thinning. In: IOP Conference Series: Earth and Environmental Science, vol. 226(1), pp. 1-7. DOI: 10.1088/1755-1315/226/1/012065.
41. Zhang, S., Belien, E., Ren, H. et al., 2020. Wood anatomy of boreal species in a warming world: a review. In: iForest, vol. 13, pp. 130-138. DOI: 10.3832/ifor3230-013.