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DENSITY OF WOOD OF PINE-TREE AND SPRUCE IN THE MIXED MATURE FORESTS OF THE NORTH-WEST RUSSIA BOREAL ZONE

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Abstract
The influence of coniferous stand composition on the density of pine (*Pinus sylvestris*) and spruce (*Picea abies*) wood is considered in this work. Processing of a large quantitative material of wood cores with the use of the ANOVA and rank analysis made it possible to reveal the influence on the macrostructure of wood of the quantitative representation of pine and spruce in the stand.
In the pine part of the stand, the correlation of the wood density with the zones of early and late xylem is weak or medium. There is no wood density correlation with the width of the annual ring for stands with different shares of pine. In pine-prevailing stands with a share of pine 80% – 100%, there is a weak but reliably straight relationship between wood density and the size of late wood zone and an inverse relationship with early zone of xylem. For forest stands with a smaller part of pine participation, the relationship between these indicators is medium and reliable.
For spruce, we observe a close relationship between the density of xylem and the parameters of its macrostructure in all its variants of participation in mixed coniferous plantations. In most of the studied mixed stands, the density of wood in spruce is not significantly differentiated and more homogeneous.
Key words: basic wood density, early and late wood zone, width of annual ring.

Introduction

In conifer forests, different in their origin, at certain age stages, the wood is formed with different physical and mechanical properties, which are connected with its structure, i.e. width of annual ring and parts of the early and late xylem. With the age, the density of wood grows till a certain stage and then it stabilizes and (or) begins reducing. It was noted that for the pine-tree, in conditions of the North-West Russia, the density of wood may grow until the age of 100-120 years, and for the spruce – even until older age, depending on the geographic zone (Poluboyarinov, 1976; Chibisov, 2010; Danilov & Skupchenko, 2014). But reduction of density of the spruce-tree wood is possible and typical, if the spruce grows in a mixed forest. Abroad, this topic has evoked a vast response among researchers, which has been confirmed by many authors in their papers. . In the Scandinavian countries, this matter was studied by Repola (2006), Jyske (2008), Kanninen (2010), Gamfeldt et al. (2013), Carnol et al. (2014). In the countries of Central Europe it was done by Zianis et al. (2005), Pretzsch & Schütze (2016). In North America, a number of authors conducted research on wood density in mixed forests: Zhu, Scott & Myers (2007), Woodall et al. (2015). In the South Asian region, also a number of papers were dedicated to wood density in conifer types in multi-specific forests: Fujiwara, Yamashita & Hirakawa (2004), Nakagawa et al. (2016).

For the forests of the boreal belt, the influence of mixed forests of pine-tree and spruce-tree upon the wood density and anatomic structure of xylem of these species in fact found the reflection only in Lomov's paper (1979), and there are no other publications on this matter for this zone. On the whole, the mechanism of xylem density formation at the anatomic level in mixed forests has not been covered deeply enough. On the basis of the above mentioned, it was decided to study the influence of mixed pine and spruce stand composition on the formation of the anatomical structure and wood density of these species.

Materials and Methods

We studied coniferous forests with different parts of participation of pine-tree and spruce-tree in the main groups of forest type of the Leningrad region. The main objects of the research are permanent plots in the territory of the experimental forestry "The Siversky forest" in the Gatchina forestry of the Leningrad region: Kartashevskoe, Orlinskoe, Druzhnoselskoe, Divenskoe, and Ontsevskoe district forestries. Permanent plots were started in the 1960s in the forests, and they were used for continuous stationary observations of the dynamics of taxational values and consideration of quantitative and qualitative changes in forestry-taxation characteristics of plantations. The experimental plots have the dimensions from 0.25 to 0.5 ha, and no forestry activities were conducted in them.

The experimental materials for the research were obtained on 26 sample areas in the mature pine-prevailing forests aged 85 – 105, without cutting, with different parts of participation of spruce-tree and with a smaller part of broadleaved species (aspen and birch). All plots have long-term data on repeated accountings. When selecting kernels, the Pressler's borer was used at a tree height of 1.3m. Two kernels were selected from each model tree. The number of the model trees depended on the diameter class distribution of the conifer species. The diameter of kernels used for the analysis was 4 – 5 mm. One of two kernels was used for the anatomical analysis whereas the other one was used to measure wood density. Basal density of wood is expressed by proportion (1.2) of the mass of absolutely dry species m_0 to its volume at humidity equal or higher than the fiber saturation point V_{max}:

$$\rho_b = \frac{m_0}{V_{\max}}\text{, kg m}^{-3} \quad (1)$$

$$\rho_b = \frac{1}{\frac{m_w - m_0}{m_0} + \frac{1}{d}}\text{, g cm}^{-3} \quad (2)$$

The measuring of this value was conducted with the maximum humidity method recommended by Poluboyarinov (1976) to define the density of species having a comparatively little volume. On the species of wood, along with density, the number of annual layers in 1 cm was defined, average width of annual rings and content of late wood in an annual ring was defined. The following parameters were used to characterize the wood macrostructure: a radial growth or annual ring width, early wood width, late wood width of a wood species for the period of tree life. The values were defined on 24 to 30 samples of wood per plot from the provided species on the experimental areas, depending on the diameter class representation. The prepared kernels were polished and processed on a scanning device with resolution 1200 dots per inch, getting high-resolution pictures. Further, the GIS treatment of early and late wood zones was conducted with scaling of kernel length in the annual ring for the period of growth by means of the program “Panorama 10”. The reliability of this information is assessed by means of statistical processing of digital material obtained as a result of the purposefully planned experiment. To define the reliable differences or similarity of the data obtained, ANOVA, rank and correlation analyses of information were used.

Results and Discussion

The processed digital material of quantitative and qualitative parameters of wood kernels of pine-tree and spruce-tree was grouped depending on the representativeness of species in the composition of plantation. The conducted analysis of information in the program ambience “Statistica 11” allowed detecting the significant regularities of influence of the forest composition on the xylem macrostructure and its density at the examined species. Statistical reliability of differences of values of the wood macrostructure in the plantations of different species composition is manifested in different ways for the pine-tree and spruce-tree part of plantation. For pine-tree cenoses, the manifestation of differences in the content of the late xylem part depending on its representativeness is traced in all forests (see Table 1). But in the versions with the part of participation of pine-tree from 60% to 40%, no significant differences are traced, which is apparently connected with reduction of quantitative representativeness of pine-trees in the forest. For the value of content of early wood in the annual ring width, there are in fact no unreliable differences in the forests with different part of participation of pine-tree, and it is connected with active formation of the conducting xylem in the pine-tree as a biological species. Since the zone of early wood prevails in the annual ring width, so we observe here the analogical correlation with the composition of plantation. With reduction of the part of participation of pine-tree, no reliable differences of wood density are observed in connection with the too weak variability of wood density on the stages of the width of the pine-tree plantation.

For the spruce-tree element of the forest, somewhat different regularities are observed than those for the pine-tree part of cenosis: at the level of wood macrostructure of spruce-tree with its participation in the composition of the mixed forest, in fact no significant differences are manifested on content of early xylem in the annual ring (see Table 2). In two cases when there are no significant differences revealed, probably either there is very little representativeness of spruce-tree in the forest composition, or, on the contrary, there is obviously equal number of spruce in the composition of the mixed forest. For the value of the early wood content in the annual ring, a different situation can be observed. With reduction of spruce-tree in the composition, the reliable difference on mixed coniferous plantations is observed.

For the forests with participation of pine-tree from 70% to 40%, in fact no reliable differences are observed on the content of early wood in the annual ring, since it is connected with the fact that the part of spruce-tree is 30 – 40%, and the broadleaved species, aspen and birch, are represented in the forests. But an interesting regularity is manifested about unreliable difference on the annual ring width for the forests with participation of pine-tree 70 – 60%, and spruce-tree 20 – 30%, probably the conditions of growth of spruce-tree in these forests are equal and the variability of the annual ring is not high. The changes at the level of xylem microstructure of spruce-tree lead to regular influence at the level of its wood density. For the spruce-tree, in connection with reduction of quantitative representativeness of pine-tree, the dimensionality of the distribution row on the stages of the forest increases, and with that, the variability of wood density of spruce-trees also increases compared with the forests where over two thirds are pine-trees in the composition.

Table 1

Statistical reliability of differences of the values of macrostructure and density of the pine-tree wood depending on composition of the forest

Reliable differences in the content of the late pine wood for the forests where pine prevails						
Composition	10P	9P	8P	7P	6P	5P
10P	-					
9P	1	-				
8P	1	1	-			
7P	1	1	1	-		
6P	1	0	1	1	-	
5P	1	1	0	1	1	-
4P	1	0	1	1	0	1
Reliable differences for the content of early pine wood for the forests where pine prevails						
10P	-					
9P	1	-				
8P	1	1	-			
7P	1	1	1	-		
6P	1	0	1	1	-	
5P	1	1	1	0	1	-
4P	1	1	1	1	1	1
Reliable differences for the annual ring width of pine wood for the forests where pine prevails						
10P	-					
9P	1	-				
8P	1	1	-			
7P	1	1	1	-		
6P	1	0	1	1	-	
5P	1	1	1	0	1	-
4P	1	1	1	1	1	1
Reliable differences for pine wood density for the forests where pine prevails						
10P	-					
9P	1	-				
8P	1	1	-			
7P	0	1	1	-		
6P	0	0	1	0	-	
5P	1	0	0	1	0	-
4P	1	1	0	1	1	0

Note: "P" – pine; "1" – differences are statistically significant at $p<0.05$; "0" – differences are statistically insignificant at $p<0.05$.

To detect the statistically significant correlations between the wood macrostructure of pine-tree and spruce-tree, the rank correlation analysis was conducted. The obtained data of statistical values on the Spearman's criterion given in Table 3 show that, depending on the part of participation of the species in the composition, a number of reliable correlations between the wood density and the zones of early and late xylem were detected. For the forests in which pine-tree accounts for 80% – 100%, the connection between the wood density and the late xylem zone is weak but reliable, whereas this connection is invalid for the wood density and the early xylem zone. For the forests in which pine-tree accounts for less than 80% the correlation between these values is moderate and reliable. The rank analysis did not detect reliable

Table 2

Statistical reliability of differences of values of macrostructure and density of spruce-tree wood depending on the forest composition

Reliable differences for the content of late spruce wood for the forests with pine prevailing					
Composition	9P	8P	7P	6P	5P
9P(1S)	-	-	-	-	
8P(2S/1S1B)	1				
7P(3S/2S1B/1S2B)	1	1			
6P(4S/3S1B)	0	1	1		
5P(4S1B/3S2B/2S1B1A)	0	1	1	0	-
4P(4S1B1A/1S4B1A)	1	1	1	1	1
Reliable differences for the content of early spruce wood and the forest composition					
9P(1S)	-	-	-	-	-
8P(2S/1S1B)	1				
7P(3S/2S1B/1S2B)	1	0			
6P(4S/3S1B)	1	0	0		
5P(4S1B/3S2B/2S1B1A)	1	0	0	1	
4P(4S1B1A/1S4B1A)	0	1	1	1	1
Reliable differences for the annual ring width of the spruce wood and the forest composition					
9P(1S)	-	-	-	-	-
8P(2S/1S1B)	1				
7P(3S/2S1B/1S2B)	1	0			
6P(4S/3S1B)	1	0	0		
5P(4S1B/3S2B/2S1B1A)	1	1	1	1	
4P(4S1B1A/1S4B1A)	0	1	1	1	1
Reliable differences of spruce wood density in the forests and the forest composition					
9P(1S)	-	-	-	-	-
8P(2S/1S1B)	0				
7P(3S/2S1B/1S2B)	0	0			
6P(4S/3S1B)	1	1	1		
5P(4S1B/3S2B/2S1B1A)	1	1	1	0	
4P(4S1B1A/1S4B1A)	0	0	1	0	0

Note: "P" – pine; "S" – spruce; "B" – birch; "A" – aspen; "1" – differences are statistically significant at $p<0.05$; "0" – differences are statistically insignificant at $p<0.05$.

connection with the annual ring width at pine-tree for the both groups. The obtained results indicate that the wood density of pine-tree correlates with microstructural anatomic parameters of xylem at the level of construction of cellular structures and their amount in the growth zones. For the spruce-tree, the obtained results indicate that with its less representativeness in the mixed forest, the correlation with the values of macrostructure and wood density of the spruce-tree is close. With increase of participation of the spruce-tree in the composition of the mixed plantation, these correlations are somewhat weaker that in the forests with higher participation of spruce-tree. Manifestation of different strategies of formation of the wood density of pine-tree and spruce-tree finds its reflection in the correlations at the level of xylem structure of these species.

Table 3

Rank analysis of correlation of macrostructure and density of the wood density of pine-tree and spruce-tree in the mixed forests (by Spearman's criterion)

Pair of Variables	For the pine-tree with its prevalence in the forest composition							
	80% – 100% in the composition				70% – 40% in the composition			
	Valid N	Spear-man R	t(N-2)	p-value	Valid N	Spear-man R	t(N-2)	p-value
late wood zone & basic wood density	108	0.311	3.371	0.0011	86	0.439	4.481	<0.001
early wood zone & basic wood density	108	-0.311	-3.371	0.0011	86	-0.439	-4.481	<0.001
annual ring width & basic wood density	108	0.098	1.015	0.313	86	-0.142	-1.318	0.191
for the spruce-tree in the forest composition with pine-tree prevailing								
late wood zone & basic wood density	65	0.745	8.873	<0.001	87	0.678	8.499	<0.001
early wood zone & basic wood density	65	-0.745	-8.873	<0.001	87	-0.678	-8.499	<0.001
annual ring width & basic wood density	65	-0.654	-6.858	<0.001	87	-0.501	-5.330	<0.001

Note: marked correlations are significant at p<0.05.

Conclusions

The following conclusions can be made on the results of the research conducted:

1. In the mixed conifer forests with pine-tree prevailing, the formation of xylem of pine-tree and spruce-tree has a different strength of correlation with the forest composition.
2. Reliable differences in the influence of the plantation composition on the wood macrostructure are more clearly observed on pine-trees. The wood density reliably depends on the forest composition with participation of pine-tree over 60%.
3. For the spruce-tree part of the mixed conifer forests, reliable correlation of the influence of the plantation composition is observed only in the zone of late wood in the annual ring. For the early wood zone, this dependence has a lower level of correlation. In fact, there is a reliable connection between the composition and the value of the annual ring for spruce-tree wood observed in all forests.
4. Influence of the forest composition on the spruce-tree wood density is detected in the stands with smaller participation of broadleaved species. In other coniferous stands, the values of spruce-tree wood density are rather homogenous. This fact can be considered as a competitive impact of the pine-tree layer on the limited variability of this parameter.
5. For the pine-tree, the correlation of wood density is weak or medium with zones of early and late xylem on the forests with different parts of pine-tree participation. This correlation is not observed with the length of the zone of the annual ring. For the spruce-tree, we observe a close correlation between the xylem density and the values of its macrostructure in all sample stands with spruce-tree participation.
6. Depending on the part of participation of pine-tree and spruce-tree, the wood of these species is formed with a different variability degree in the zones of the annual ring and the xylem density.

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