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Growth and structure of pre-mature mixed stands of Scots pine created by direct seeding in the boreal zone

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Abstract: The purpose of the research is to analyse the successful creation of an artificial pine forest by seeding and develop recommendations for the guaranteed reproduction of pine stands in Northern European Russia. In recent decades, there has been a steady decline in the share of pine stands and their replacement with low-value and low-yielding tree species. We surveyed 12 permanent sample plots that were laid out in various variants of forest crops. The taxation parameters were obtained by a standard analysis of the experimental data. The evaluation parameters of the stands vary within the following limits: the average diameter of the pine trees varied from 21.9 to 30.9 cm; the total basal area of the pine varied from 19.1 to 38.8 $m^2 \cdot ha^{-1}$; the average height of the pine varied from 20.1 to 26.8 m; the number of growing trees varied from 754 to 1 952 ha^{-1}; the pines varied from 382 to 762 ha^{-1}; the growing stocks of stands varied from 416 to 608 $m^3 \cdot ha^{-1}$. The distribution of pine trees by thickness steps showed that all the studied samples were close to the normal distribution curve. The results of the correlation and multidimensional analyses showed that the creation method of the forest crops had a significant impact on the value of the taxation parameters. It was found that the best options for growing pure pine stands that can be recommended for practical production are plots with a large share of soil cultivation and the size of the seedbed.

Keywords: Scots pine; diameter distribution; reforestation; stands evaluation parameters

The unsatisfactory reforestation of cutting areas with valuable tree species in intensive forest regions is one of the main problems of forestry not only in Russia, but also in other countries. Therefore, valuable coniferous forests are replaced with less valuable soft-leaved ones.

The Scots pine (*Pinus sylvestris* L.) is one of the most common tree species in the forests of Northern Europe (Krakau et al. 2013) and Northern European Russia (Smirnova et al. 2017). Pines are of great economic importance due to their productivity and wide range of uses. However, the change from pines to soft-leaved species and spruce in the boreal zone has become very widespread, which has led to a decrease in pine forests. To prevent the further replacement of pines with other tree spe-

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cies and the deterioration of the forest structure, the reforestation system must be improved.

The afterlogging period is an important stage in reforestation. A successful reforestation can be achieved by natural or artificial means (planting and seeding). In Northern European Russia, the main reforestation activity is to promote natural reforestation (retaining seed trees in groups, the preservation of the undergrowth and young growth, soil surface mineralisation, etc.). However, natural reforestation does not ensure the renewal of pine trees (in the case of a prior renewal absence), as it is less predictable compared to sowing or planting. In Scandinavia, a part of the Scots pine stands can also be restored naturally or by seeding (Ackzell 1993; Miina, Saksa 2008). However, planting seedlings is almost always a key component of forest-related activities (Nilsson et al. 2010; Oliet, Jacobs 2012; Stanturf et al. 2014; Sikström et al. 2020). Although seeding and planting have advantages and limitations, the results from pine seed seeding in Sweden and Finland show that the recovery is successful using this method (Ackzell 1993; Wennström 2001; Wennström et al. 2002).

The problem with reforestation activities is that they are often expensive and the cost of restoration usually increases with an increased disturbance to the forest ecosystems. Therefore, the success of reforestation after natural and anthropogenic impacts is an important task.

Studies show that the main reasons why seeding is so rare is the risk of unsuccessful reforestation due to the greater influence of biotic and abiotic stress factors on the seed germination than on planting seedlings (Mäkitalo 1999; De Chantal et al. 2003; Willoughby et al. 2004). At the same time, sowing seeds has its advantages. First, the labour cost of reforestation is lower than the cost of growing and planting seedlings (Wennström et al. 2007; Birch et al. 2010; Palmerlee, Young 2010). Second, seeding imitates the natural regeneration. Third, forest stands that are formed this way, growing at a high stand density, are characterised by a high wood quality (Aleksandrowicz-Trzcińska et al. 2017). Another advantage is the reduced risk of root and stem deformations caused by the containers growing and/or transplanting (Wennström 2001). To create optimal conditions for seed germination and self-seeding growth in continuous clear cuttings, a mechanical soil preparation is recommended (Löf et al. 2012), so that competition with other tree species is limited in terms of light, water and nutrients (Nilsson, Örlander 1999). A mechanical soil treatment changes its physical properties (available moisture content, aeration, temperature and soil compaction density) and chemical properties (organic matter content, nutrient availability and acidity) (Archibold et al. 2000). The influence of a mechanical soil treatment on the seed germination, as well as on the growth and self-seeding survival, varies depending on the climatic factors, the types of forest conditions on the sites and the tree species (Munson, Timmer 1995; MacKenzie et al. 2005; Wallertz, Malmqvist 2013).

Despite extensive research conducted in various countries (Löf et al. 2018), there is still a lack of knowledge, so general rules for successful direct seeding cannot be deduced as the autoecology of the tree species and abiotic conditions vary greatly. Some authors emphasise that seeding, as a method of reforestation, should be promoted as this is the most environmentally acceptable method and with proper soil preparation, and seeding is not inferior to planting forest crops (Aleksandrowicz-Trzcińska et al. 2017).

Up-to-date information about the historical experience of creating forest crops and the current state of such crops is an indicator of an information vacuum. The experience of Russian forestry has always been trial and error with the most daring experiments. Long-term scientifically-based observations of stationary objects allow one to get a more complete picture and make adjustments to the existing ideas about the structure, growth and development of the stands. In this regard, the historical, scientific and practical interest in permanent objects, for example, the experimental pine crops named after S.V. Alekseev from 1927–1930, deserves the most careful study. Pine crops are of particular value being the oldest and most northern experimental crops in Northern European Russia. The purpose of the research is to analyse the successful creation of pine forest crops by seeding and develop recommendations (the selection of the methods) for the guaranteed reproduction of pine stands in the boreal zone of Northern European Russia.

The research tasks: (*i*) analyse the taxation parameters (mean diameter and height, number of trees per hectare, basal area, standing volume, tree species composition) in the various ways of creat-

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ing forest crops, (*ii*) study the structure of the pine stands by comparing the distribution series of pine trees by normal and natural thickness steps, and (*iii*) establish the influence of the soil cultivation and forest crop methods on the taxation parameters of the pine stands.

MATERIAL AND METHODS

Site location and environmental conditions. The research was carried out in Northern European Russia in the Arkhangelsk region (Figure 1). The research area, according to the forest zoning, belongs to the taiga zone and the northern taiga subzone (Kurnaev 1973).

The climate of the district is moderate continental. The climate is determined by the geographic location of the area, the influence of the cold waters of the Arctic seas and its considerable length from north to south. The frequent change of air masses associated with the passage of cyclones from the Atlantic Ocean is a feature of the climate in this area.

The average annual air temperature is 0.4 °C. The average temperature of the warmest month (July) is 16.1 °C and the coldest (January) is minus 14.1 °C. The annual precipitation ranges from 380–690 mm, which contributes to the excessive soil moisture in the area. The precipitation in the winter mainly falls in a solid form. A stable snow cover is established from October to April. The average height of the snow cover in the study area in winter is 75–85 cm. The average relative humidity varies from 67% to 87% per year. The relative proximity of the seas and the presence of numerous rivers, lakes and swamps contribute to this high humidity. The average annual wind speeds vary from 8 to 3 $m \cdot s^{-1}$. The geographical distribution of various wind directions and speeds is determined by the seasonal regime of baric centres. The territory of the northern taiga subzone is a relatively flat plain sloping to the White Sea. The main watershed plateaus and individual elevations rarely exceed 200–300 m above sea level. The region's soils and soil resources are very diverse and heterogeneous. The main reasons are the different ratios of the climate, topography, soil-forming rocks and vegetation, etc. The podzol formation process dominates and is most pronounced in the central part of the district.

In general, the climate conditions are favourable for the growth of tree species such as the pine, spruce, larch, birch, aspen and others. The share of coniferous wood species in the northern taiga subzone is 82.4% and the share of deciduous wood species is 17.6%.

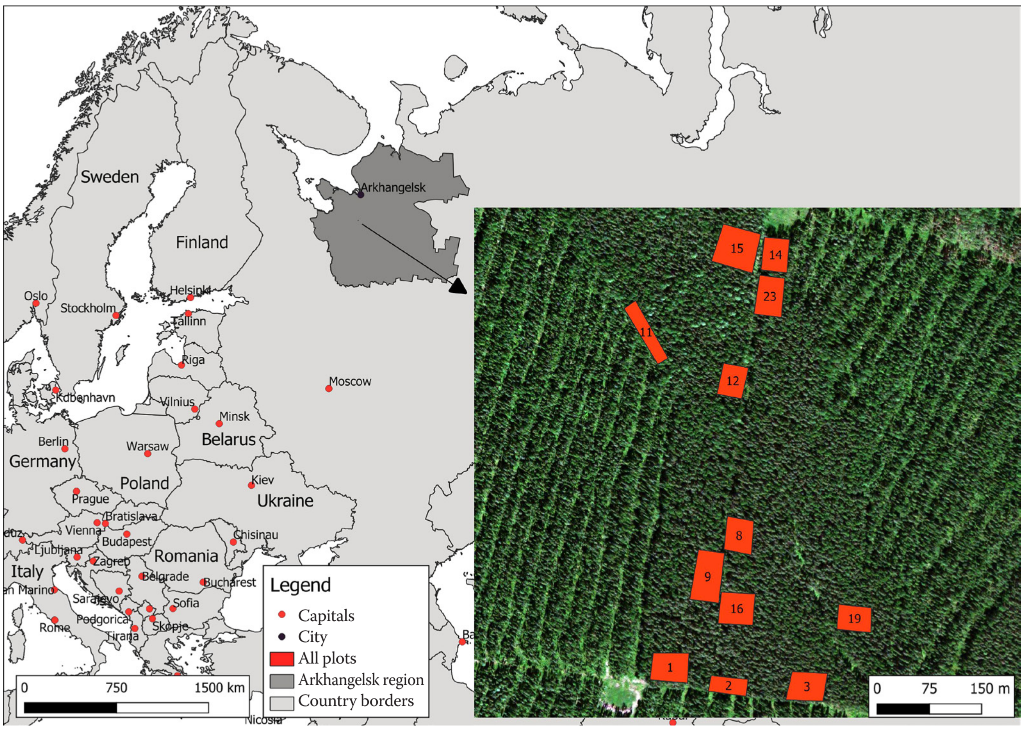

Figure 1. Location of the study area and permanent sample plots

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Brief history of the creation and characteristics of forest stands. This research was carried out at the 'Experimental forest crops of pine trees named after S.V. Alekseev 1927–1930' in the Obozersky forest in the Arkhangelsk region. Alekseev's crops were created by sowing from 1927–1930 in an area of 32 ha.

The purpose of the crop creation was because of the lack of experience in creating stands by artificial means. The main goal of the experiments was to find rational ways to produce pine forest crops. To create crops, Alekseev chose a clear cutting in 1916–1917, which was carried out in the winter period. The geographical position of the territory was determined at 63.5° north latitude and 40.5° east longitude, along the border of the middle and northern subzones of the taiga (Ipatov 2003). Before cutting, the site had a mixed stand with the following taxation characteristics: species composition of 7P3S (this means that 70% of the standing volume is pine, 30% – spruce), a relative density of 0.6, a growing stock of 250 $m^3 \cdot ha^{-1}$, an age of the main breed of 200–220 years, an average height of 23 m and an average diameter of 33 cm. On the site, larch and birch were rarely found and the undergrowth contained spruce at a height of 0.5 to 7 m. The living ground cover was represented by blueberries with cranberries, green mosses and cuckoo flax, forest type *Pineta myrtillosum*. The site was subject to repeated fires in 1919 and 1925 that led to the formation of a wasteland with a total area of about 200 hectares with pines being very rare. Due to the logging and fires on the site, natural seeding was unfavourable; even in the vicinity of the forest walls, it was unsatisfactory (Alekseev 1932).

The terrain was represented by a slightly elevated plateau with an almost flat surface and it was this feature that gave the crops an experimental character (Prokopiev 1977). The soil was albic podzols (IUSS Working Group WRB 2015). The method of crop creation was sowing, as it is closer to nature and gives higher-quality stands. The cultivated species was pine. The main goal of the experiments was to select the most rational way of creating experimental crops for production, so Alekseev tested various options (Borisov 1964).

To create a plantation, 5–20 seeds were sown in each variants' sites. The seed consumption per 1 ha was 0.4–0.5 kg. During an inspection in the autumn, it was found that there were several seedlings in the site, about 3–4, a maximum of 10, but many sites were empty. This was because of a dry summer and the poor seed germination (22.5%). In the following years, these same seeds were more thickly sown - several hundred seeds were thrown into a metre-long area. As a result, the sites were overgrown with seedlings. Alekseev concluded that the main thing was not the quantity of the seeds, but their quality (Ipatov 2003).

The preparation of the soil for sowing was partially carried out in places by platforms or strips, at different sizes and distances between them in the processed sample areas (Table 1, Figure 2).

After planting forest crops in 1930, a partial inventory was carried out, which showed that all the methods were similar, only the variant with the fire preparation of the soil differed. However, Alekseev (1932) noted that the conclusion was preliminary, as this method required further study and verification.

In 1936, Alekseev examined the individual variants. In his conclusions, he noted that most of the healthy crops were located on the edges of the sites and furrows where the forest floor was raked. In all the variants, the removal of the turf and organogenic horizon negatively affected the crop growth.

Alekseev conducted a detailed survey of the crops from 1951–1952. When analysing the growth, he noted that by the age of 22–25 years, the greatest changes occurred inside the treated sites, espe-

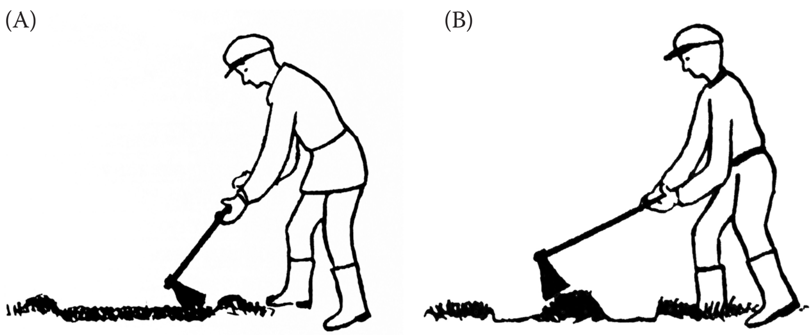

Figure 2. Plot preparation schemes: soil treatment with small-scale loosening sites (A), create a mound in the site or band (B) (Ipatov 2003)

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Table 1. Methods of soil preparation for creating the plantings (Alekseev 1932)

Plot No.	No. of treatments	Creation year	Area (ha)	The size of the sites (strip width, m)	The distance between the centres of the sites (strips, m)	No. of sites (strips) per ha	The treated area (%)	Site preparation
11	2	1927	5.26	0.5 × 0.5	from 2 to 2.5	2 400	5.9	Soil treatment with sites. Shallow loosening (6–7 cm) of the soil surface with preliminary stripping and removal of blackened parts.
12	2	1927	5.26	0.5 × 0.5	from 2 to 2.5	2 400	5.9	
15	2	1927	5.26	0.5 × 0.5	from 2 to 2.5	2 400	5.9	
8	3	1929	1.50	0.5 × 0.5	2.0 × 2.0	2 500	6.25	
2	4	1928	1.0	1 × 1	2.5 × 2.5	1 600	16	
9	4	1929	0.82	1 × 1	2.5 × 2.5	1 600	16	
16	6	1929	1.50	4 × 4	10 × 10	100	16	
23	6	1929	1.50	4 × 4	10 × 10	100	16	
3	8	1929–1930	0.5 + 0.64	1 × 1	2.5 × 2.5	1 600	16	Creating a mound in the site. In the middle of the site, a mound was raked at the expense of the podzolised horizon E and partly B from the edges of the site.
19	9	1929–1930	0.50 + 0.67	1 × 1	2.5 × 2.5	1 600	16	
1	12	1930	0.87	0.5	through 3.0	30	15	Soil treatment with strips. Raking the soil from the edges to the middle left untreated
14	13	1928	5.2	–	–	–	–	Fire soil preparation. Burning piles of firewood collected during cleaning. The location of piles is not uniform 500–700 per ha

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cially in the overgrown places. For example, in the variants with a size of 1 × 1 m, the average number of trees on the site was between 10 and 13. In variant 6 with a 4 × 4 m treated site, the average number of trees was 54. The conservation of plants in the dense sites was twice as high as in the sparse ones. Alekseev explained this difference as a characteristic phenomenon for the north - squeezing the seedlings by frost. The growing stock of the artificial pine ranged from 25 (option 8) to 66 $m^3 \cdot ha^{-1}$ (option 4). Taking the natural self-seeding of pine, birch, aspen and spruce into account, the largest stock was recorded in the 4th variant at about 110 $m^3 \cdot ha^{-1}$ (Ipatov 2003).

Borisov (1964) organised a survey of forest crops where the age of the plants was 32–35 years. He noted that the planting in different variants of creating forest crops differs in the main taxational parameters. For example, in option 6, the number of trees on the site decreased to 12. Based on this study, it was concluded that not all the crops created by groups can provide good results (Ipatov 2003).

In 1968, some variants of the forest crops were examined by Prokopiev. By the age of 39–40 years, the participation rate of the pine among the variants ranged from 70 to 98% in the number of trees. At the same time, two-thirds of the pine stock was represented by artificial plants and one-third by trees of natural origin. The relative completeness was 1.1–1.3, which is explained by the placement of trees in biogroups and the non-compliance with the completeness standards for forest crops. The total stock of the artificial stands and natural regeneration ranged from 185 to 231 $m^3 \cdot ha^{-1}$ (Prokopiev 1977; Ipatov 2003).

Since 1972, the Department of Silviculture and Forest Management laid out trial plots where field research was conducted every 5 years until 2000. By 2000, self-thinning was completed at the sites. The average density was 1946 trees per ha, including 569 pine trees per ha. As noted earlier, a large loss of seedlings occurred at the beginning of the life of the plantation due to the high density of the plants. The self-thinning over the years occurred unevenly and abruptly. Furthermore, the decrease in the density was facilitated by the differentiation of the trees by size and death. Pine (65%), birch (22%), aspen (8%) and spruce (5%) dominate the sites, the larch is rare. The average height in the different variants ranged from 19.8 to 24.9 m. By the year 2000, the crops were not in a complete alignment in the average heights. The influence of the creation method on the stands average diameter was noticeable by 2000. The number of trees was concentrated in thickness steps from 20 to 24 cm. In all the variants, the relative completeness exceeded 1.0 and the closeness of the canopy was 0.7–0.9. The total stand stocks reached high values for the research area, from 267 to 439 $m^3 \cdot ha^{-1}$, with an average of 357 $m^3 \cdot ha^{-1}$ (Ipatov 2003).

Data collection and standard analysis. For the preparatory stage of the fieldwork, we studied the previous materials used in the field research. The collection of the field data was carried out on the permanent sample plots from 2018–2019. We examined 12 permanent sample plots, the size of which varied from 0.13 to 0.28 ha, laid out in forest crops created by sowing with different soil preparation options and different densities.

In the test plots, the trees at a height of 1.3 m were listed. The calculation was carried out by the tree species and the diameters with a gradation of 0.1 cm. All the trees that reached a diameter of 6 cm were classified as a tree stand and those that did not reach the height were classified as the undergrowth. To determine the average height of the main tree layer and the other species, the heights of 15–20 trees were measured using an ultrasonic altimeter, a rangefinder and a Haglof Vertex IV/60 (accuracy ± 0.1 m). In the tree species with proportions less than three units, we measured three heights of the three central thickness grades. Based on the collected field data, the main taxational parameters (mean diameter and height, number of trees per hectare, basal area, standing volume, tree species composition) of the plantation were calculated following a standard analysis (Pretzsch 2009).

The mean diameter was determined via the basal area (*ba*) of all the trees using the following Equation (1):

$$ba_{1.3} = \frac{\pi}{4} d^2 \tag{1}$$

where:

π – constant;

d – average diameter of each diameter class (cm).

Dividing the sum of the cross-sectional areas of all the trees by the total number of trees, we get the basal area that a tree of average thickness has by Equation (2):

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$$ba_m = \frac{ba_1 \times n_1 + ba_2 \times n_2 + ... + ba_k \times n}{n_1 + n_2 + ... + n_k} = \frac{\sum ba \times n}{\sum n} \quad (2)$$

where:

ba_m – basal area of the mean diameter (cm^2);

$ba_1, ba_2, ..., ba_n$ – basal area tree of each diameter class (cm^2);

$n_1, n_2, ..., n_k$ – tree number in the diameter class.

The average cross-sectional area of the tree was used to determine the average diameter (d_m) Equation (3):

$$d_m = \sqrt{\frac{4 \times ba_m}{\pi}} \quad (3)$$

The mean basal area per hectare was determined by dividing the sum of the cross-sectional areas by the area of the test plot.

The mean height for the main breed was found graphically, taking a nonlinear statistical dependence into account. For each sample plot, we constructed the values of the diameter and height using a Cartesian coordinate system, where we obtained a point cloud that was aligned using a logarithmic equation. Putting the average diameter value into the equation, we got the average height. For each thickness step (each diameter class), where the measured trees fell, the height values were removed from the regression curve.

The mean age at the time of the study was calculated based on the number of years since the crops were planted. The site index (site class) was set by the ratio of the average height of the prevailing breed and the average age. The standing volume for the individual tree species was calculated using empirical formulas based on the relationship between the average height and the thickness steps. The species composition of the stands was established by the stock. The forest site type was determined by the prevailing types of ground cover in the geobotanical description.

Comparison of distribution series by diameter. To compare the distribution series by the sample plots, we used the method of distributing the number of trees by the natural thickness steps (Anuchin 1982). The value of the natural thickness step is expressed in tenths of the average diameter, taken as a unit. The average diameter of each sample plot was used as the basis for the distribution by the natural thickness steps. This method allowed us to compare the distribution curves established in the stands with the different average diameters, to determine the degree of variation in the number of trees in the same thickness steps (0.1, 0.2, etc.) and to note their commonality and significant differences.

The Laplace-Gaussian function was used to construct an equalised distribution curve of trees by the diameter. The theoretical normal distribution series is expressed by the following Equation (4):

$$n = \frac{N}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \quad (4)$$

where:

n – number in the diameter class;

N – total number of trees of all thickness levels;

σ – mean deviation;

e – base of the natural logarithms;

x – deviation of the average diameter from the stage diameter.

Statistical analysis. The statistical analyses were performed at a 5% probability level. The following main statistical indicators were calculated: the average value (M), standard deviation (δ), basic error of the average value (m), confidence of the average value (t), coefficient of variability (C), skewness and kurtosis.

The obtained diameter distribution curves were checked for the normality of the distribution (Kolmogorov-Smirnov criterion). To determine the degree of difference between the theoretical and actual size of the distribution, Pearson's criterion was calculated (χ^2).

The correlation and multivariate analyses were performed to establish the relationship between the creation methods of the artificial stands.

The data processing was performed using specialised statistical programs, Minitab (Version 17) and STATISTICA (Version 12).

RESULTS

Stand characteristics and standing volume (growing stock)

The analysis of the taxational parameters of the studied stands indicates that highly productive stands have formed on the plots (Table 2).

The average diameter of the pine trees varied between 21.9 and 30.9 cm. The smallest average diameter was marked on test plot 2 and the largest on test plot 9. The basal area of all the growing trees varied from 40.3 to 54.5 $m^2 \cdot ha^{-1}$. The smallest ab-

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solute completeness was marked on test plot 16. A basal area greater than 50 $m^2 \cdot ha^{-1}$ was determined on test plots 1, 8, 9, 12 and 23. The basal area of the growing pine trees varied from 19.1 to 38.8 $m^2 \cdot ha^{-1}$. The smallest absolute completeness was marked on sample plot 11. A basal area of about 38 $m^2 \cdot ha^{-1}$ was determined on sample plots 1, 8 and 15.

The average height of the pine trees varied from 20.1 to 26.8 m. The lowest average height was marked on test plot 2. The highest average height was observed in test plots 1 and 14.

The site class was an indicator of the fairly high productivity of the experimental forest crops, the value of which varied from I to III. Site class I was marked on trial plots 1 and 14. Site class III was marked on only two trial plots. All the other trial plots were characterised by site class II. The high planting productivity was due to the optimal combination of the tree species and timely reduction of the density as a result of the self-thinning.

The type of forest on all the trial plots was *Pineta myrtillosum*. In the blueberry forest, the dominant groundcover was *Vaccinium myrtillus* L. (75% projective cover, 100% occurrence). There was quite a lot of the genus *Sphagnum* and *Polytrichum commune* Hedw. (the projection coverage was 30% and 40%, respectively) as well as *Vaccinium Vitis-idaea* L., *Maianthemum bifolium* (L.) F. W. Schmidt (projective coverage of 15% and 10%, respectively) and other singular species.

In all the studied variants of the forest crops, by the age of 90 years, fairly dense tree stands were formed. Due to in part to the natural regeneration of the spruce, birch and aspen, the total number of growing trees varied from 754 to 1 952 per ha. The largest number of trees was registered on trial plot 2 and the smallest number of trees was registered on trial plot 15. The number of growing pine trees varied from 382 to 762 per ha. The largest number of pine trees was registered on trial plot 2 and the smallest number of trees was registered on trial plot 11.

The growing stock of all the trees varied from 416 to 608 $m^3 \cdot ha^{-1}$. A stock of more than 550 $m^3 \cdot ha^{-1}$ was marked on trial plots 1, 8, 9, 11, 12, 14, 15 and 23. The pine growing stock varied from 214 to 449 $m^3 \cdot ha^{-1}$. A stock of more than 400 $m^3 \cdot ha^{-1}$ was marked on test plots 1, 8 and 15. The species composition of the stands consisted mainly of pine and, to a lesser extent, spruce, birch and aspen. The share of the pine in the stock varied from 38 to 89%. The smallest share of the pine stock was observed in trial plots 11 and 12, the share of pine in the stock of more than 70% was noted in trial plots 1, 3, 8, 15 and 16. The percentage of spruce on the stock varied from 2% on sample plot 15 and up to 20% on sample plot 19. In the remaining sample plots, the share of spruce was more than 10%. The percentage of birch stock varied from 7% on trial plot 3 up to 36% on trial plots 11 and 12. The proportion of as-

Table 2. Results of the standard analysis for the experimental plots

Plot No.	No. of treatment	Species composition of the stand (%)				Mean (Scots pine)		Tree No. per ha		Basal area ($m^2 \cdot ha^{-1}$)		Standing volume ($m^3 \cdot ha^{-1}$)	
		SP	NS	SB	AS	height (m)	diameter (cm)	Scots pine	all species	Scots pine	all species	Scots pine	all species
2	4	68	19	9	4	20.1	21.9	762	1 952	28.7	46.2	284	416
3	8	78	15	7	-	23.0	24.3	660	1 420	30.7	42.9	342	441
16	6	72	14	13	1	23.7	26.4	491	1 420	26.9	40.3	308	433
19	9	66	20	13	1	23.1	24.5	555	1 775	26.2	43.8	292	444
1	12	77	14	9	-	26.8	28.9	552	1 692	36.3	52.0	449	585
9	4	66	16	14	4	25.0	30.9	425	1 755	31.8	51.7	369	559
8	3	74	11	15	-	24.5	28.9	590	1 675	38.8	54.4	443	597
11	2	38	10	35	17	23.3	25.2	382	1 587	19.1	49.2	214	565
12	2	49	12	36	3	25.4	24.7	524	1 883	25.0	50.2	304	584
14	13	66	10	15	9	26.7	28.6	461	1 577	29.7	47.7	378	574
15	2	89	2	9	-	24.8	29.9	529	754	37.1	41.2	436	488
23	6	60	10	23	7	24.7	29.7	458	1 679	31.8	54.5	374	608

SP – Scots pine; NS – Norway spruce; SB – silver birch; AS – Eurasian aspen

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pen varied from 1% in trial plots 16 and 19 and up to 17% on trial plot 11. There were no aspen trees in trial plots 1, 3, 8 and 15.

Tree diameter distributions by absolute diameter gradations

Checking for the normality of the distribution of the number of pine trees (Figure 3) showed that all the studied samples were close to the normal distribution function (the Laplace-Gaussian function) since the Kolmogorov-Smirnov coefficient (d) varied between 0.05 and 0.11 ($P > 0.2$). Pine trees were distributed within all the diameter gradations (from 6 to 48 cm). Most of the trees were observed in the central thickness grades from 18 to 34 cm, but there were significant variations in the trees in the trial plots.

At the same time, there was a shift of the series relative to the average value in all the test plots, i.e., left and right-sided asymmetry. The distribution of the number of pine trees in sample plots 2, 3, 8, 11

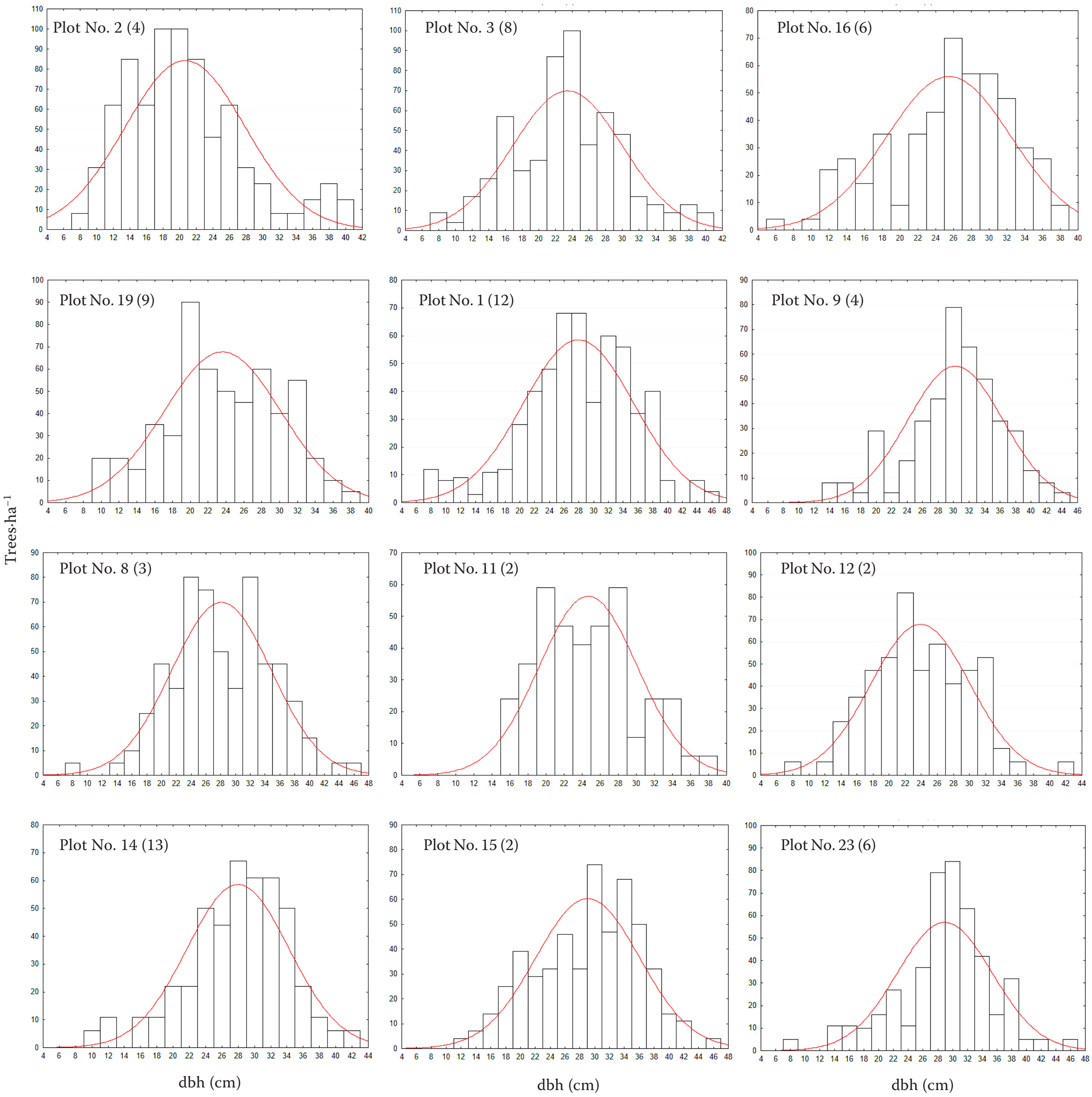

Figure 3. The distribution of the number of pine trees at the absolute thickness grades (the red line is the expected normal distribution); the number in brackets means the number of treetments on the plot; dbh – diameter at breast height

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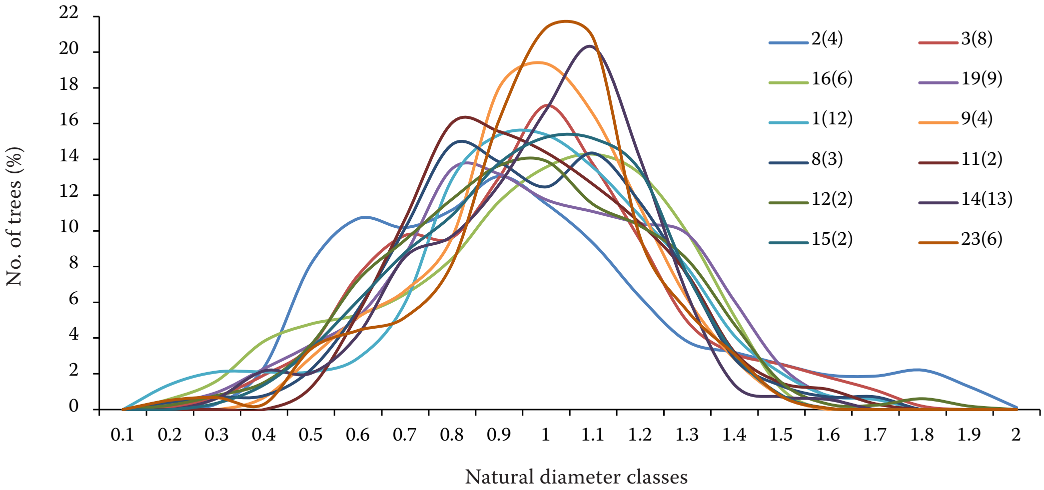

Figure 4. Actual distribution of the number of pine trees by the natural (relative) thickness steps

and 12 was characterised by a left-sided asymmetry and the skewness coefficient varied from 0.01 ± 0.22 to 0.82 ± 0.24. The distribution curves had a small positive asymmetry. The distribution of the number of pine trees in trial plots 1, 9, 14, 15, 16, 19 and 23 was characterised by a right-sided asymmetry and the coefficient varied from –0.12 ± 0.23 to –0.57 ± 0.26.

In all the cases, the asymmetry of the diameter distribution series was not proven and was explained by random causes.

The distribution density of the number of pine trees by the diameter was marked as a sharp-like and a flat-topped. The density of the distribution of the pine trees in sample plots 1, 2, 3, 9, 14 and 23 was characterised as sharp-like, the kurtosis varied from 0.02 ± 0.42 to 1.20 ± 0.51. The distribution curves had a slight positive excess.

The density of the distribution of the pine trees in sample plots 8, 11, 12, 15, 16 and 19 was characterised as flat-topped, the value of the excess varied from –0.07 ± 0.50 to –0.61 ± 0.40. The distribution curves had a slight negative kurtosis.

In all the cases, the kurtosis deviation of the considered curves from the normal distribution curve was not proven.

Distribution of the number of trees by natural (relative) thickness steps

The actual distribution of the number of pine trees by the natural thickness steps is shown in Fig-

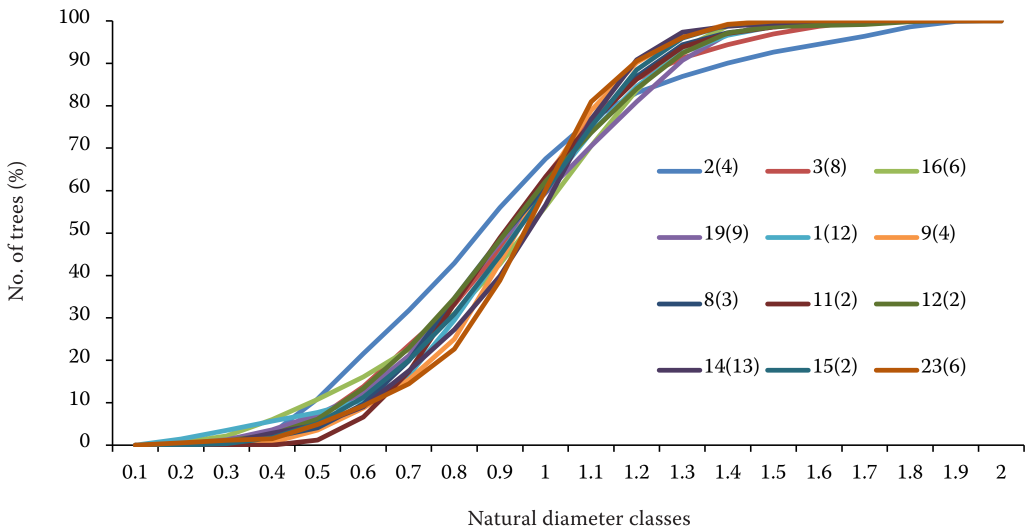

Figure 5. The ratio between the ranks and reduction in numbers of the trees in the diameter on the different test plots

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ure 4. The distribution series varied from 0.1 to 2.0 of the natural steps.

The average diameter of the test plot stands divided the distribution curves into two unequal parts. The number of trees in the central step was divided in half. At the same time, common patterns were observed in all the test plots.

Almost all of the trial plots showed a predominance of pine trees up to an average diameter, that is, the left branch accounted for 61.8% of the trees in trial plot 2 and 52.5% in trial plot 1. In trial plots 14, 16 and 23, the number of trees above the average diameter prevailed. The right branch accounted for 51.7%, 50.5% and 50.5% of the number of trees, respectively.

The ratio between the ranks and reduction numbers (natural thickness steps) of the trunks in the diameter on test plots is shown in Figure 5.

The position of the average tree relative to the thinnest tree did not differ in the sample plots. The position of the average tree in the studied stands varied from 67.5% in test plot 2 to 56.2% in test plot 16. The average tree in all the trial plots was 61% of the total number of trees.

The aligned distribution of the number of pine trees using the normal distribution function (Laplace-Gaussian) according to the natural thickness steps is shown in Figure 6.

Comparing the results of the actual and theoretical tree numbers showed that the sample populations obeyed the general distribution law, which was applied to equalise the number of pine trees. Thus, the χ^2 criterion varied from 7.6 in test plot 23 to 1.8 in test plot 1. The probability of error when rejecting the null hypothesis (P-value) varied from 0.27 in trial plot 23 and up to 0.93 in trial plot 1, which suggests that there is no difference between the theoretical and actual number of pine trees.

The influence of forest plantation methods on stands taxation parameters

To determine the influence of the plantation methods on the stands' parameters that they reached during the study period, various analyses were carried out. Using a correlation analysis, it was found that the soil processing method, namely, the area of planting seats processed, had the greatest influence on the size characteristics – the average height and average diameter of the trees (the correlation coefficient was 0.73 and 0.67, respectively). Figure 7 shows the influence of the site processing area on the average diameter of the stands, which confirms the established pattern. The influence of the processing area of the experimental forest crops on the number of trees and the total growing stock of the stands is characterised by an even higher correlation (R = –0.74 and 0.94, respectively).

The factor analysis showed the highest degree of the factor grouping and factor load magnitude for the factors related to the method of creating the forest crops (Figure 8). Factor 1 can be designated as a quantitative characteristic of the studied objects, factor 2 as the qualitative one.

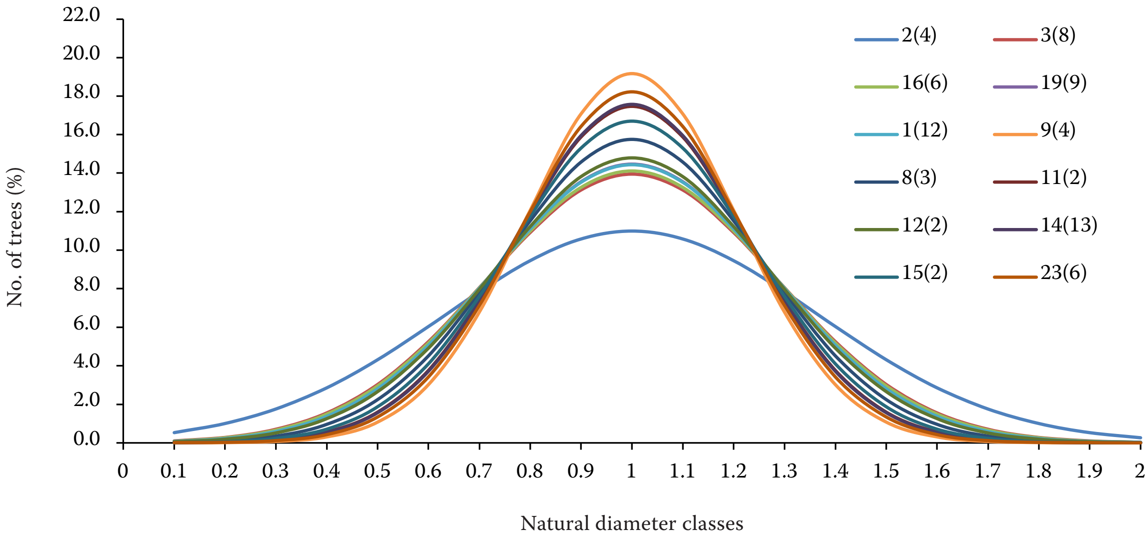

Figure 6. Equalised distribution of the number of pine trees by the natural (relative) thickness steps

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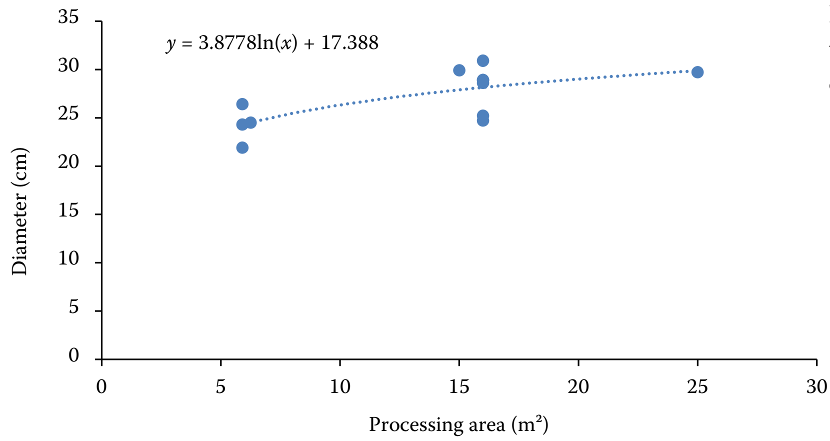

Figure 7. Dependence of the diameter of the average trees on the processing area of the experimental forest crops

DISCUSSION

The results showed that the forest crops are not inferior to and, in some cases, exceed the naturally formed stands (Soldatova, Ilintsev 2020).

The distribution of trees by diameter was one of the main taxation indicators that characterised the structure of the stands (Burkhart, Tomé 2012; Kershaw et al. 2017). The distribution of the number of trees by the diameter also played an important role in the stand modelling (Newton et al. 2005). The structure of a tree stand by a natural thickness step is of great practical importance for evaluating stands, so based on the ocular taxation data, you can use the series to approximate the number of trees and the stock by the thickness steps, without making a list of trees (Gusev 1964).

The distribution of the number of trees by the usual (absolute) thickness steps has a significant disadvantage. It does not allow for the comparison of the rows or distribution curves established in the stands with different average diameters that differ in age or growing conditions. Furthermore,

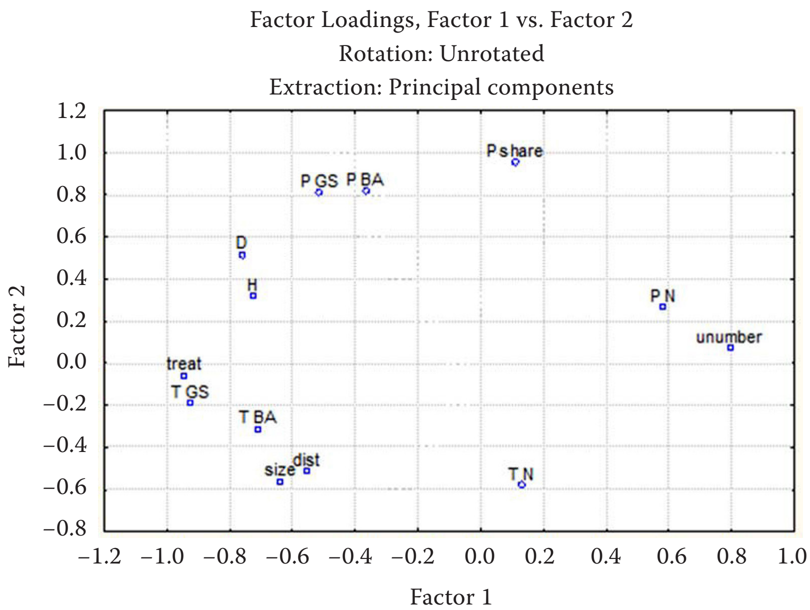

Figure 8. Distribution of the main factors determining the effectiveness of the forest planting

D, H – the average diameter and height of the stands, respectively; treat – the treated area (%); size – the size of the site; unumber – number of site units per ha; dist – distance between the centres of sites; P share – share of pine in the stand composition; PN – number of pine trees per ha; TGS – total growing stock ($m^3 \cdot ha^{-1}$); PGS – pine growing stock ($m^3 \cdot ha^{-1}$); TBA – total basal area ($m^2 \cdot ha^{-1}$); PBA – pine basal area ($m^2 \cdot ha^{-1}$)

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it does not allow for the determination of the degree of variation in the number of trees in the same thickness stages nor noticing the commonalities or significant differences in them. In this respect, the method of distributing the number of trees by natural thickness steps was proposed by A.B. Tyurin (Anuchin 1982). The distribution of the number of trees was represented as the distribution curves over the normal (Figure 4) and natural (Figure 6) thickness steps. Left or right-sided asymmetry was observed in all the test plots as a consequence of the competition between the trees. The left branch, which represents lagging trees, is longer. This means that there are fewer larger trees in the stand than those that are lagging in growth. Subsequently, asymmetry decreases with age due to the weakened trees falling (Ipatov 2003).

The nature of the distribution of the number of trees is influenced by many factors that affect the intensity of the differentiation of the trees by the thickness (Anuchin 1982). At the same time, the distribution series in the sample plots under consideration are close to each other, which confirms similar growth conditions.

The reduction in the trees of the same rank changed in the different test plots (Figure 5). To the middle tree in the ranked row, the reduction in number in terms of the diameter of the same rank were lower and they increased in higher ranks. This difference is explained by the fact that all the species under consideration have different average diameters. The smallest reduction in numbers was observed in sample plot 2.

The ratio between the ranks and reduced numbers of trunks in the diameter, as well as the parameters of the distribution series, change depending on the age, the average diameter of the stand and the age structure (Gusev 1977).

The studied phenomena of nature, as a rule, obeys a certain mathematical law and is expressed in various kinds of smooth curves or straight lines (Gusev 1964; Pretzsch 2009). Applying diameter distribution models in combination with stand characteristics result in a consistency between the actual diameter measurements (Palahí et al. 2007). This is because the distribution of the taxational tree parameters in the stand often deviates from the normal distribution and can be approximated by other theoretical functions that take the degree of asymmetry and kurtosis of variational series into account. To describe the distribution of the tree diameters in the stands, various types of parametric functions are used, including normal, log-normal, gamma, beta, Johnson's SB, Weibull, Pearson's type I function, Gram-Charlier distribution and others.

The considered regularities of the distribution of the trees by the diameter on all test plots (Figure 6) obey the Laplace-Gaussian law (normal distribution). At the same time, the theoretical and actual numbers do not completely coincide in the sample plots, as we are dealing with a sample population and individual characteristics for creating forest crops (sample plots).

CONCLUSION

The forest crops created by Alekseev are of great importance for the guaranteed cultivation of stands with a predominance of pines in Northern European Russia. The artificial stands created by Alekseyev's method are not inferior in their growth activity to natural stands.

Earlier in the survey of forest crops, Ipatov (2003) noted that the productivity of the stands on the site of the experimental forest crops is unique for crops growing on the border of the northern and middle subzones of the taiga. In the natural 70-year-old blueberry pine forests, such wood stock was not previously found.

By the age of 90 years, the total growing stocks of the forest crops have reached high levels for the northern taiga forests. The stock is, on average, 525 (from 416 to 608) $m^3 \cdot ha^{-1}$, including 349 pine trees (from 284 to 449) $m^3 \cdot ha^{-1}$ and is not inferior to the normal stands of Northern European Russia and, in some cases, exceeds them.

The distribution of the number of pine trees by the thickness steps is close to the normal (the Laplace-Gaussian function) in all the test plots. The indicators of asymmetry and kurtosis of the distribution curves obtained at the points of observation are from random causes.

In nine trial plots, the predominance of pine trees smaller than the average diameter was observed, with the left branch accounting for 52.5 to 61.8%. In three trial plots, the number of trees with a diameter greater than the average prevails, the right branch accounts for 50.5–51.7%. The position of the average tree in the studied stands varied from 67.5% to 56.2%.

The analysis of the results (correlation and multidimensional) showed that the creation method of

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the forest crops had an impact on such important taxation parameters as the mean height, diameter at breast height, basal area, and standing volume. It was found that the best options for growing pure pines are areas with a large share of soil cultivation and the size of the seedbed. The forest crops growing in trial plots 1, 9 and 23 (option 12, 4 and 6), were the best options surveyed. The method used to create these variants can be recommended for adaptation in forest industrial practice.

The experience of creating the first forest crops by seeding in northern conditions showed that reforestation can be successful and high-performance stands are formed. The results obtained in this study complement the existing knowledge about the restoration of pines in boreal forests.

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