FOREST SCIENCE, 2025, No. 1, pp. 12–20

ORIGINAL ARTICLES

SCOTS PINE TREES' SAP WOOD DENSITY IN TRANS-VOLGA FORESTS OF THE MARI EL REPUBLIC[1]

© 2025 Yu. P. Demakov, E. S. Sharapov*, A. S. Korolev, and O. V. Sheikina

Volga State University of Technology,
Lenin sq. 3, Yoshkar-Ola, 424000 Mari El Republic, Russian Federation
**e-mail: sharapoves@volgatech.net*

Received January 30, 2024
Revised August 05, 2024
Accepted November 15, 2024

Abstract. The relevance of the study is due to the need to improve the accuracy of assessing the quality of the Russia's forests resource potential and the efficiency of its use. That can only be done via an in-depth study of the tree coenopopulations' structure regarding their economically valuable traits, one of which is the basic density of wood. The purpose of the study is to assess the patterns of individual and group variability in the basic sapwood density of Scots pine trees in forest stands of different ages, origins, density and growing conditions located in the Mari El Republic, which will allow to select and subsequently reproduce the most economically promising individuals. The studies were conducted on 13 sample plots in pure, even-aged forest stands. To estimate the value of the basic density of sapwood, which was carried out by stereometric and hydrostatic methods, we used 50 mm long cores, manually extracted with a Pressler borer from 1072 trees at a height of 1.3 m from the base of the trunk. Standard methods of mathematical statistics were used in processing the empirical material. Results. It was found that the value of the estimated parameter varies in trees from 291 to 660 $kg \times m^{-3}$, overlapping with the limits established by domestic researchers. It is virtually independent of growing conditions, density and origin of tree stands, rank position of individuals in coenopopulations, width of the annual wood growth and the proportion of the late summer layer in it, and is mainly linked to the age of the trees ($R^2 = 0.9$). It has been proven that the ecological requirements for environmental conditions are different for trees with different wood density, which is reflected in the nature of their radial annual growth dynamics. A scale has been developed for assessing the economic value of trees in coenopopulations of different ages based on the density of their sapwood. Natural selection of trees based on wood density in coenopopulations that reaches its maximum at the age of 100–110 years does not occur, and thus targeted selection based on this parameter will not subsequently affect the productivity of plantations.

Keywords: *Scots pine, tree coenopopulations, wood, density, variability, economically valuable genotypes*

DOI: 10.31857/S00241148250102e1

Rational use of wood resources and increasing the ecological and resource potential of Russian forests determine the relevance of improving the methods and tools of tree selection according to the target economically valuable parameters, one of which is wood density (Poluboyarinov, 1976; Auty et al., 2014; Kimberley et al., 2015; Gil-Moreno et al., 2024). To successfully solve this problem, it is necessary, first of all, to study in detail the nature of the influence of external and internal factors, as well as growing regimes of plantations on the values of this parameter, using the latest arsenal of equipment and methods of nondestructive control of wood density in living trees.

Despite the long-standing interest of researchers to the question of the causes of variability in the density of Scots pine wood (*Pinus sylvestris* L.) in different regions of Russia and the vast amount of accumulated material, there is still no unambiguous answer to it, which is due to the diversity of forest biogeocenoses and methodological approaches to solving the problem. Thus, according to some authors, the value of density varies depending on the growing conditions of trees, as they improve it either increases (Zhilkin, 1936; Buesgen, 1961; Krasnov and Gursky, 2007) or decreases (Petrusha, 1959), or there is no relationship between these parameters (Poluboyarinov, 1976; Konovalov, 2007; Shchekalev, 2021). No differences between natural stands and plantations have also been found (Ovodovodov, 2010). The results of studying the effect of initial stand density of forest plantations on wood density are also far from ambiguous (Ryabokon

[1] The research work was supported by the Russian Science Foundation (RSF, No. 23-16-00220), https://rscf.ru/en/project/23-16-00220/ using equipment of the Core Facility Centre «Ecology, biotechnologies and processes for obtaining environmentally friendly energy carriers» of Volga State University of Technology, Yoshkar-Ola.

and Litash, 1981; Melekhov et al., 2003; Podoshvelev, 2008; Lomov and Sukhorukov, 2009; Revin et al., 2010; Danilov and Stepanenko, 2013; Kimberley et al, 2015; Demakov et al., 2019; Šilinskas et al., 2020; Demakov, 2022; Sharapov et al., 2024) and the rank position of trees in cenopopopulations (Zhilkin, 1936; Poluboyarinov, 1976; Danilov and Smirnov, 2014; Tyukavina et al., 2017; D.A. Zaitsev, 2018; Fabisiak and Fabisiak, 2021)

This trait is fixed, according to a number of authors, in the genotype of trees (Konofalska et al., 2021; Szaban et al. 2023), manifesting itself in trees differently depending on the prevailing conditions of their growth, which is confirmed by the results of studies in geographical cultures laid in different regions of Russia. Thus, in the Bryansk region, wood density of pine was highest in Lipetsk and Penza, and lowest in Lithuanian, Estonian, Grodno, and Vitebsk (Latsevich, 2001) climatypes; in Siberia and Kaluga region, seed progenies of populations from southern regions outperformed local climatypes (Kuzmin, Vaganov, 2007; Melnik et al, 2007; Kuzmin and Rogovtsev, 2016; Kuzmin, 2018), which in Kazakhstan were significantly inferior to trees from Kara gandinsky, Orenburg and Kurgan oblasts (Maruschak, 2007; Maruschak and Maximov, 2014).

The aim of the study was to assess the limits and regularities of individual and group variation in the values of basic sapwood density of Scots pine trees in stands of different age, origin, density and growing conditions in the Republic of Mari El in order to select and further reproduce the most economically promising individuals.

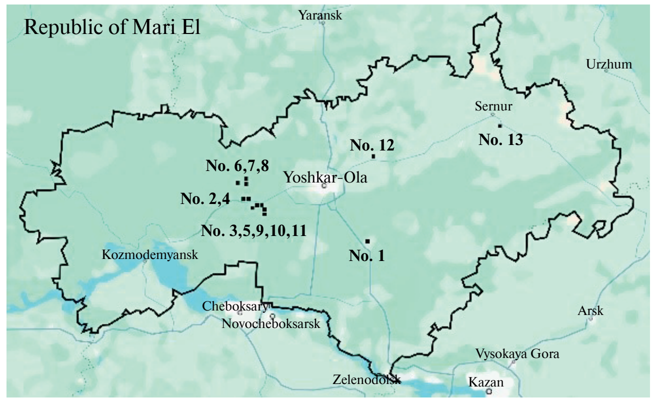

Fig. 1. Location of research objects (sample areas) in the territory of the Republic of Mari El.

OBJECTS AND METHODOLOGY

The studies were conducted in 2023 on 13 experimental plots in pure single-aged natural forests and plantations of Scots pine growing in the left-bank (Zavolzhskaya) part of the Republic of Mari El (Fig. 1, Table 1), which belongs to the subzone of coniferous-broadleaved forests (Kurnaev, 1973). The climate in this territory is temperate continental, the average annual air temperature is 3.1 °C, the solar radiation arrival is 350 kJ× cm^{-2} per year, the sum of effective temperatures is 2200 °C,

Table 1. Brief characterization of research objects

Plot number	Location	TLU	Age	Origins	Sample size
1	Silikatnoye lesnichestvo, quarter (sq.) 20	A_1	45	Plantation	100
2	Starozhilskoye lesnichestvo, Q. 34 (PPP 35)	A_{1-2}	55	Plantation	30
3	Starozhilskoye lesnichestvo, sq. 49 (PPP 37)	A_{1-2}	62	Plantation	101
4	Starozhilskoye lesnichestvo, Q. 17 (SPT 29)	A_2	95	Natural	90
5	Starozhilskoye lesnichestvo, Q. 17 (PPP 30)	A_2	125	Natural	130
6	GPZ "Bolshaya Kokshaga", sq. 90 (PPP 9L)	A_1	95	Natural	101
7	Bolshaya Kokshaga" GPZ, square 90 (PPP 90-4)	A_2	95	Natural	100
8	Bolshaya Kokshaga SPA, square 87	A_3	185	Natural	20
9	Starozhilskoye lesnichestvo, Q. 35 (PPP 33)	A_5	95	Natural	25
10	Starozhilskoye lesnichestvo, Q. 35 (PPP 28)	A_5	185	Natural	25
11	Starozhilskoye lesnichestvo, Q. 38 (PPP 36)	B_2	72	Plantation	30
12	Protective plantations on the Managa River	C_2	55	Plantation	60
13	Bushkovskoye lesnichestvo, sq. 39, plus tree clone archive	C_{2-3}	30	Plantation	262

Note. PPP — permanent sample area, SPZ — state nature reserve, TLU — type of forest conditions (A_1 — lichen-lichen pine forest on dry sandy soils, A_{1-2} — lichen-mossy pine forest on fresh sandy soils, A_2 — lingonberry pine forest on fresh sandy soils, A_3 — bilberry pine forest on moist sandy soils, A_5 — sphagnum swampy pine forest, B_2 — linden pine forest on fresh sandy loam soils, C_2 — nettle-grass pine forest on fresh loamy soils, C_{2-3} — linden broadleaf pine forest on fresh loamy temporarily overwatered soils).

the sum of precipitation is 566 mm (Kolobov, 1968; Agroclimatic resources..., 1972; Demakov, 2023). Soils are mainly sod-podzolic, different in granulometric composition: from sands to heavy loams (Smirnov, 1968).

In each experimental plot, the trunk diameter with the bark was measured at a height of 1.3 m from the ground and cylindrical cores with a nominal diameter of 5.15 mm and length of 50 mm were taken from the northern side of the tree using a Pressler increment borer (Haglöf Sweden AB, Longsele, Sweden) and placed in individual plastic containers to preserve wood moisture. Laboratory measurements and weighing of the samples were carried out during the same day. Basic density of wood was estimated by both stereometric (according to GOST 16483.1—84) and hydrostatic methods (Poluboyarinov 1976). In the first case, the volume of the raw core was determined by its geometric dimensions (length and average diameter along and across the fibers) measured with a caliper with an error of ± 0.01 mm. When using the hydrostatic method of wood density estimation, the core was pre-moistened to reduce the probability of air bubble formation on its surface and immersed in a measuring vessel with distilled water using a metal needle without touching its walls and bottom. The mass of displaced water (m_{dw}) of known density (ρ_{dw}) was measured on a ViBRA ALE-623 scale (Shinko Denshi Co., Ltd., Tokyo, Japan) with an error of 10^{-6} kg. The cores were then dried at 103 °C to a constant mass (absolutely dry state), and the same scales were used to measure this mass. The

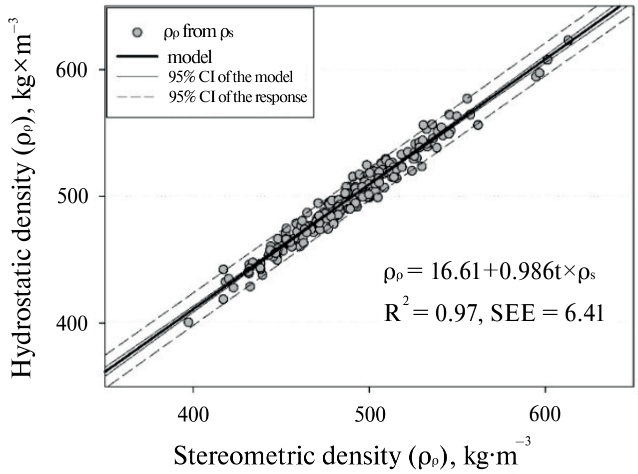

Fig. 2. Correlation between the values of the basic density of cores from experimental plots No. 4 and No. 5 (216 samples), estimated by stereometric and hydrostatic methods. R^2 — coefficient of determination, SEE — standard error of approximation, CI — confidence interval for model and response, respectively (model coefficients are significant).

following expressions were used to calculate the basis density of wood:

stereometric method: $\rho_c = m_0 / V_{\max}$.   hydrostatic method: $\rho_d = (m_0 \cdot \rho_{dw}) / m_{dw}$,

where ρ_c, ρ_d — stereometric and hydrostatic density of core (sample) wood, kg×m^{-3}; m_0 — sample mass in absolutely dry condition, kg; $V_{\max}$ — volume of

Table 2. Variability of wood basic density in single-age pine populations (sorted by the average value of the parameter)

Plot number	Values of statistical indicators of the estimated parameter*					
	$M \pm m$	X_{min}	X_{max}	S_x	CV	$r_{\rho\text{-}d}$
13	357.6 ± 1.7	290.6	446.4	27.8	7.8	–0.172
12	428.6 ± 3.7	368.9	491.2	28.7	6.7	0.427
1	432.8 ± 3.1	356.0	491.5	30.5	7.0	0.110
10	451.5 ± 9.5	371.6	594.3	46.7	10.4	–0.512
2	467.2 ± 7.2	369.7	521.8	39.5	8.5	0.485
3	469.7 ± 4.5	372.1	660.2	45.3	9.7	0.379
5	483.0 ± 3.0	397.3	596.7	34.2	7.1	–0.339
6	485.5 ± 2.8	421.7	557.6	30.5	6.3	0.228
11	489.3 ± 5.7	435.6	570.2	31.6	6.5	0.318
9	493.9 ± 9.7	429.5	647.7	47.8	9.7	–0.106
4	494.8 ± 3.7	431.6	613.0	35.1	7.1	–0.086
7	496.1 ± 3.8	402.6	628.2	38.8	7.8	0.115
8	500.1 ± 10.3	424.5	588.1	45.9	9.2	–0.835

*Note. $M\pm m$ — mean value of the parameter and its errors; X_{min}, X_{max} — minimum and maximum values of the parameter; S_x — standard deviation of the parameter values; CV (%) — coefficient of variation; $r_{\rho(-)(d)}$ — Pearson's correlation coefficient between the series of values of wood basic density and tree diameter.

cylindrical shape core sample at green wood moisture content, m^3; ρ_{dw} — density of distilled water, kg×m$^{(-3)}$ (GSSSD2—77); m_{dw} — mass of displaced water when the core is immersed in the vessel, kg.

The obtained results, reflecting the values of the estimated parameters in 1072 trees, were processed on PCs using application program packages for statistical processing and graphical presentation of data: Microsoft Excel® 2016, SigmaPlot 14 (Systat Software Inc., San Jose, CA, USA) and Statistica 10 (Dell, Round Rock, TX, USA). Determination of the significance of differences between group averages of basic density was performed using analysis of variance and Tukey HSD test (Tukey HSD) at 95% confidence level.

RESULTS AND DISCUSSION

Calculations showed that the differences between the values of wood basic density estimated by stereometric and hydrostatic methods from cores taken from trees in experimental plots No. 2 and 4 (Table 1), do not exceed ±3% in most cases (Fig. 2), i. e. do not exceed the required accuracy of the experiment. In this regard, we decided to estimate the value of this parameter at the remaining study sites only by stereometric method (hereinafter denoted as ρ).

On the basis of the analysis of the collected empirical material, it was found that the value of sapwood basic density varied in pine forests of the Mari El Republic from 291 to 660 kg×m^{-3} (Table 2), overlapping the limits established by domestic researchers for the entire range of this tree species (Poluboyarinov, Fedorov, 1985; Groshev et al., 1980; Borovikov, Ugolev, 1989; Usoltsev, Tsepordey, 2020). At the same time, foreign scientists have established wider limits of variation of the basic density of Scots pine wood: 340—783 kg×m^{-3} with an average value of 514 kg×m^{-3} (Konofalska et al., 2021) and 274—697 kg×m^{-3} with an average value of 423 kg×m^{-3} (Auty et al., 2014).

The average value of the parameter was highest in the bilberry pine forest at plot No. 8, while it was lowest in the plantation of plus-tree clones in TLU C_{2-3} (Table 2). The tree with the maximum wood density was found in the sphagnum pine forest (plot No. 3), and the minimum — at plot No. 13.

Some of the available cenopopulations, as shown by analysis of variance and the test of homogeneity of mean (Tukey), are significantly different from each other in the mean value of the estimated parameter, despite the significant internal variation of its values, the contribution of which is 30.6% (probability of error < 0.001). The variability of the parameter is greatest in the cenopopulation of trees in the upper bog (plots No. 9, 10), while it is minimal in the clone plantation. Cenopopulation No. 13 with the lowest value of wood density is significantly different from all others, and cenopopulations № 4, 7 and 8, whose trees have on average the highest value of the parameter, are significantly different from only five: No. 1, 3, 9, 12 and 13. The high internal variation of the parameter value indicates the principal possibility of selection in cenopopulations of the most valuable trees for economic purposes, for which the most suitable plots were No. 3, 7 and 9, where individuals with high wood density.

One of the factors of dispersion of the wood basic density is tree diameter, which varied in the study plots from 7 to 57 cm, but its contribution, as calculations have shown, is generally small and varies in the aggregate of cenopopopulations within very large limits, indicating the specificity of the structure of each of them. The closest correlation between values of tree diameter and sapwood density, which was negative, was observed in the stand at plot 8 (r= — 0.835), while in other cases the value of the correlation coefficient varied from –0.512 to 0.482. Trees of different rank in cenopopulations differ insignificantly in wood basic density, although on average its value is the highest in individuals of III and IV Kraft classes (Table 3).

The absence of close conjugation between wood basic density and tree diameter in single-age cenopopulations indicates a weak dependence of wood basic density on average annual ring width, which was confirmed by the results of direct measurements of their values over

Table 3. Average and maximum values of wood basic density in trees of different Kraft classes in one-aged lichen-mossy pine forests

Plot	Wood basic density in trees of different development classes, kg×m^{-3}*							
	I		II		III		IV	
	$M \pm m$	X_{max}	$M \pm m$	X_{max}	$M \pm m$	X_{max}	$M \pm m$	X_{max}
No. 4	475.2 ± 9.3	545	491.1 ± 6.1	601	508.6 ± 5.9	613	491.0 ± 9.2	595
No. 5	452.4 ± 8.4	526	484.1 ± 3.8	562	496.4 ± 7.0	662	497.6 ± 11	536
No. 7	492.2 ± 13.0	555	502.6 ± 9.1	628	495.9 ± 5.0	573	492.3 ± 8.7	566
Overall	469.2 ± 6.1	555	489.4 ± 3.2	628	499.7 ± 3.5	662	492.8 ± 5.5	595

*Note. $M \pm m$ — average value of the parameter and its errors; X_{max} — maximum value of the parameter.

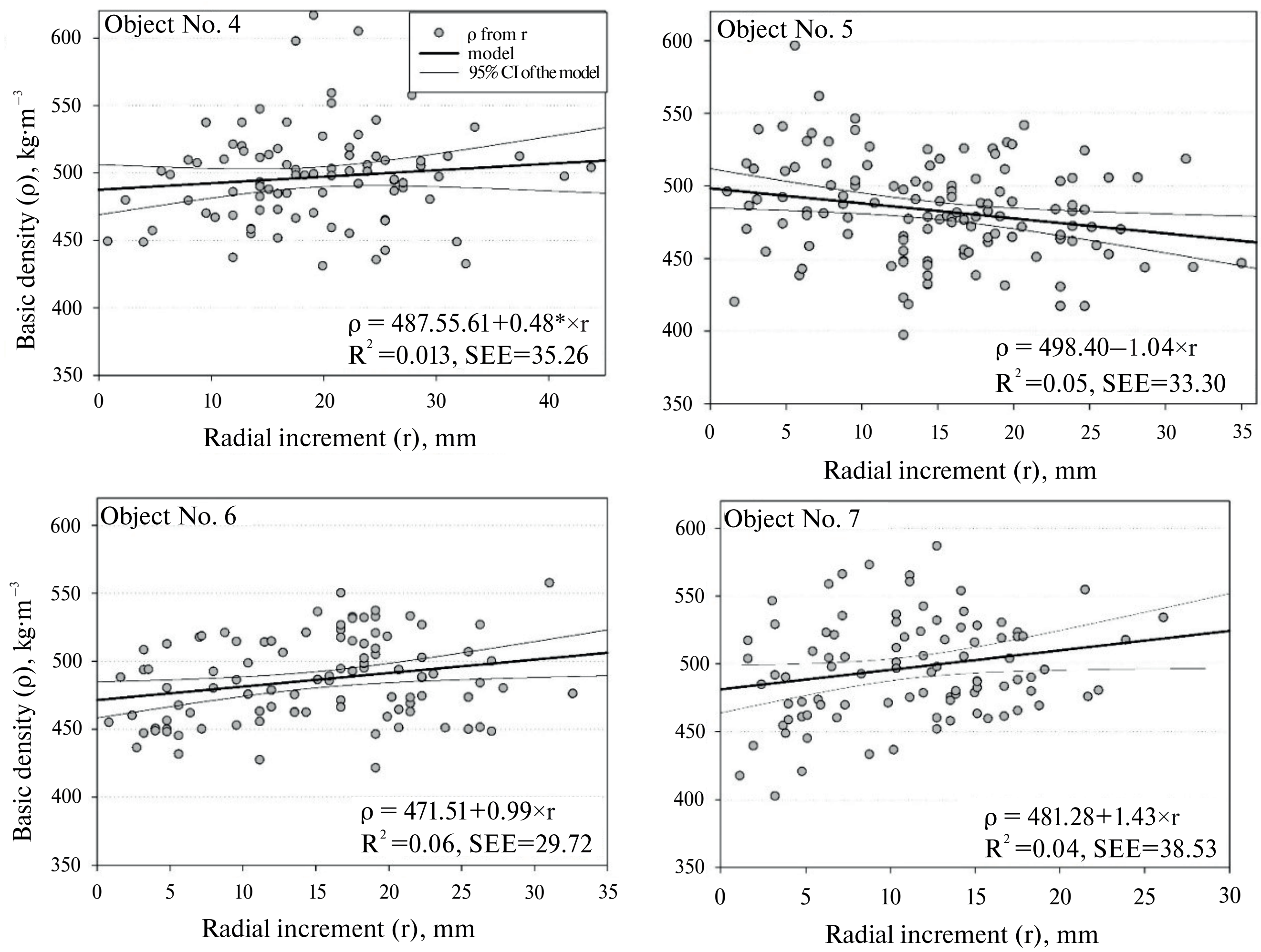

Fig. 3. The nature of the relationship at experimental plots 4—6 between the value of radial growth of trees over the last 20 years and wood basic density.

Table 4. Variability of wood density and its relationship with tree diameter in 45-year-old pine plantations with different initial stand densities

Initial density, ex/ha	Values of statistical indicators of sapwood basic density*					
	$M \pm m$	X_{min}	X_{max}	S_x	nCV,%	$r_{\rho\text{-}D}$
500	436 ± 5.7	396	476	79.9	63.2	0.102
1000	437 ± 10.0	378	579	200.3	76.6	0.118
3000	428 ± 8.4	358	483	124.7	53.4	0.626
5000	429 ± 6.8	356	484	128.2	41.8	0.132
10000	441 ± 6.1	390	492	101.7	53.5	- 0.028

*Note. $M \pm m$ — mean value of parameter and its errors; X_{min}, X_{max} — minimum and maximum values of parameter; S_x — standard deviation of parameter values; pCV (%) — normalized coefficient of variation $pCV = 100\times S_x / (M - X_{min})$; $r_{\rho(-)(d)}$ — Pearson correlation coefficient between series of values of wood basic density and tree diameter.

Table 5. Diameter of trees at the plot and their latewood the last 10 years

Parameter	Average values of parameters in different variants of the experiment				
	500 trees/ha	1000 trees/ha	3000 trees/ha	5000 trees/ha	10000 trees/ha
Diameter, cm	22.7 ± 0.60	20.3 ± 0.60	14.9 ± 0.90	12.2 ± 0.60	9.9 ± 0.50
Latewood width, mm	0.6 ± 0.03	0.48 ± 0.02	0.32 ± 0.02	0.31 ± 0.01	0.25 ± 0.01
Ratio of layer,%	34.2 ± 0.60	31.2 ± 0.50	32.1 ± 0.40	29.1 ± 0.20	29.7 ± 0.50

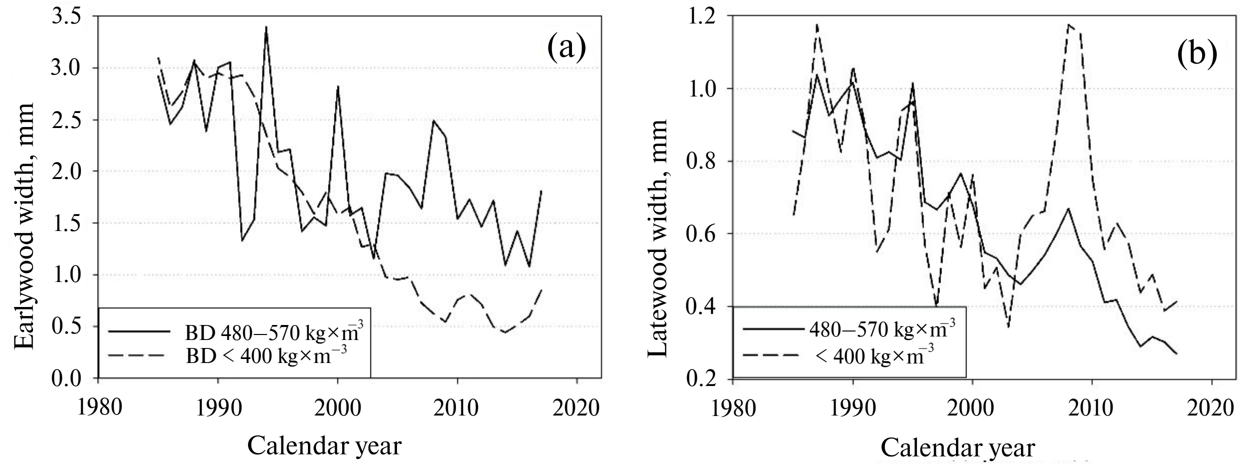

Fig. 4. Dynamics of the width of early- (a) and latewood (b) in trees with different sapwood density (Sharapov et al., 2024).

the last 20 years (Fig. 3). The lack of close relationship between the estimated parameters also indicates that natural selection of trees by wood density does not occur in cenopopulations and targeted selection of individuals will not eventually lead to a decrease in the volume of stem wood produced by plantations.

Wood density also appeared to be independent of stand density (Table 4), an increase in which leads to a decrease in the average diameter of trees with age, as well as in the width of their annual rings and latewood (Table 5). The reason for this is related, in our opinion, to the fact that wood density, which mainly depends on tracheid wall thickness (Buesgen, 1961; Tyukavina et al., 2017; Ryabokon and Litash, 1981), is limited at the plots No. 1 of our study not by stand density, but by soil poverty and dryness (Sharapov et al., 2024). The main contribution to the variance of the estimated parameters here, as well as at other plots, is also made by individual characteristics of trees, probably fixed in their genome and manifested in the series of initial data in the form of "noise" that distorts the influence of the studied factor. Different share of genotypes in the samples is reflected in the value of the standard deviation of wood density values, which is the highest in the experiment variant with planting density of 1 thousand trees per ha, as well as in the nature of the relationship between this parameter and tree diameter. In other forest conditions the obtained results may be different.

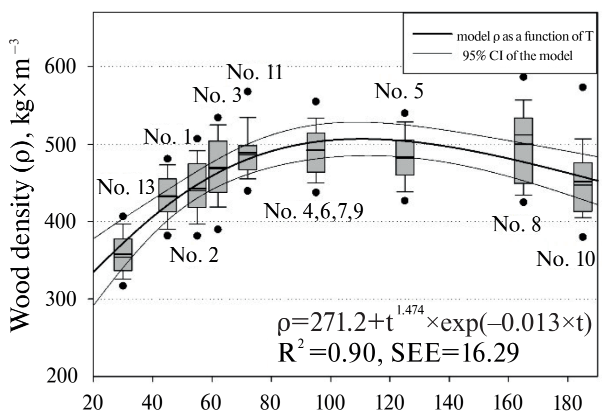

Fig. 5. Relationship between average value of wood basic density (ρ , kg×m^{-3}) in the Scots pine cenopopulation and stand age (t, years). R^2 — coefficient of determination, SEE — standard error of approximation (model coefficients are significant). Numbers denote spread diagrams corresponding to samples of density values by study sites (Table 1). The boundaries of the "box" of the scatter diagrams are the 25th and 75th percentiles, the boundaries of the "whiskers" are the 10th and 90th percentiles, the points are the 5th and 95th percentiles, respectively, the thin line in the middle of the "box" is the median, and the bold line is the mean.

The studies also showed that the width of the earlywood of the annual ring of trees with high wood density fluctuates very strongly by years and becomes much higher than that of trees with low density as they grow (Fig. 4). In contrast, the dynamics of latewood width, the value of which strongly decreased after the 2010 drought, is diametrically opposite. This fact, in our opinion, is another convincing confirmation of the presence in cenopopulations of different genotypes of trees with their own ecological requirements.

The most important factor influencing the change in the average value of wood basic density (ρ, kg×m^{-3}) in the entire population of individuals in a cenopopulation is, as studies have shown, the age of trees (t, years). Mathematically, this regularity, into which all objects of our study, including plantations with different stand densities as well as clones of plus trees, fully fit, approximates with very high accuracy (R^2 = 0.90) the equation $\rho = 271.2 + t^{1.474} \times \exp(-0.013 \times t)$. As follows from this equation, the trajectory of change of the estimated parameter in trees has a dome-shaped form in the chosen coordinate

Table 6: Criteria for distinguishing trees of different quality categories in pine cenopopulations based on the basic density of their sapwood

Category trees	Range of values of wood basic density in stands of different ages, kg×m^{-3}							
	20 years	30 years	40 years	50 years	60 years	80 years	100 years	120 years.
Pluses	390—425	420—450	450—480	470—500	490—520	520—555	540—575	545—590
Elite	426—460	451—490	481—515	501—535	521—555	556—590	576—615	590—630

system with a maximum approximately at their age of 100—110 years (Fig. 5). Underestimation or ignoring of this factor of variability of the wood basic density, which was also revealed by foreign researchers (Fabisiak and Fabisiak, 2021), but for another, shorter range of tree age variation (5—75 years), are, in our opinion, one of the reasons for the contradictions that occur in the works of different authors.

The variability of values of wood basic density in trees in cenopopulations with age, as follows from the presented data, does not decrease with age, but, on the contrary, even tends to increase, which indicates the absence of natural selection of individuals by this parameter. The level of gene pool diversity is not disturbed during the establishment of forest cultures, because the variability of values of wood basic density in stands of natural and artificial origin is the same.

One of the important practical results of our research was the development of a scale for assessing trees by their sapwood density in cenopopulations of different ages, including very young ones (Table 6). It was developed on the basis of regression equations describing the trajectories of changes in the values of the estimated parameter deviating from the mean level by different values of standard deviation (S_ρ): single, double and triple. Trees with wood density from $M + S_\rho$ to $M + 2S_\rho$ can be conditionally considered as plus trees, from $M + 2S_\rho$ to $M + 3S_\rho$ -elite, and more than $M + 3S_\rho$ -super-elite.

Direct measurements of wood basic density values in the field are impossible, since the samples need to be kept for some time in a desiccator, bringing them to an absolutely dry state. Therefore, it is relevant to use modern methods and tools for non-destructive indirect determination of wood density in growing trees (Gao et al., 2017; Downes et al., 2018; Sharapov et al., 2024) or related reliable morphological traits of trees, as well as detection of DNA markers, which are the main objectives of our future studies.

CONCLUSION

Based on the analysis of literary sources and the empirical material we have collected, the following main conclusions can be drawn:

1) Basic density of sapwood varies in trees of Scots pine in the Mari Volga region from 291 to 660 kg×m^{-3}, overlapping the limits established by domestic researchers for the whole area of this tree species;

2) the value of sapwood density is practically not related to the width of annual rings of trees, the ratio of latewood in it, their rank position in cenopopulations, growing conditions, stand density and origin of stands, but depends mainly on the age and individual characteristics of trees, on the basis of which it is possible to carry out their target selection;

3) plantations and natural stands do not differ from each other in the average value and variation of basic sapwood density in trees;

4) basic density of sapwood interacted with tree age ($R^2 = 0.9$), reaching a maximum at 100—110 years of age, which is associated with changes in the thickness of tracheid walls, providing increased stability of the trunk to mechanical loads, which increase with increasing trunk length;

5) trees with different wood density have different ecological requirements to environmental conditions, which is clearly manifested in the dynamics of their radial annual growth;

6) natural selection of trees by wood density in cenopopulations does not occur, as evidenced by the tendency to increase the standard deviation of the value of this parameter as stands age;

7) targeted selection of trees by the value of wood basic density, which is practically unrelated to the width of their annual rings and competitiveness, should not lead to a decrease in the productivity of plantations.

ACKNOWLEDGEMENTS

The research work was supported by the Russian Science Foundation (RSF, No. 23-16-00220), https://rscf.ru/en/project/23-16-00220/ using equipment of the Core Facility Centre «Ecology, biotechnologies and processes for obtaining environmentally friendly energy carriers» of Volga State University of Technology, Yoshkar-Ola.

REFERENCES

1. *Agroklimaticheskie resursy Mariiskoi ASSR,* (Agro-climatic resources of the Mari ASSR), Leningrad: Gidrometeoizdat, 1972, 107 p.

2. Auty D., Achim A., Macdonald E., Cameron A.D., Gardiner B.A., Models for predicting wood density variation in Scots pine, *Forestry*, 2014, Vol. 87, No. 3, pp. 449—458. https://doi.org/10.1093/forestry/cpu005
3. Borovikov A.M., Ugolev B.N., *Spravochnik po drevesine* (Wood reference book), Moscow: Lesnaya promyshlennost', 1989, 296 p.
4. Byusgen M., *Stroenie i zhizn' nashikh lesnykh derev'ev* (The structure and life of our forest trees), Moscow: Goslesbumizdat, 1961, 424 p.
5. Danilov D.A., Smirnov A.P., Vliyanie struktury drevostoya na plotnost' drevesiny sosny i eli v chernichnom tipe lesa (Effect of stand structure on density of pine and spruce wood in myrtillus forest type), *Lesotekhnicheskii zhurnal*, 2014, No. 4, pp. 13—20.
6. Danilov D.A., Stepanenko S.M., Stroenie i plotnost' drevesiny eli i sosny v plantatsionnykh kul'turakh Leningradskoi oblasti (Structure and density of wood of spruce and pine in forest plantation of Leningrad region), *Izvestiya Sankt-Peterburgskoi lesotekhnicheskoi akademii*, 2013, Issue 204, pp. 35—45.
7. Demakov Y.P., Demitrova I.P., Nureeva T.V., Simatova T.Y., Vliyanie nachal'noi gustoty i intensivnosti izrezhivaniya drevostoya v kul'turakh sosny na prirost i plotnost' drevesiny (The effect of initial density and thinning intensity of a pine stand on growth and wood density), *Vestnik Povolzhskogo gosudarstvennogo tekhnologicheskogo universiteta. Seriya: Les. Ekologiya. Prirodopol'zovanie*, 2019, No. 2, pp. 26—40.
8. Demakov Yu.P., *Rezul'taty mnogoletnikh opytov po sozdaniyu i vyrashchivaniyu kul'tur sosny obyknovennoi v Respublike Marii El* (Results of long-term experiments on the creation and cultivation of Scots pine crops in the Republic of Mari El), Yoshkar-Ola: PGTU, 2022, 242 p.
9. Demakov Yu.P., *Vliyanie faktorov sredy na rost derev'ev v sosnyakakh Respubliki Marii El* (The influence of environmental factors on tree growth in pine forests of the Mari El Republic), Yoshkar-Ola: PGTU, 2023, 480 p.
10. Downes G.M., Lausberg M., Potts B., Pilbeam D., Bird M., Bradshaw B., Application of the IML resistograph to the infield assessment of basic Density in Plantation Eucalypts, *Australian Forestry*, 2018, Vol. 81, No. 3, pp. 177—185. https://doi.org/10.1080/00049158.2018.1500676
11. Fabisiak E., Fabisiak B., Relationship of tracheid length, annual ring width, and wood density in Scots pine (*Pinus sylvestris* L.) trees from different social classes of tree position in the stand, *BioResources*, 2021, Vol. 16, No. 4, pp. 7492—7508. https://doi.org/10.15376/biores.16.4.7492—7508
12. Gao S., Wang, X., Wiemann M.C. et al., A critical analysis of methods for rapid and non-destructive determination of wood density in standing trees, *Annals of Forest Science*, 2017, Vol. 74, 27 p. https://doi.org/10.1007/s13595-017-0623-4
13. Gil-Moreno B., Manso R., O'Ceallaigh C., Harte A.M., The influence of age on the timber properties and grading of Scots pine and larch in Ireland, *Forestry,* 2024, Vol. 97, No. 1, pp. 133—146. https://doi.org/10.1093/forestry/cpad027 *GOST 16483.1-84*.
14. Grinin A.S., Orekhov N.A., Novikov V.N., *Matematicheskoe modelirovanie v ekologii* (Mathematical modeling in ecology), Moscow: YuNITI-Dana, 2003, 269 p.
15. Groshev B.I., Sinitsyn S.G., Moroz P.I., Seperovich I.P., *Lesotaksatsionnyi spravochnik* (Forest Taxation Guide), Moscow: Lesnaya promyshlennost', 1980, 288 p.
16. Kimberley M.O., Cown D.J., McKinley R.B., Moore J.R., Dowling L.J., Modelling variation in wood density within and among trees in stands of New Zealand-grown radiata pine, *New Zealand Journal of Forestry Science*, 2015, Vol. 45, 22 p. https://doi.org/10.1186/s40490-015-0053-8
17. Kolobov N.V., *Klimat Srednego Povolzh'ya* (Climate of the Middle Volga Region), Kazan: Izd-vo Kazanskogo universiteta, 1968, 252 p.
18. Konofalska E., Kozakiewicz P., Buraczyk W., Szeligowski H., Lachowicz H., The technical quality of the wood of Scots pine (*Pinus sylvestris* L.) of diverse genetic origin, *Forests*, 2021, Vol. 12, No. 5, 619 p. https://doi.org/10.3390/f12050619
19. Konovalov D. Yu., *Kachestvo drevesiny kul'tur sosny v severnoi i yuzhnoi podzonakh taiga. Avtoref. diss. kand. s.-kh. nauk* (Quality of wood of pine crops in the northern and southern subzones of the taiga: author's abstract. Extended abstract of Candidate's agric. sci. thesis), Arkhangelsk, 2007, 16 p.
20. Krasnov A.V., Gurskii A.A., Izmenenie plotnosti drevesiny sosny v nasazhdeniyakh gosudarstvennoi zashchitnoi lesnoi polosy Orenburgskogo leskhoza (Pine timber density variations in the state forest shelterbelts of the Orenburg Forest enterprise), *Izvestiya Orenburgskogo gosudarstvennogo agrarnogo universiteta*, 2007, No. 3, pp. 42—44.
21. Kurnaev S.F., *Lesorastitel'noe raionirovanie SSSR* (Zoning of forest sites in the USSR), Moscow: Nauka, 1973, 203 p.
22. Kuz'min S.R., Osobennosti drevesiny u sosny obyknovennoi raznogo proiskhozhdeniya v geograficheskikh kul'turakh Zapadnoi i Srednei Sibiri (Wood features of Scots pine of different origin in the provenance trials in Western and Central Siberia), *Wood structure, properties and quality — 2018*, *in honor of B.N. Ugolev*, Proc. of The 6-th RCCWS International Symposium dedicated to the 50th anniversary of the Regional Coordinating Council of Wood Science, Krasnoyarsk, September 10—16, 2018, Novosibirsk: FUE "Publishing House SB RAS", pp. 126—130.
23. Kuzmin S.R., Rogovtsev R.V., Radial'nyi rost i dolya pozdnei drevesiny u sosny obyknovennoi v geograficheskikh kul'turakh v Zapadnoi i Srednei Sibiri (Radial growth and percent of latewood in Scots pine provenance trials in Western and Central Siberia), *Sibirskii lesnoi zhurnal*, 2016, No. 6, pp. 113—125.
24. Kuz'min S.R., Vaganov E.A., Anatomicheskie kharakteristiki godichnykh kolets u sosny obyknovennoi v geograficheskikh kul'turakh Priangar'ya (The Anatomic Characteristics of Scots Pine Tree Rings in Provenances in the Angara River Basin), *Lesovedenie*, 2007, No. 4, pp. 3—12.

25. Latsevich A.V., Svoistva drevesiny sosny obyknovennoi raznogo geograficheskogo proiskhozhdeniya (Properties of Scots pine wood of different geographical origins), *Trudy BGTU. Seriya: Lesnoe khozyaistvo*, 2001, Issue 9, pp. 143—146.

26. Lomov V.D., Sukhorukov A.S., Osobennosti anatomicheskogo stroeniya drevesiny sosny v kul'turakh s raznoi gustotoi posadki (Peculiarities of the anatomical structure of pine wood in crops with different planting densities), *Ekologiya-2007* (Ecology-2007), Conf. Proc., Moscow: MGUL, 2009, pp. 62—65.

27. Marushchak V.N., *Bioekologicheskaya kharakteristika klimatipov sosny obyknovennoi (Pinus sylvestris L.) v Kazakhstane. Avtoref. diss. kand. s.-kh. nauk*. (Bioecological characteristics of climatypes of Scots pine (*Pinus sylvestris* L.) in Kazakhstan. Extended abstract of Candidate's agric. sci. thesis), Ekaterinburg, 2007, 22 p.

28. Marushchak V.N., Maksimov S.A., Nasleduemost' mekhanicheskikh svoistv drevesiny u sosny obyknovennoi v geograficheskikh kul'turakh (Heritability of mechanical properties of Scots pine wood in provenance trials), *Vestnik Altaiskogo gosudarstvennogo agrarnogo universiteta*, 2014, No. 11, pp. 65—69.

29. Melekhov V.I., Babich N.A., Korchagov S.A., *Kachestvo drevesiny sosny v kul'turakh* (The quality of pine wood in crops), Arkhangelsk: Izd-vo Arangel'skogo gos. tekh universiteta, 2003, 110 p.

30. Mel'nik P.G., Savos'ko S.V., Stanko Ya.N., Dyuzhina I.A., Stepanova O.V., Geograficheskaya izmenchivost' produktivnosti i fiziko-mekhanicheskikh svoistv drevesiny sosny obyknovennoi (Geographic variability of productivity and physical and mechanical properties of Scots pine wood), *Lesnoi vestnik*, 2007, No, 6, pp. 33—38.

31. Ovodov A.V., *Kachestvo drevesiny sosny v nasazhdeniyakh, sozdannykh posevom i posadkoi: Avtoref. diss. kand. s.-kh. nauk* (Timber quality of pine plantations grown from saplings and from seeds. Extended abstract of candidate's agric. sci. thesis), Arkhangelsk: SAFU, 2010, 16 p.

32. Petrusha A.K., *Tekhnicheskie svoistva drevesiny osnovnykh porod BSSR* (Technical properties of wood of the main species of the BSSR), Minsk: Gosizdat BSSR, 1959, 151 p.

33. Podoshvelev D.A., Dinamika izmeneniya fiziko-mekhanicheskikh svoistv drevesiny sosny v zavisimosti ot gustoty (Dynamics of changes in physical and mechanical properties of pine wood depending on density), *Trudy BGTU. Seriya I. Lesnoe khozyaistvo*, Minsk: BGTU, 2008, Issue 14, pp. 143—146.

34. Poluboyarinov O.I., Fedorov R.B., Vliyanie klimaticheskikh faktorov na plotnost' drevesiny sosny obyknovennoi v lesnoi zone evropeiskoi chasti SSSR (The influence of climatic factors on the density of Scots pine wood in the forest zone of the European part of the USSR), *Izvestiya vuzov. Lesnoi zhurnal*, 1985, No. 2, pp. 5—9.

35. Poluboyarinov O.I., *Plotnost' drevesiny* (The density of wood), Moscow: Lesnaya promyshlennost', 1976, 160 p.

36. Revin A.I., Smol'yanov A.N., Starostyuk N.B., Fizikomekhanicheskie svoistva drevesiny kul'tur sosny razlichnoi gustoty posadki v Tambovskoi oblasti (Physical-mechanical Wood Properties of Pine Culture of Different Planting Density in Tambov Region), *Izvestiya vuzov. Lesnoi zhurnal*, 2010, No. 2, pp. 38—43.

37. Ryabokon' A.P., Litash N.P., Fiziko-mekhanicheskie svoistva drevesiny sosny v kul'turakh raznoi gustoty (Physical and mechanical properties of pine wood in plantations of different density), *Lesovedenie*, 1981, No. 1, pp. 39—45.

38. Sharapov E., Demakov Y., Korolev A., Effect of Plantation Density on Some Physical and Technological Parameters of Scots Pine (*Pinus sylvestris* L.), *Forests*, 2024, Vol. 15, No. 2, 233 p. https://doi.org/10.3390/f15020233

39. Shchekalev R.V., *Zakonomernosti stroeniya i svoistv drevesiny sosny obyknovennoi (Pinus sylvestris L.) v lesonasazhdeniyakh na evropeiskom severo-vostoke. Avtoref. diss. d-ra s.-kh. nauk* (Patterns of structure and properties of Scots pine wood (*Pinus sylvestris* L.) in forest plantations in the European northeast. Extended abstract of Doctor's agric. sci. thesis), Arkhangelsk, 2021, 40 p.

40. Šilinskas B., Varnagiryte-Kabašinskiene I., Aleinikovas M., Beniušienė L., Aleinikovienė J., Škėma M., Scots pine and Norway spruce wood properties at sites with different stand densities, *Forests*, 2020, Vol. 11, No. 5, 587 p. https://doi.org/10.3390/f11050587

41. Smirnov V.N., *Pochvy Mariiskoi ASSR, ikh genezis, evolyutsiya i puti uluchsheniya* (Soils of the Mari ASSR, their genesis, evolution and ways of improvement), Yoshkar-Ola: Marknigoizdat, 1968, 531 p.

42. Szaban J., Jelonek T., Okińczyc A., Kowalkowski W., Results of a 57-Year-Long Research on Variability of Wood Density of the Scots Pine (*Pinus sylvestris* L.) from Different Provenances in Poland, *Forests*, 2023, Vol. 14, No. 3, 480 p. https://doi.org/10.3390/f14030480

43. Tyukavina O.N., Klevtsov D.N., Drozdov I.I., Melekhov V.I., Plotnost' drevesiny sosny obyknovennoi v razlichnykh usloviyakh proizrastaniya (Wood Density of Scots Pine in Different Growth Conditions), *Izvestiya vuzov. Lesnoi zhurnal*, 2017, No. 6, pp. 6—64. DOI: 10.17238/issn0536-1036.2017.6.56.

44. Usol'tsev V.A., Tsepordei I.S., *Kvalimetriya fitomassy lesnykh derev'ev: plotnost' i soderzhanie sukhogo veshchestva* (Qualimetry of forest tree biomass: density and dry matter content), Ekaterinburg: UGLTU, 2020, 178 p.

45. Zaitsev D.A., *Vliyanie struktury khvoinykh dendrotsenozov na stroenie i plotnost' drevesiny sosny i eli. Avtoref. dis. kand. s.-kh. nauk* (The influence of the structure of coniferous dendrocenoses on the structure and density of pine and spruce wood. Extended abstract of Candidate's agric. sci. thesis), Saint Petersburg, 2018, 20 p.

46. *Zaitsev G.N., Matematicheskii analiz biologicheskikh dannykh* (Mathematical analysis of biological data), Moscow: Nauka, 1991, 183 p.

47. Zhilkin B.D., K voprosu o vliyanii uslovii mestoproizrastaniya na anatomicheskoe stroenie, fizicheskie i mekhanicheskie svoistva drevesiny sosny (On the influence of growing conditions on the anatomical structure, physical and mechanical properties of pine wood), *Trudy Bryanskogo lesnogo instituta*, 1936, Vol. 1, pp. 29—56.