Density formation along the trunk radius in various wood species based on latitudinal or altitudinal zoning

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Abstract. Wood is a material characterized by anisotropy of structure and variability of properties in the tree trunk. The indicators of wood properties can be predicted by the density value. Wood density formation in a tree trunk is influenced by many factors. The most important are: age changes, the position in the trunk and the impact of the environment. The purpose of this study is to establish the regularity of wood density formation along the trunk radius. Regularity is based on growing conditions and latitude zoning for Scots pine (Pinus sylvestris L.) and altitude zoning for European chestnut (Castanea sativa Mill.). The studies have been performed on cores including wood sections from bark to core obtained using coring instrument. Density of each annual layer by measuring buoyancy force of specimens immersed in a liquid was determined. The formation features and periods of the maximum density of pine and chestnut wood along the trunk radius were established based on latitudinal and altitudinal zoning of wood in the temperate continental climate of the European part of Russia.

1. Introduction
Wood is a material of biological origin, which is characterized by anisotropy of structure and variability of properties in the tree trunk. Variability of physical and mechanical properties of wood connecting with the efficiency of process flows of its processing, the quality and durability of products, can be predicted by the density value.

Wood density is a universal indicator determining many properties of wood [1]. Wood density formation highly depends on age changes, the position in the trunk, and the impact of the environment (latitude and altitude zoning).

Over the past few decades, a number of studies have been devoted to the influence of climate conditions on wood density. The studies considered artificial plantations of pine wood growing in the same environmental conditions [2, 3] and the influence of climatic factors on the stand, taking into account the interaction of main rocks and undergrowth also in the same climate zone [4-8]. There are studies covering coniferous stands of North American boreal forests [9, 10] and deciduous plantings [11]. Several papers describe the influence of zoning and climatic change on forest mountain ecosystems of Central Asia [12]. During the studies the researchers have found the influence of climate and latitude zoning on stands for various species growing in the North of the European part [13] and the East of the Russian Federation [14] in various climatic conditions.
Over the past few decades, a number of studies have been devoted to the formation of wood density in ontogenesis. Density is greatly influenced by stand density, which affects the age of juvenile wood transition to mature wood and more rapid increase in wood density from the core outward [2, 3]. The formation of density at an early age is greatly influenced by climatic conditions. The role of climatic conditions on the density formation in the stands of the southern taiga (forest-steppe) is particularly important and variability of weather conditions is a determining factor in the variability of growth in the forest-steppe [4]. Available research was carried out in the forests at the initial stage of density formation or in plantations, but influence of climate on the formation of wood structure is not so significant in more humid climatic conditions [5].

The influence of climatic factors on the density of wood in the stands with varying degrees of dominance of individual tree species, as well as taking into account the mutual influence of dominant species and underbrush, has been considered. The obtained results show that the relationship between wood density and climate is influenced by the differences in the social status of trees within the stand [6-8] and the influence of climatic factors on the tree species of one functional group is insignificant [9-10].

Formation of wood structure and density is influenced by altitude zoning: amount of precipitation is the determining factor for growth (in these conditions). The fact is that humidity becomes the dominant factor with increasing altitude [11, 12] and the formation of wood density in the northern and middle taiga depends on latitude zoning and climatic region. Growing conditions become more severe with an increase in latitudinal zoning in the area of temperate continental climate. So, the qualitative indicators of plantations decrease [13]. In the area of the monsoon climate, in the same zonal distribution (eastern regions of the Russian Federation), an increase in latitudinal zoning contributes to the increase in the wood density of the stands [14].

Currently, there is little information about the influence of climate conditions and latitude zoning in the Central European part of the Russian Federation on pine plantations. Questions on the influence of climate zoning on the stands of valuable wood species growing in the mountains of the North Caucasus are covered very poorly. Therefore, the purpose of this study is to characterize the regularities of wood density formation along the trunk radius, taking into account the growing conditions and latitude zoning for Scots pine (Pinus sylvestris L.) wood in the Central European part of Russia and high-altitude zoning for European chestnut (Castanea sativa Mill.) wood in the North Caucasus mountains.

The established relations between the formation of wood quality and growing conditions can be useful when selecting areas for its primary artificial re-establishment, selecting high-yielding stands of wood species and harvesting wood with specified properties.

2. Materials and methods
The study of density formation in the region of a temperate continental climate, taking into account the geographical zoning, was carried out on the coniferous wood of Scots pine (Pinus sylvestris L.). European chestnut (Castanea sativa Mill.) was taken for high-altitude zoning. More detailed knowledge of this density variability can help improve the assessment of wood quality.

Pine wood was selected in the conditions of the southern border of forest steppe zones (the first test plot was in Voronezh region, Educational and Experimental Forestry of Voronezh State University of Forestry and Technologies named after G.F. Morozov (52 °N and 39 °E)). The selected site belongs to the moderate continental type of climatic conditions. The type of growth conditions for the southern border of the forest steppe was taken into account by selecting test areas in dry pine forest (A1) and fresh subor (B2) conditions. Dry forest is considered to be less favorable for the growth and development of plants compared to the conditions of fresh subor. Pine plantation aged 125 years with the height of 25 m. Trees, belonging to the II site class, had the diameter of 36 cm.

The second test plot was located in the southern taiga zone: the South-Western part of the Vologda region, Ustyzhanskiy special forestry (58°50' N and 36°5' E).The climatic zone of the selected site is moderate continental one. The type of growing conditions was fresh subor (B2) with grass subor and
oak (SBT-2). The forest consisted of 125 years plant with the average height of 26 m. Trees, belonging to the II site class, had the diameter of 44 cm.

Two types of growth conditions were selected for the southern taiga zone: lichen pine forest and blueberry-cranberry pine forest. Lichen pine forest consisted of 140 years old plants with the average height of 20 m. Trees, belonging to the III site class, had the diameter of 26 cm. Blueberry-cranberry pine forest consisted of 140 years old plants with the average height of 23 m. Trees, belonging to the III site class, had the diameter of 28 cm. Blueberry-cranberry pine forest is considered to have more favorable growing conditions for Scots pine.

Chestnut (in conditions of natural growth, in Russia) is found only in the Caucasus, growing at the altitude from 200 to 1500 m above sea level. At the altitude of 200 to 600 m above sea level, the chestnut stands are found only at the base of the slopes. Narrow shady gorges with high humidity are the most favorable conditions for growing, and chestnut successfully competes with oak at the upper limit of distribution line and goes to the southern slopes.

The forests of the Tuapsinsky district of the Krasnodar territory in Pshishsky forestry were selected to study the influence of vertical zoning on the structure of chestnut wood. They are located on the North-Eastern slopes of the Main Caucasian ridge, which corresponds to 44 °N and 38 °E. We selected areas of naturally growing chestnut stands, but different in altitude zoning above sea level, to harvest the material. The first plot was at a height of 500 m (plant age was 117 years, average height of trees was 30 m, average diameter was 40 cm, II site class). The second plot was at a height of 900 m (plant age was 115 years, average height was 30 m; trees, belonging to the II site class, had the diameter of 36 cm). The third plot was at a height of 1200 m (plant age was 115 years, average height was 25 m, trees, belonging to the II site class, had the diameter of 30 cm).

Sixteen model trees were selected at each trial plot for core preparation breast height (1.3 m from the ground) from the bark to the core in North-eastern direction using an age drill. Wood cores were used to measure the annual layer width and determine wood density of each annual layer.

Specimens for density determination were obtained by dividing the core into segments with a length of one annual layer with numbering. After that, all the specimens (irregular in shape) were soaked in distilled water until they reached a moisture content of 100-130% at a temperature of 20±1°C. Therefore, the density of wood was determined by the method of measuring the buoyancy force of specimens immersed in a liquid [1]. It was recommended for determining the basis density of wood specimens of irregular shape.

A glass vessel with distilled water with a capacity of 30 ml at 20±1°C was placed on VIBRA AF-220CE analytical balance (Japan, ± 0.0001 g). A needle was attached to a tripod holder of the vessel. The holder, together with the needle, could be moved in a vertical plane using a screw lifting device. Before the measurement, the needle was lowered into a vessel with water by a fixed value (mark on the needle). At this moment, the vessel with water was weighed and the holder was raised to the uppermost position. Before weighing, excess moisture was removed from the specimens with a moist rag. At the same time, excessive drying of the specimens should not be allowed. Then each specimen, the volume of which was to be determined, was placed on a needle. After that, the specimen was lowered into a vessel with distilled water until it was completely immersed to the set mark on the needle. At this point, the second weighing of the vessel with water was carried out. An additional load on the weighing pan was created by overcoming the buoyant force acting on the specimen. The force was numerically equal (if the water density is 1) to the specimen volume. Therefore, the difference in the reports on the balance gives the desired value of the specimen volume in the moisturized state.

The density of the liquid used in the experiment (distilled water) depends on the air temperature in the laboratory. Therefore we took into account the correction factor for the density of distilled water depending on the ambient temperature Moisture content of the specimens was determined by drying to an absolutely dry state. Drying of specimens to an absolutely dry state was carried out in a laboratory drying chamber at 103±2°C. Weighing of an absolutely dry specimen was carried out in a hermetically sealed weighing bottle to prevent moisture sorption by the specimen from surrounding space.

The basic density ($\rho_b$, kg/m$^3$) values in our research were calculated by the formula (1):
\[ \rho_b = \frac{m_o}{V_{max}} \rho \]  

where, \( V_{\text{max}} \) is the maximum volume of the specimen, which is the difference between the weight of the vessel with water and the specimen immersed in it, and the weight of the vessel with water, but without the specimen; \( m_o \) – weight of absolutely dry specimen, calculated as the difference between the weight of the closed bottle with dry specimen and weighing the same bottle without specimen; and \( \rho \) – density of distilled water at test temperature.

Subsequently, basic density of the annual layer was the average of 16 measurements for the annual layer corresponding to the age for each of the selected plots, according to the type of growing conditions. Static indicators were calculated for each geographic area: arithmetic mean of the entire specimen collection (M) and standard deviation (SD) of specimen collection.

3. Results and discussion

3.1. Research results of Scots pine wood growing under various environmental conditions

The average values of the basic density of pine wood along the trunk radius from various geographical zones and growing conditions are shown in table 1.

| Geographical area   | Favorable conditions | Unfavorable conditions |
|---------------------|----------------------|------------------------|
|                     | M, kg/m³  | SD, kg/m³ | M, kg/m³  | SD, kg/m³ |
| Forest-steppe       | 420^a      | 2.3       | 410^a      | 2.3       |
| Southern taiga      | 429^a      | 2.3       | 393^b      | 2.3       |

^ab – different letters denote significant deviations at the level \( p = 0.05 \)

During ontogenesis, density of wood is slightly higher under favorable growing conditions than under unfavorable ones (table 1). Density value increases from south to north under favorable growing conditions. Basic density is somewhat higher in the forest-steppe under unfavorable growing conditions, in comparison with the southern taiga zone. It is imperative to take growing conditions of model trees to establish general patterns in the geographic variability of density into account. In northern latitudes, the negative impact of unfavorable growing conditions increases. Density of pine wood under unfavorable conditions turned out to be lower than in the forest-steppe. The indicator of density variability is not large and ranges from 6% to 9% during ontogenesis. It was found that growing conditions had the greatest influence on the density. Their strengthening is recorded at the stage of mature wood structure. To a greater extent, the influence of growing conditions is manifested in the taiga zone.

Figures 1 and 2 show the dependences of wood density formation for the conditions of the southern taiga zone. The first five annual layers located near the core related to the juvenile period were not taken into account when determining the density by annual layers. It was experimentally established that (for the southern taiga zone) the maximum values of the basic density in pine wood were from 470 kg/m³ to 480 kg/m³. They are reached at the age of 55-95 years under favorable growing conditions. Talking about unfavorable growing conditions, the maximum values of wood density did not exceed 400-410 kg/m³. Regardless of the growing conditions, the maximum density values were reached on average by a 75-year-old annual layer or 2/3 of the trunk radius. High density value for the age of 135-140 years was noted in the conditions of blueberry-lingonberry pine forest. Under unfavorable growing conditions of the southern taiga zone, the difference in the basic density along the radius of the trunk did not exceed 15% compared to 21% in favorable growing.
Figure 1. Pine wood density formation along the trunk radius in the southern taiga zone under adverse conditions (lichen pine forest A₁).

Figure 2. Pine wood density formation (\textit{vaccinium} and \textit{myrtillus}) along the trunk radius in the southern taiga zone, under favorable growing conditions (blueberry-cranberry pine forest B₂).

It was established that (in the forest-steppe zone) the basic density reached its maximum values by the 45-year-old annual layer, at a distance of about 56-60% along the trunk radius from the core (figure 3). In the southern taiga zone the maximum values were reached to the 60-year annual layer at a distance of about 66% of the trunk radius (figure 4). Under unfavorable growing conditions of the forest-steppe zone, the difference in the base density along the trunk radius did not exceed 16% compared to 26% under favorable growing conditions.

The data obtained on the influence of latitudinal zoning are valid for one climatic zone of the Russian Federation and the influence of latitudinal zoning is different in other climatic zones for the same tree species. According to [5], the value of the average density of pine wood growing in the monsoon climate zone, taking into account latitude zoning within the Amur region of the Russian Federation, can change by a factor of 2.
Growing conditions have a great influence on the density of wood. According to [4], growing conditions in the northern European part of the Russian Federation are unfavorable ones. Therefore, if the latitude zoning increases above 60°N in this region, the average density of pine wood decreases.

Information about the influence of latitude zoning on wood density is important when solving issues with the reproduction and processing of wood raw materials. It is necessary to obtain accurate data on the properties of wood and latitude zoning and growing conditions of each tree species must be taken into account.

The density of wood (under the influence of geographic zoning) changes only under unfavorable growing conditions and increases from the North to the South. Under favorable growing conditions, no differences in density values connected with geographic zones were revealed. Growth conditions rather than geographic zoning affect the density value during ontogenesis. Under unfavorable growing conditions, irrespective of latitude zoning, wood, which is more equal in density, is formed along the trunk radius.
3.2. Research results of European chestnut wood growing in different environmental conditions

Average values of the basic density of European chestnut wood along the trunk radius from different altitude zoning and growing conditions are shown in table 2. The maximum average values of the basic wood density (414 kg/m$^3$) are reached in favorable growing conditions at an altitude of 500 m above sea level. Basic wood density of wood decreases up to 394 kg/m$^3$ with an increase in the height of growth to 1200 m.

Table 2. Average values (M) and standard deviation (SD) of the basic density of European chestnut wood at different growth heights.

| Growth height, m | M, kg/m$^3$ | SD, kg/m$^3$ |
|------------------|-------------|-------------|
| 500              | 414.6$^a$   | 5.93        |
| 900              | 406.1$^a$   | 3.74        |
| 1200             | 394.5$^b$   | 3.63        |

$^{a,b}$ — different letters denote significant deviations at the level $p = 0.05$.

Growing conditions for wood deteriorate with an increase in height, and density of wood decreases with deterioration. Moreover, the magnitude of this decrease increases with height: in the range of heights from 500 to 900 m, wood density decreases (on average) by 2.125 kg/m$^3$ for every 50 m. At an altitude of 900 to 1200 m, the decrease in wood density will be higher. It is already (on average) 3.86 kg/m$^3$ for every 50 m.

Wood density is unevenly distributed along the radius of the trunk. It was experimentally established that the highest density of European chestnut reaches at the early stage of growth in the period up to 50 years. Growth height does not affect the duration of the period of formation of high wood density along the trunk radius. However, it was found that at an altitude of 500 m above sea level density of wood along the trunk radius reaches its maximum average values of 563 kg/m$^3$ by the age of 25 in more favorable growing conditions (figure 5, curve 1). Under less favorable growing conditions at an altitude of 900 m above sea level wood density reaches a maximum value of 460 kg/m$^3$ by the age of 18-20 (figure 5, curve 2).

Figure 5. Density formation of European chestnut wood along the trunk radius: 500 m (curve 1), 900 m (curve 2) and 1200 m (curve 3) above sea level.

Under more unfavorable conditions at an altitude of 1200 m above sea level wood density reaches its maximum value of about 420 kg/m$^3$ by the age of 16-18 (figure 5, curve 3). Wood density decreases
throughout the life cycle after reaching the maximum value. In this case, the magnitude of density decrease is different and by the age of 50, regardless of growing conditions, wood density decreases to the value it had at an early (juvenile) age. A period of relative stabilization of wood density begins at the age of 51-100 years. The density of wood decreases at all considered heights by an average of 15% in the period from 100 to 117 years.

With an increase in the growth height of European chestnut stand from 500 to 1200 m, the average density of wood decreases by 20%. The difference (uneven distribution) of density along the trunk radius decreases as follows: 180 kg/m³ at an altitude of 500 m, 135 kg/m³ at an altitude of 900 m and 110 kg/m³ at an altitude of 1200 m (average values are given). Hence, density difference along the trunk radius decreases. Wood is more evenly dense with an increase in altitude and deterioration of growing conditions.

4. Conclusion
The results of the research show that density reaches its maximum values earlier in the forest-steppe zone (by the 45-year-old annual layer). In the southern taiga zone maximum is reached by the 60-year-old annual layer. Geographical zoning does not affect the character of density formation along the trunk radius in Scots pine. Tightening of climatic conditions causes an increase in differences in density values for growing conditions compared to the regions with milder climate conditions, where these differences are insignificant. Increasing latitude zoning causes shift in the maximum density of pinewood from the core to the bark. The density increases by 8-10 % (on average) for the studied regions. As the height of chestnut stand increases from 500 to 1200 m, the average density of wood decreases by an average of 2.85 % for every 100 m. With increasing growth height, the difference in wood density along the trunk radius decreases by 10 kg/m³(on average) for every 100 m, meaning that wood becomes more even.

The performed studies can be useful in the selection of highly productive plantings, harvesting wood with specified properties and in the selection of sites for priority artificial reforestation.

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