

STUDY OF THE DEPENDENCIES BETWEEN THE ANATOMICAL STRUCTURE AND PROPERTIES OF DOUGLAS WOOD

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ABSTRACT

The wood of coniferous tree species is mainly made up of tracheids. Abstractly viewed in cross-section, these tracheids can be considered as elements of some structure. In early wood, tracheids are larger in size and have thinner walls. In late wood, they are smaller in size and thicker cell walls. All this implies an uneven structure.

The paper examines the distribution of tracheids within the annual rings. The Douglas wood is examined in a cross-section. The number of cells in the early and late wood is measured. Tangential stripes of tracheids have been examined. These stripes are arranged in a radial sequence, gradually moving away from the axis of the stem. Dependencies between the anatomical elements in the areas of early and late wood with different widths of the growth rings are sought. A correlation analysis has been made between the structure and some physical properties of the wood. The coefficient of unevenness is determined.

Key words: Douglas, anatomical structure, unevenness coefficient, shrinkage, swelling, density

INTRODUCTION

Coniferous wood is characterized by a more orderly structure and anatomically similar annual rings. It is made up of one type of cells – tracheids. Annual rings are well expressed because of the different cell wall frames and cell gaps in early and late wood (Bluskova 2009, Bardarov 2014, Wagenfur, Scheiber 1996). In each coniferous tree species, there is a certain ratio of the size of the early tracheids to the late ones. The transition from early to late wood is also very important. There, the tracheids have intermediate dimensions of the cell wall and cell cavity (Bardarov 2008, 2009). This transition depends on both the tree species and the habitat conditions. It is these conditions that determine the amount of hormones that determine the formation of late wood (Higuchi, 1997).

The formation and size of the late wood area is an important part of technical anatomy. It investigates the influence of anatomical structure on the technical properties of wood. In addition, the structure of the wood affects the processes of its processing – drying, cutting, etc. (Rosas *et al.* 2000, Bardarov and Novoselets, 2013). The relationships between anatomical structure and physical properties have also been investigated in some deciduous tree species. The authors found that the higher the thickness of the cell wall, the frequency of the vessels and the frequency of the rays, the greater the basic density of the wood. The larger the fiber diameter, lumen diameter, vessel diameter, beam height, and beam width, the higher the moisture content of the wood (Eloy *et al.*, 2024).

Variations in the length of tracheids are also influenced by cambial age, place and conditions of growth. The study identified significant differences in tracheid length between early wood and late wood, both within one and between different plants. The authors suggest that factors, such as climate and soil conditions, play an important role in determining the structure of wood. Relationships between tracheid length and growth rates have been established. It has been

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suggested that other factors, possibly genetic or environmental, may have a more significant influence on tracheid development (Balzano et al, 2024).

The North American Douglas fir has emerged as a promising coniferous species, better suited to future climatic conditions and capable of producing high timber yields (Graf *et al.*, 2025). Its impact on biodiversity is likely to vary depending on the type of forest and management practices. There is limited evidence of adverse effects on biodiversity in European forests, highlighting the need for more in-depth research into this tree species.

The tracheids of the Douglas of the early wood are polygonal in shape, thin-walled with a wall thickness of 2.0-4.0-6.0 μm . Their cell cavities are wide, with a size of 35-40-48 μm . Their density is about 550 pcs.mm⁻². Tracheids of the late wood are rounded rectangular to angular, radially flattened, thick-walled with a wall thickness of 8.0-12.0-16.0 μm . at the end of the ring cleft – from 20-22.5-25 μm . Their density is about 600 pcs.mm⁻² (Bardarov 2014, Wagenfur, Scheiber 1996).

In Douglas, the transition between early and late wood within the annual period is gradual to abrupt. The share of late wood is significant – about 35-50%. The wall density varies from 0.14 for early to 0.53 for late tracheids. Tracheids are 2500–5600-7000 μm long, occupying about 95.3% of the wood volume. Under these conditions, the wood reaches a density of 560 kg.m⁻³ (Bardarov 2014, Wagenfur, Scheiber 1996).

On the other hand, the anatomical structure of wood can be considered abstractly, as a set of structures with varying degrees of ordering (Stoenchev and Bardarov, 2016). Coniferous wood itself is an uneven structure. The degree of unevenness can be a strong indicator of the relationship between structure and technical properties.

The aim of this work is to study annual rings with different characteristics and to look for a relationship between the structure of the wood and the degree of unevenness in the distribution of tracheids. This would provide an opportunity for a step towards objectifying conclusions about the relationship between the anatomical structure and physical properties of Douglas wood.

METHODS AND MATERIALS

Anatomical measurements

A light microscope of the "Laboval" brand, working with preparations with transmitting light, was used in the study. The studies were carried out at a magnification of 32 \times (mainly the density and number of tracheids), 100 \times (the location of the tracheids) and 400 \times (the size of the tracheids). The dimensions of the tracheids in the radial and tangential directions were measured, and the number of cells in the radial direction between two boundaries of the annual rings was determined. as well as the size of the studied area in the radial and tangential directions. From these, the density of cells in the annual ring in the individual zones was calculated. The area of cell walls and cell gaps are calculated. For such analyses at low magnifications, a semi-automated high-performance sample preparation, gigapixel imaging, and analysis of the anatomy of the end surfaces of disks and incremental cores can be used (Van den Bulcke *et al.*, 2025). This pipeline allows researchers to perform highly detailed anatomical analysis of large surfaces.

A problem in the work is the inevitable inaccuracies associated with the manufacture of the microscopic preparation and its measurement (von Arx Georg *et al.* 2016). According to the authors, potential measurement errors in many steps are between 5 and 20 or even 30%, which is in the same range as the variability of anatomical indicators. The key to performing a good

quantitative analysis of the anatomical images of wood is high-quality thin sections, the choice of location for making xylem sections, and the dimensions of these sections (Huang and Li 2022). In addition, the authors claim that at least six trees are needed to establish reliable tree anatomical time series.

To determine the degree of unevenness in the distribution of tracheids in the cross-sectional field of the studied material, a comparison of the real structure of the tracheids was carried out, determined experimentally with a uniform reference structure obtained at four segments of equal area (i.e. tangential stripes). The mechanism of comparison is based on the logic of the coefficient of unevenness, which can be considered as a special case of the integral coefficient of structural differences proposed by Prof. Gatev (Stoenchev and Bardarov, 2016):

$$I = \sqrt{\frac{\sum_{i=1}^k (v_{i1} - \frac{1}{k})^2}{\sum_{i=1}^k v_{i1}^2 - \frac{1}{k}}} \quad (1)$$

where:

v_{i1} – components of the real structure;

k – components of a uniform standard structure.

When determining the coefficient of unevenness in the annual ring, four stripes of equal width are selected, located one after the other in a radial direction. In each strip there is a certain number of v cells, called components.

Determination of physical properties

Of the physical properties, the density, maximum water content, drying and swelling of wood were studied. Standard methodologies and standard test bodies were used to determine them. These test bodies were subsequently used to make microscopic slides designed for anatomical measurements.

Statistical analysis

In anatomical measurements, all values for the dimensions of the tracheids of early and late wood are taken for one sample. The values of each sample are determined by the classical statistical indicators – arithmetic mean value standard, variation coefficient and accuracy indicator. The standard of the tangential size of the tracheids in the early and late wood is also determined arithmetically.

Correlation analysis

In addition to the test bodies from which the slides are made, the basic physical properties have also been tested. Therefore, correlations between cell sizes and these properties have been sought.

RESULTS AND DISCUSSION

Physical properties

It should be pointed out that the current results are part of a larger study of the physical properties of wood. The sample bodies in this article are the typical representatives of the initial samples. They were designed to make microscopic slides from them and to conduct anatomical measurements. Therefore, the average values do not pretend to represent the properties of the wood of the studied stems.

After they were made, the water content was immediately determined on the test bodies. The average value obtained for the wood was 80% and was not divided into kernel and sapwood. This was done in a special study. The drying was also determined, with the mean value $\beta_v = 13.0\%$. The obtained values for drying in the radial and tangential directions are $\beta_r = 5\%$, respectively, 7% , $\beta_t = 7.8\%$, with the value of anisotropites being 1.4. These values are higher than those indicated in the literature $\beta_v = 11.6\%$, respectively in the radial $\beta_r = 4.5\%$, and tangential $\beta_t = 7.3\%$ direction, with the value of anisotropites being 1.6 (The Wood Database). Similar are the values proposed in Holzatlas – $\beta_v = 11.5-12.5\%$, respectively in radial $\beta_r = 4.0-4.8\%$, and tangential $\beta_t = 7.0-7.7\%$ and desiccation coefficient $K\beta = 0.38-0.42\%$ (Wagenführ, Scheiber, 1996).

After these measurements, the test bodies were soaked to the maximum swollen state, and the maximum water content $W_{\max} = 123$ was determined. These values were also averaged for core and sapwood wood. Under these conditions, the dimensions were again measured and the swelling of the wood was determined. The volumetric swelling has an average value of $\alpha_v = 16.6\%$, and in the radial direction the wood swells $\alpha_r = 6, 3\%$, and tangentially – $\alpha_t = 8.8\%$. Under these conditions, the anisotropy of the swelling is 1.4.

The density in the raw state is $\rho_{\text{wet}} = 878 \text{ kg.m}^{-3}$. The density in the absolute dry state is $\rho_0 = 567 \text{ kg.m}^{-3}$. The density in the maximum swollen state is $\rho_{\max} = 1078 \text{ kg.m}^{-3}$, and the basic density is $\rho_{\text{bas}} = 486 \text{ kg.m}^{-3}$. These values are significantly higher than indicated in the literature $\rho_{12} = 510 \text{ kg.m}^{-3}$ and $\rho_{\text{bas}} = 450 \text{ kg.m}^{-3}$ (The Wood Database). The values given in Holzatlas are also lower. The absolute dry density there is $\rho_{0=470} \text{ kg.m}^{-3}$. And the standard density is $\rho_{12} = 550 \text{ kg.m}^{-3}$ and the raw density is $\rho_{\text{wet}} = 670 \text{ kg.m}^{-3}$ (Wagenführ, Scheiber, 1996).

Correlation analysis

After the physical properties of the Douglas fir sample bodies were determined, microscopic slides were made from them, anatomical measurements were made on them at magnifications of $100\times$ and $400\times$. At the lower magnification, the tangential dimensions of the tracheids in the early and late wood were determined. The purpose of this measurement was to look for a correlation between the cell sizes and the physical properties of the wood.

No correlation was found between the volumetric drying (β_v) and the statistical indicators of tracheid sizes in the tangential direction. This applies to both early and late wood. In the early wood, there is a weak straight and inverse relationship between the number of cells (n) and the drying in the radial ($R\beta_{rn} = 0.35$) and tangential ($R\beta_{tn} = -0.41$) directions. β) and the number of cells ($RA\beta_n = -0.51$). A similar trend was observed in the late wood, with correlation coefficients being respectively ($RA\beta_{rn} = 0.45$) for drying in the radial direction and ($RA\beta_{tn} = -0.45$) for drying tangential direction. As a result, there is an average correlation between the drying anisotropy and the number of cells ($RA\beta_n = -0.62$). There is also an average correlation between dispersion and

anisotropy ($R_{A\beta\sigma=0.48}$). These results show that with an increase in the number of tracheids (respectively with a decrease in their size), the anisotropy of desiccation decreases. However, with an increase in the diversity in the tangential size (σ) of the tracheids, the anisotropy of desiccation increases.

When examining the values in early wood of the maximum water content ($wmax$) and the number of cells, there is a strong but inverse correlation, such as $R_{wn}=-0.71$. Inversely between the variance of the tangential size of the cells and the maximum water content, there is a weak direct correlation, such as $R_{wn}=0.38$. A similar trend exists in the late wood, and the coefficients are respectively $R_{wn}=-0.71$ and $R_{wn}=0.51$. This shows that with an increase in the number of cells, the possibility of them containing a large amount of free water decreases. However, why the increased dispersion will allow this is not entirely clear.

A similar trend is observed when analyzing the values of cells and the swelling of wood. Looking at the values of the different types of wood density, the following can be noted:

- In early wood, there is a weak inverse correlation between the raw density (ρ_{wet}) and the arithmetic mean of the tangential size (m) $R_{\rho m}=-0.38$. In addition, there is an average inverse correlation between this density and the dispersion (σ) $R_{\rho\sigma}=-0.54$. A similar trend occurs in late wood, with the coefficients being $R_{\rho\sigma}=-0.34$ and $R_{\rho\sigma}$ respectively $-0,34$. This means that as the size of the tracheids increases and their diversity, the density in the raw state decreases. This statement is explained by the possibility of cells retaining more free water.
- In the case of early wood, a similar trend is observed in the density in the maximum swollen state (ρ_{max}), with the values of the correlation coefficient being $R_{\rho m}=-0.38$ and $R_{\rho m}=-0.33$. In the case of late wood, there are only weak dependencies, with correlation coefficients being $R_{\rho\sigma}=-0.32$ and $R_{\rho\sigma}=-0.13$.
- In early wood, there is an average correlation between the number of tracheids (n) and the absolute dry density values (ρ_0) $R_{\rho n}=0.54$ and the basic density (ρ_b) $R_{\rho n}=0.58$. In the case of late wood, the dependencies are strong, with correlation coefficients being $R_{\rho n}=0.69$ (for absolute dry density) and $R_{\rho n}=0.71$ (for the ground density). This means that the greater the number of tracheids in the wood, the greater its density.
- In the early wood, there is a weak inverse correlation between the dispersion of the tracheids (σ) and the absolute dry density values (ρ_0) $R_{\rho\sigma}=-0.35$ and the basic density (ρ_b) $R_{\rho\sigma}=-0.38$. In the case of late wood, these dependencies are average, with correlation coefficients being $R_{\rho\sigma}=-0.47$ and $R_{\rho\sigma}=-0.50$. This means that the more uneven the structure of the wood, the lower its density.

There is no correlation between the coefficient of unevenness (A) and the dimensions of the cell walls and cell voids of the wood. There is also no correlation between the coefficient of unevenness and the physical properties of the wood.

CONCLUSIONS

- With an increase in the number of tracheids (respectively with a decrease in their size), the anisotropy of desiccation decreases. However, as the diversity in the tangential size of the tracheids increases, the drying anisotropy increases.

- As the number of cells increases, the possibility of them containing a large amount of free water decreases. However, why the increased variance would allow it is not entirely clear.
- With an increase in the size of tracheids and their diversity, the density in the raw state decreases.
- There is a weak inverse correlation between the density in the maximally swollen state and the arithmetic mean value of the tangential size. There is no correlation between the variance of these values and the number of cells.
- The greater the number of tracheids in the wood, the greater its density.
- The more uneven the structure of the wood, the lower its density.

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