The effect of tree distribution by diameter classes on the density of pine and spruce trees in mixed coniferous forest stands without forestry impact

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Abstract. In this paper, we consider the influence of tree distribution rows by the diameter classes on the wood density of pine and spruce in coniferous stands not covered by felling. Dependences of the wood density in pure and mixed coniferous stands were studied with changes in the composition of the stand and the quantitative representation of pine and spruce trees by diameter classes. On the basis of the obtained quantitative material, the relationship between the density of wood and trunks thicknesses was modeled according to the diameter classes of pine and spruce trees. The developed regression equations make it possible to predict the density changes of pine and spruce wood in stands with different shares of their participation.

1. Introduction

Mixed stands of pine and spruce are widespread in the boreal zone. Such stands grow in the most productive conditions; they are distinguished by high productivity and resistance to unfavorable factors in comparison with pure coniferous stands [1, 2]. The predominance of one or another species in a mixed coniferous forest stands can have an impact on the forest ecosystem relationships and the formation of stem biomass of pine and spruce trees [3, 4].

The distribution of tree rows according to the diameter classes and the completeness of the stand in general determine the phytomass of the stand, as noted in previous studies [5-7]. Close attention is paid to modeling for understanding and predicting how species interaction factors will affect the growth, productivity and other functions of forests in mixed stands [4]. For the systematization of data on the differentiation of trees in the stand and their influence on productivity, various mathematical models for mixed stands were developed [8, 9]. These models allow predicting the dynamics of stand phytomass taking into account the spatial position of trees or their groups and the species composition. Allometric equations for the estimation of phytomass of dendrocenoses and individual trees in the forest are widely used in ecological and silvicultural researches [9, 10]. Models for pure plantations at the stand level are simpler and more generalized alternative to models of interaction within mixed stands [3]. Nevertheless, many processes occurring in pure stands can also be modeled at the level of...
mixed stands. However, these models often do not sufficiently take into account the interaction between species in a mixed stand [4].

Models describing the productivity of the stand must take into account not only the features of the structure of the plantations, but also the ecosystem parameters (light, water, terrain). However, only the effect of mixing coniferous species in a certain area can give a significant increase in productivity, due to the different ecological niches occupied by the different species. Moreover, in other forest-typological conditions this effect may be much weaker [11], so we studied pine and spruce stands in the most productive polytrichum group of forest types.

When studying interactions in mixed coniferous stands, an important aspect is the scaling of processes from the level of physiology and intraspecific variability at the tree level to the level of the external structure of the plantations, i.e. species composition, distribution row of trunks by the diameter classes [7, 12]. It is important to know what changes in the structure and composition of the stand during forest management will lead to the change in the wood density of pine and spruce in one direction or another. On this basis purpose of the study was to determine how the external structure of the stand (i.e., the stand composition and distribution of the trunks by diameter classes) affected on the density of pine and spruce wood in stands with different composition.

2. Experimental part
The objects of the study are natural formed pure and mixed stands in the polytrichum group of forest types with dominance of pine (Pinus sylvestris) and spruce (Picea abies) 100-120 years old. These permanent registration objects (44 trial plots total) were not affected by forestry impact. They are located on the territory of the Leningrad region in the Gatchina forestry, Russia (59°N 30°E).

Methods of research
A continuous counting of trees on 4-fold diameter classes was carried out on experimental objects according to generally accepted methods. The selection of wood samples was carried out on model trees, at least 25-30 samples per plot (depending on diameter class representation). Sample kernels were taken from 1.3m tree height with Pressler’s borer. The determination of the basis density of pine and spruce wood samples was carried out using the maximum moisture method [13, 14]. According to the conversion equations proposed for the studying region [14], the basis density at a height of 1.3m was calculated to the basis density of the whole trunk.

The relationship between the diameter classes representing of the stand and the basis wood density can be presented as three-dimensional scatter diagrams. To approximate the point values of the function on that scatter diagrams the method of least squares for polynomial models was used [15], which is one of the basic regression analysis methods for estimating unknown parameters of regression models from sample data. The application of the method consists in finding the values of the model coefficients, which correspond to the smallest value of the function of these two values. This method shows at what coefficients the sum of the squared deviations of the experimental data from the constructed model will be the smallest [15, 16]. Processing of quantitative data was carried out using the application package “Statistica 10” at a confidence level of 95%.

3. Result and discussion
As a result of the study of the basis wood density in pine stands with different shares of its participation, it can be observed that in stands with a share of 70-80% of pine, the density of its wood is the highest (Figure 1). For conditionally pure pine stands, for the most represented diameter classes, a pronounced dependence of the wood density of the diameter class on its participation share in the stand composition is observed. The high wood density of the lowest diameter classes seems to be associated with the small annual growth of xylem. And in the extreme large diameter classes the higher wood density is associated with the age differences of these trees. In stands with a share of pine from 70 to 80% in the composition, we can observe a slightly different picture. In fact, the densest wood is formed in smaller diameter classes from 12 to 20 cm. Medium diameter classes (from 24 to 36 cm) tend to decrease the density of wood from a larger to a smaller diameter class. In stands with a
share of pine 50-60% in the composition there is a uniform decrease in the wood density, from 462 to 402 kg/m³, from smaller to larger diameter classes. In the largest diameter classes, we observe a smooth increase in the density of pine wood from 40 to 52 cm (413-440 kg/m³).

**Figure 1.** Diameter classes distribution and density of wood in pine-prevailing stands on experimental objects.

In stands with a prevalence of spruce, the distribution row of the trunks by the diameter classes has a left displacement, which is associated with a greater representation of small diameter trees (Figure 2). However, a row of spruce trees have a longer extension by the presented diameter classes than in pine-prevailing stands. The most presented diameter classes of spruce (16-28 cm) tend to increase the wood density, depending on the quantitative representation. In the largest diameter classes (36-52 cm), the smallest wood density of spruce is observed. With a decrease in the proportion of spruce in stand composition to 70-80 %, an increase in the wood density in the diameter classes from 28 to 48 cm is observed (from 461 to 475 kg/m³). However, the highest wood density of spruce (as well as in conditionally pure stands) is observed in the smallest diameter classes of 12-16 cm. Such values of the wood density of spruce by the diameter classes of the stand can be explained by the shape of the distribution row, where the quantitative distribution of spruce trunks tends to decrease from medium to large diameter classes. It should be noted that in stands with 50-60% of spruce in the composition, the most extended distribution row of trees by the diameter classes is observed – from 12 to 68 cm (Figure 2). With a decrease in the share of spruce, the distribution row of its trees by the diameter classes acquires an inverse exponential distribution, in which 40% of the trees are represented in diameter classes of 12-16 cm. The change in the wood density of spruce according to the diameter classes actually coincides with the curve of the distribution row of its trunks (Figure 2). The density of wood in studied stands is higher than the average for the region [14]. This can be
explained by the fact that the average wood density for the region is calculated in pure stands and the species mixing play its role in wood density increasing.

![Figure 2](image.png)

**Figure 2.** Diameter classes distribution and density of wood in spruce-prevailing stands on experimental objects.

The obtained quantitative and qualitative data of diameter classes and wood density distribution allow us to predict the direction of the increase or decrease in the wood density, depending on the external structural indications of the stand.

On the basis of the data obtained, according to the method of least squares, we developed equations for the dependence of the wood density on two parameters of the stand structure – the quantitative representation of trees according to the diameter classes and tree diameter. In our case, a polynomial of the second degree is fitted to the points of the three-dimensional scattering diagram, where the argument “A” is the diameter class, cm; argument “B” – the representation of the diameter class, %. Instead of the points of the original data, a surface is represented on statistical charts of this type, representing a smoothed image of the data obtained by one of the possible procedures of fitting or transformation.

For conditionally pure pine stands, which are not affected by forestry influence, the relationship between the medium basis wood density ($\rho_{\text{med.basis}}$, kg/m$^3$) and the quantitative representation of trees by the diameter classes in the stand can be expressed in the form of equation:

$$\rho_{\text{med.basis}} = 328,17 + 18,15 \cdot A - 16,75 \cdot B - 0,37 \cdot A^2 + 0,06 \cdot A \cdot B + 0,44 \cdot B^2$$

(1)

For stands with a share of pine 70-80 % of composition, the equation obtained is as follows:

$$\rho_{\text{med.basis}} = 561,25 - 5,51 \times A - 4,69 \cdot B + 0,06 \cdot A^2 + 0,13 \cdot A \cdot B + 0,04 \cdot B^2$$

(2)

For stands with a share of pine 50-60 % of composition:
\[ \rho_{\text{med.basis}} = 541.73 - 9.34 \cdot A - 4.27 \cdot B + 0.13 \cdot A^2 + 0.04 \cdot A \cdot B + 0.14 \cdot B^2 \] (3)

Graphically, the relationship between the wood density (“Z” axis) and the structural indicators of the stand can be expressed by a three-dimensional surface diagram (Figure 3). The change in the surface curve occurs to a greater extent in the index of the diameter class (“A”) and, to a lesser extent, in the quantitative representation of the diameter class (“B”). Comparative analysis of calculated data on the wood density with measured actual data showed a good descriptive ability of diagrams. (coefficient of determination \( R^2 = 0.80 - 0.90 \); standard error of the mean is 4.5 - 6.0). Consequently, for pine stands, the resulting relationship between these parameters and the wood density can be used for approximate calculation without sampling the wood.

\[ \rho_{\text{med.basis}} = 494.78 - 0.56 \cdot A - 6.69 \cdot B + 0.04 \cdot A^2 + 0.03 \cdot A \cdot B + 0.25 \cdot B^2 \] (4)

Figure 3. Relationship between the wood density (“Z” axis), diameter class (“A”) and diameter class representing (“B”) in pine-dominating stands on experimental objects.

For conditionally pure spruce stands, the relationship between the density of its wood and the quantitative representation of trees by the diameter classes in the stand can be expressed in the form of equation:

\[ \rho_{\text{med.basis}} = 494.78 - 0.56 \cdot A - 6.69 \cdot B + 0.04 \cdot A^2 + 0.03 \cdot A \cdot B + 0.25 \cdot B^2 \] (4)

Article I. Comparative analysis of the calculated data on the wood density and the measured data for this indicator have a determination coefficient \( R^2 = 0.84 \) (standard error of the mean is 5.2), which indicates a good descriptive ability of the diagram. Graphically, the relationship is expressed by a three-dimensional curved surface (Figure 4).
Figure 4. Relationship between the wood density (Z axis), diameter class (A) and diameter class representing (B) in conditionally pure spruce stands on experimental objects.

An attempt to simulate the graphic dependence of the stand structure parameters with the wood density of spruce in stands with a share of spruce less than 80% did not lead to positive results. In stands with a lesser share of spruce in the composition, the relationship is not described by this modeling method, since it has a more complex relationship between the qualitative and quantitative characteristics of the stand structure being investigated. This is due to the fact that the distribution rows by the diameter classes of the spruce stand, with the share of other species, do not have a pronounced normal distribution of spruce trunks, as noted above.

The composition of the stand is an integral value, which reflects the change in its taxation indicators, such as diameter classes distribution. In our opinion, when sampling homogeneous objects, exactly differences in species composition are important to study the wood density. So, in this case, we can explain the variation in wood density in the stands of different compositions by changing the quantitative representation of trees by diameter classes. The obtained calculations showed satisfactory similarity with the results of other authors [2, 4]. However, it’s not necessary to discard other parameters which can affect the wood density and do not depend on soil or climatic conditions. For example genetic variability of tree species or trees distribution on the plots may have an impact on the wood structure [1, 3, 6], but that parameters were not included in our study objectives. Some of the studies conducted on varying the phytomass of the trees by diameter classes showed clearer relationships with the developed allometric equations [5, 10]. In our case for a more accurate calculation of phytomass, we will need to cut down model trees on our experimental objects, which may be carried out later.

4. Conclusion

According to the results of the study, the following conclusions can be drawn:
- With a decrease in the quantitative representation of the diameter classes in the distribution row of the pine stand, we observe the formation of less wood dense.
- In the spruce stands, the density of spruce wood decreases with increasing diameter class.
- Modeling of wood density parameters with the parameters of the quantitative representation of trees in the stand by the method of least squares of three-dimensional scattering diagrams gives a positive result for pine stands with different shares of its participation in the composition.
- In conditionally pure tree stands, there is a close relationship between the obtained graphical dependencies and the calculated regression equations, which is related to the close to normal row distribution by the diameter classes in such stands.
In stands with a share of spruce less than 80%, the relationship is not described by this modelling method, since it seems to have a more complex character of the relationship between the wood density with others inside and the external structure indicators of the stand.

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