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Wood Quality along the Trunk Height of Birch and Aspen Growing in the Restoring Forests of Central Russia

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Abstract: The structure of forests has changed with an increase in soft-wooded broadleaved species over the past decade. The demand for hard-wooded broadleaved species can be met by replacing them with compressed wood of soft-wooded broadleaved species. Existing compressed wood technologies do not fully take into account the density variations that exist along the height of a tree trunk. In this study, we examined the variability of birch and aspen microstructures along the height of the trunk, including vessels per square millimeter and the diameter (tangential and radial) of the vessel lumina. The research was carried out on aspen and birch species growing in Central Russia. The vessels per square millimeter in both species increased from the base to the top of the trunk and their diameters decreased from the base to the top of the trunk. Birch demonstrated greater changes in these values than aspen. There was a strong relationship between the diameter of the vessel lumina and the trunk height. A decrease in the density of the stemwood from the base to the top of the trunk was caused by an increase in the vessels per square millimeter. These results affected the density of the stemwood and determined the degree of compression as well as the initial size of the blanks required to obtain material with uniform quality indicators, regardless of the source location of the raw materials in the tree trunk.

Keywords: trunk height; wood microsection; *Betula pendula* Roth; *Populus tremula* L.; radial diameter of vessel lumina; tangential diameter of vessel lumina; forest landscape restoration

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1. Introduction

Depending on developing expectations [1] and the choice of technological processes [2], the compensatory nature of contemporary afforestation [3,4] requires a qualitative [5,6] and selectively improved [7,8] evaluation of forest reproductive material (FRM) [9–11]. FRM should promote increased productivity from artificial forest plantations. Ecological expectations stemming from the accelerated production of high-quality wood for commercial use are characterized by the prioritization of planted forest growth [12]. Wood is widely used in various sectors of the national economy due to its inherent and diverse features. *Betula pendula* Roth has achieved almost a "double growth rate on former agricultural lands" [13] compared with natural stands. Nevertheless, the choice of tree species for future commercial plantations is determined by its properties and its stocks in natural stands. The stock of hardwood in the natural stands of Central Russia is 176 million m^3; softwood is more 1 909 million m^3. However, the demand for soft-wooded broadleaved species is low, which contributes to the accumulation of stocks of this wood [14].

By hardness [15], tree species can be divided into soft-wooded and hard-wooded. Soft-wooded species have a hardness of 500 kg cm^{-2} or less; hard-wooded, above 500 kg cm^{-2} [16]. *Betula pendula* Roth (13% of the standing volume of Central Russia with a wood stock of 248.2 million m^3) and *Populus tremula* L. (3.5% of the standing volume with a wood stock of 66.8 million m^3) have the greatest distribution in the region among the soft-wooded broadleaved species. Trees at an age of technical maturity are the most interesting for commercial use. For birch, this age is 55–60 years, with a trunk diameter of 26–32 cm. For aspen, the age of technical maturity is 30–50 years, with a trunk diameter of 32–40 cm. The reference literature shows the physical and mechanical properties of stemwood for the trunk part ("at chest height" of 1.3 m), but does not take into account the variability of stemwood properties in the remainder of the tree trunk.

The study of tree specimen microstructures (with specimens made using a microtome) enables us to determine the dynamics of the phenological phase [17] as well as the genetic [18], physical and mechanical [19] properties of wood. Assuming that birch and aspen trees have the same anatomical structure of cross-microsections along the entire height of the trunk at the age of technical maturity, one can disregard where the block is cut from when choosing model trees for subsequent processing or examinations. However, if the wood microstructure at different heights from the base to the top of the trunk is significantly different in the cross-sections, this should be taken into account when seeking to improve the quality properties of wood. A number of studies have confirmed that the strength of wood (of all species) can be increased by wood densification, including compressed wood [20], massive wood [21] and veneer for plywood [22]. For birch and aspen, a potential improvement can be made through heat treatments [23], impregnation using an antiseptic composition with a stabilizer [24] and compaction [19,20], if this compaction is not connected to the destruction of cell walls [25].

Wood is a material with a biological origin; the structure and properties change in a tree trunk. The relationship between the main indicator of wood quality (density) and its microstructure, which varies from the base to the top of the trunk, is not sufficiently studied in the literature sources. Khukhryansky claimed that features in the anatomical structure of a particular wood species made minor changes to this relationship [25]. The results of research connected to the dependence of wood quality on its microstructure have been reported [13,19,26–31]. Changes in the anatomical structure of wood underlie fluctuations in its quality indicators; namely, the density and strength along the height of the trunk. However, data on the microstructure gradient (i.e., the number and diameter of capillaries along the height of the trunk) for birch and aspen are lacking.

Our study was conducted for a typical forest area located in Central Russia and answered the following questions: How does the microstructure of birch and aspen stemwood differ along the height of the trunk? What effect does the wood species have on the wood microstructure? How can we rationally use knowledge about the wood microstructure to improve the wood quality?

2. Materials and Methods

2.1. Study Site and Model Tree Selection

The study was performed on two species of soft hardwood that were most common in the region: *Betula pendula* Roth (13% of the stand, with a volume of 248.2 million m^3) and *Populus tremula* L. (3.5% of the stand, with a volume of 66.8 million m^3). The selection of the model trees (*Betula pendula* Roth and *Populus tremula* L.) for the study was conducted in the autumn of 2021 in a natural mixed birch–aspen tree stand located in the Kon-Kolodezskiy forest area of the Scientific and Experimental Timber Enterprise of the Voronezh State University of Forestry and Technologies (coordinates of the nodal point: N 52°05′49.8″ E 39°12′33.2″; altitude 153 m a.s.l.). Healthy trees were selected without any pathological symptoms showing on the trunk or in the crown. The model trees (n = 6) were randomly chosen from trees that, according to the stem diameter at a height of 1.3 m, corresponded with technical maturity (Table 1).

Table 1. Characteristics of model trees selected for the study.

Features	*Betula pendula* Roth.	*Populus tremula* L.
Age, years	57–62	31–40
Diameter at breast height in two mutually perpendicular directions, cm	28–32	30–34
Tree height, m	22–24	23–26
Distance to the crown base, m	9.5–11.0	10.5–12.0

2.2. Sample Preparation, Measurement and Analysis

The selected model trees were cut into blocks. A total of 9 blocks with a length of 1 m were cut from each tree using a petrol-driven power saw (Husqvarna AB, Stockholm, Sweden). Crosscutting was done from the stem base, according to the scheme presented in Figure 1. Each block was numbered, counting from the base to the top of the trunk. A disc with a thickness of 3.0–3.5 cm was cut out at the beginning of each block. After this, the debarking was performed in such a way that the bast was removed from the tree trunk.

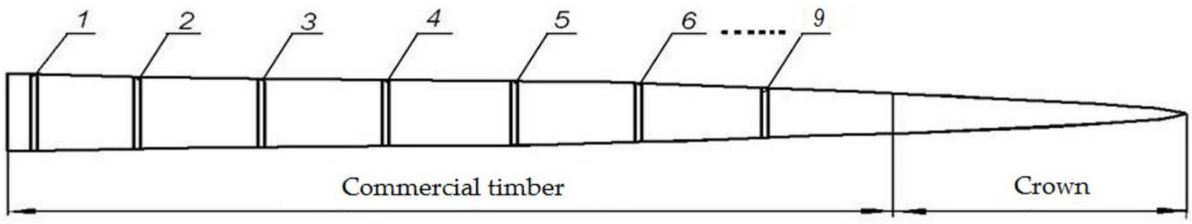
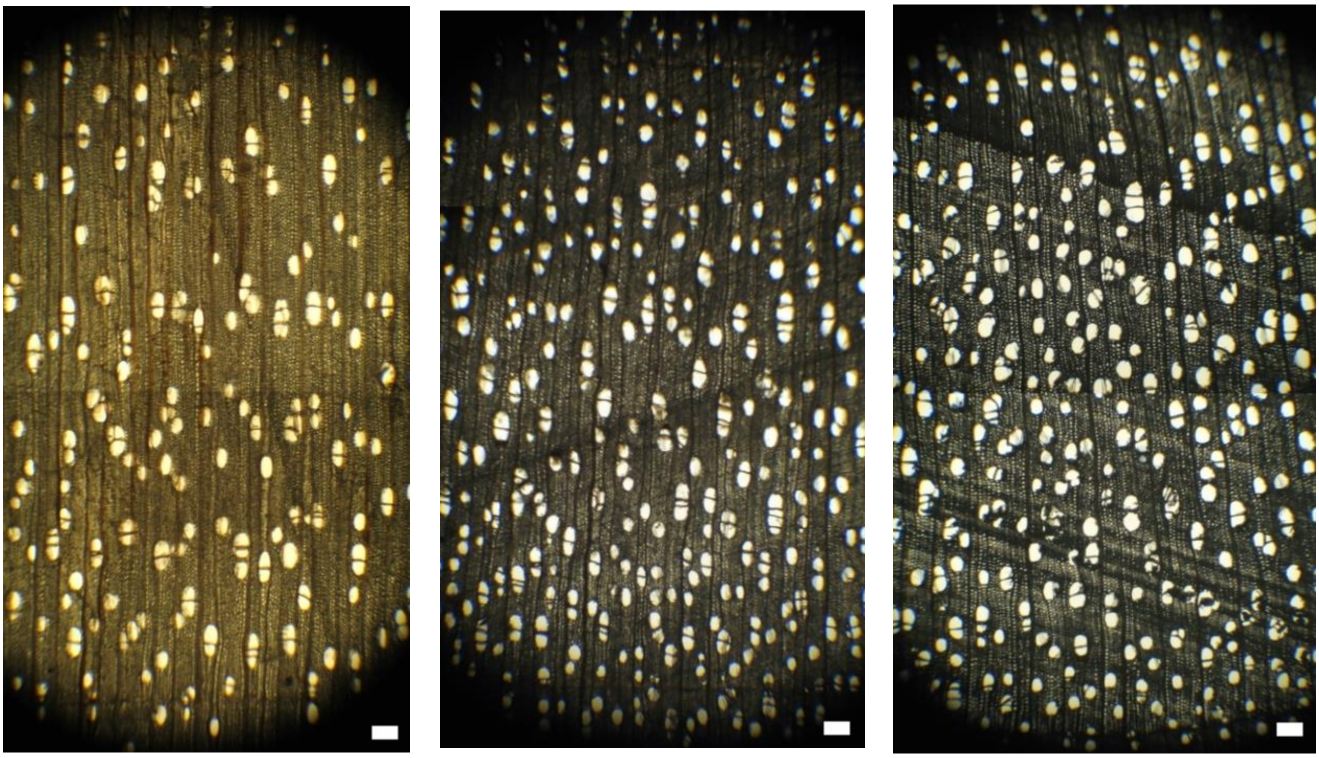


Figure 1. The scheme of cutting sections from the tree trunk: 9 cuts of wood cut from the trunk at 1 m intervals.

Small clear specimens (n = 5) were made from each disc cut at heights of 1, 5 and 9 m (base, middle and top of the trunk). The cutting out from each disc was performed in such a way that one of the specimen axes was a mandatory location along the wood fibers. Growth rings on the end surfaces of the specimens were parallel to one pair of opposite faces and perpendicular to the other. Right angles were maintained between the adjacent faces of the specimens. The maximum deviations from the nominal dimensions of the working part of the specimens did not exceed ± 0.5 mm.

Microcut specimens for the anatomical study were taken from the obtained small clear specimens. The small clear specimens were kept in a solution of glycerin and alcohol at a 1:1 ratio for 24 h before the microcuts were prepared. This eliminated the possibility of air bubbles and reduced the hardness of the birch and aspen to allow them to be cut on the microtome. Transverse microsections of wood with a thickness of 10–15 μm were obtained using a MC-1 sledge microtome (ORION MEDIC, St. Petersburg, Russia). Before conducting the optical studies, the microsections were washed in alcohol to reduce noise bands appearing in the photographs.

The study of the wood microstructure was performed using an Optical Binocular Microscope (OBM) (Biolam, LOMO, St. Petersburg, Russia) with a nozzle for a Canon Power Shot A620 digital camera (Canon Inc., Tokyo, Japan). A 4× lens was used. The free image processing and analysis program Image Tool v. 3.0 (UTHSCSA, San Antonio, TX, USA) was used to process the obtained photographs of the wood microstructure (Figure 2—birch; Figure 3—aspen). The program enabled the measurement of the linear dimensions of the micro-objects. The vessels per square millimeter of the transverse microsection of the growth ring were counted and the diameter of the vessel lumina (μm) in radial and tangential directions was measured.

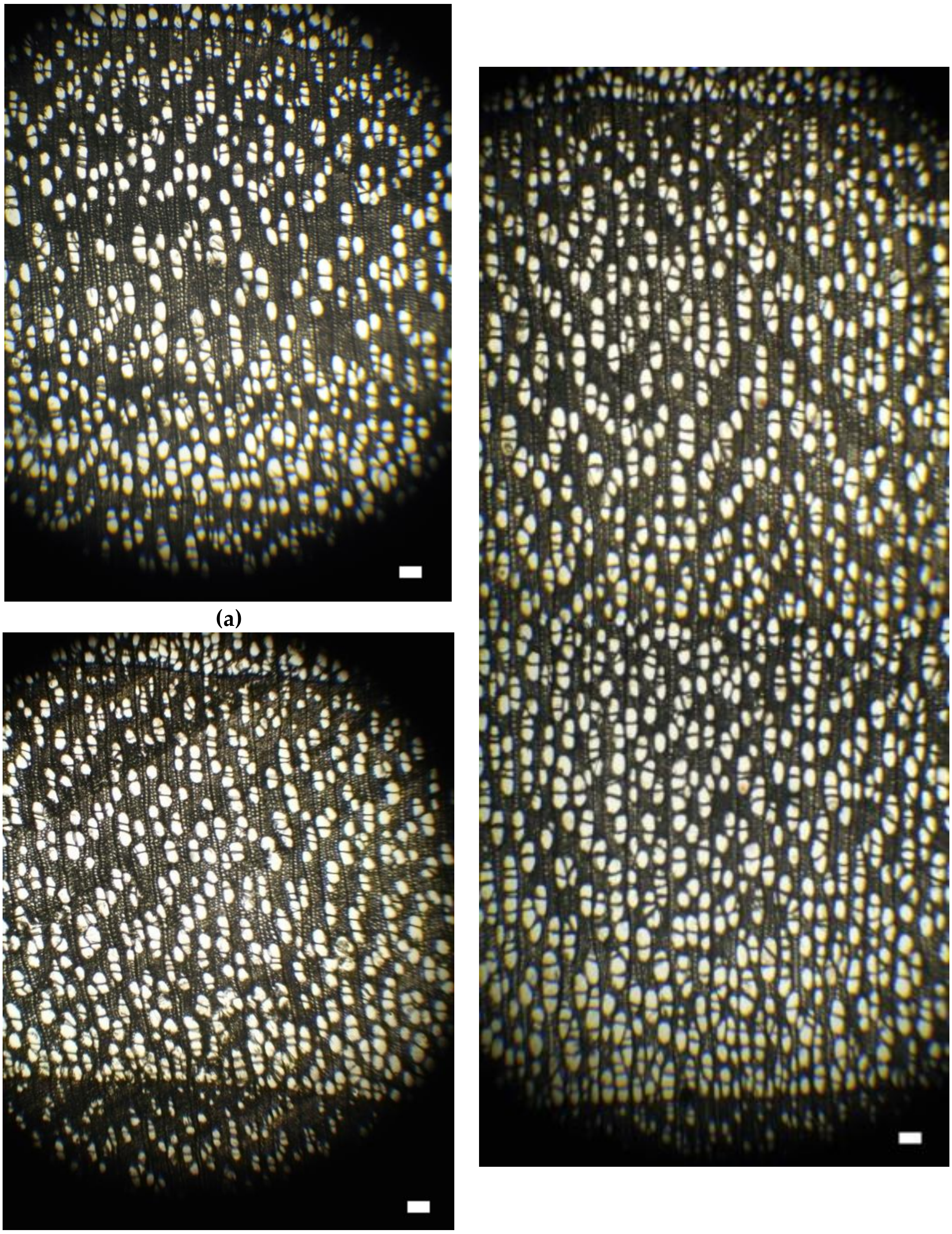


(a) (b) (c)

Figure 2. OBM micrographs of birch (*Betula pendula* Roth, ×4) on transverse section of small clear specimen, cut out from disc at a height of 1 (**a**), 5 (**b**) and 9 (**c**) meters from the stem base. Scale bars = 100 µm.

2.3. Data Analysis

The terms of the anatomical structure of the diffuse-porous wood were harmonized in accordance with IAWA feature lists [32]. A one-way analysis of variance (ANOVA) was used to check the differences between the average values of the diameters in the capillary cavities of the wood microsections (the specimens were taken from different heights of the tree trunk). The descriptive statistics included the sample number, mean, standard deviation, coefficient of variation, minimum value and maximum value. The mean values were compared using a post hoc Tukey test for an unequal number of samples with a significance level of alpha = 0.05.



(a) **(b)** **(c)**

Figure 3. OBM micrographs of aspen (*Populus tremula* L., ×4) on transverse section of small clear specimen, cut out from disc at a height of 1 (**a**), 5 (**b**) and 9 (**c**) meters from the stem base. Scale bars = 100 µm.

3. Results

The microstructure of the diffuse-porous woods used in this study was represented by a variety of anatomical elements (Figures 2 and 3).

The first group of these elements consisted of libriform fibers; the fiber tracheids performed a mechanical function. The second group of elements (vessels and vascular tracheids) performed a conductive function. The vessels were formed by thin-walled cells (segments) and appeared as a vertical row of cells (on a longitudinal section) in which the transverse partitions had partially or completely disappeared. Vascular tracheids are thin-walled cells with bordered pores.

Figures 2 and 3 show that the aspen stemwood had significantly more vessels than birch. An increase in the number of vessels in the direction from the base to the top of the trunk was also clearly seen in the birch wood. The difference in the number of vessels at a height of 5 m and 9 m was visually poorly distinguishable in the aspen wood.

The measurement results of the tangential and radial diameters of the vessel lumina of the birch (Table 2) and aspen trees (Table 3) relative to the transverse section were characterized by different effects of the trunk height.

Table 2. Several parameters of vessels of *Betula pendula* Roth stemwood measured on a transverse microsection depending on the different distances from the base of the trunk.

Cutting Microsection on Distance from the Base of the Trunk, m	Vessel Lumina Measurement Directions	Vessels per Square Millimeter	Diameter of Vessel Lumina, µm				
			Mean ± SE	Min	Max	SD	CV
1 (Stem base)	Tg	34	54.58a ± 2.74	16.49	78.57	16.00	29,31
	Rad	34	80.02b ± 4.63	25.29	128.54	26,98	33.71
5 (Middle part)	Tg	57	39.31c ± 1.42	24.00	72.11	10.75	27.36
	Rad	57	47.23ac ± 1.79	20.40	82.46	13.51	28.60
9 (Top of the trunk)	Tg	39	44.74acd ± 2.51	18.86	99.04	15.67	35.02
	Rad	39	56.54a ± 3.03	9.48	87.62	18.95	33.51

Mean—average diameter of vessel lumina values in radial (Rad) and tangential (Tg) directions, µm; Min—minimum value; Max—maximum value; SD—standard deviation; CV—coefficient of variation, %. Mean values followed by a different letter were statistically different ($p < 0.05$).

Table 3. Several parameters of vessels of *Populus tremula* L. stemwood measured on a transverse microsection depending on the different distances from the base of the trunk.

Cutting Microsection on Distance from the Base of the Trunk, m	Vessels per Square Millimeter	Diameter of Vessel Lumina, µm									
		Mean ± SE		Min		Max		SD		CV	
		Rad	Tg	Rad	Tg	Rad	Tg	Rad	Tg	Rad	Tg
1 (Stem base)	68	55.72b ± 2.36	40.90a ± 1.63	13.41	12.00	99.40	85.99	19.42	13.41	34.86	32.79
5 (Middle part)	86	39.79a ± 1.80	34.59ac ± 1.27	9.00	6.00	71.02	57.33	16.65	11.74	41.85	33.94
9 (Top of the trunk)	167	45.32a ± 1.29	31.91c ± 0.91	12.34	3.90	87.05	74.19	16.61	11.70	36.66	36.67

Mean—average diameter of vessel lumina in radial (Rad) and tangential (Tg) directions, µm; Min—minimum value; Max—maximum value; SD—standard deviation; CV—coefficient of variation, %. Mean values followed by a different letter were statistically different ($p < 0.05$).

A strong statistically significant effect of the trunk height on the tangential diameter of the vessel lumina was observed in the birch stemwood. The size of the stemwood radial diameter of the vessel lumina in the base of the trunk was significantly different from the values seen in the middle and top parts (Figure 4).

The influence of the stem height on the diameter of the vessel lumina was less pronounced in the aspen stemwood, especially in the middle part. At the same time, the stemwood radial diameter of the vessel lumina in the base of the trunk was significantly higher than in the middle and top parts. In the tangential direction, the diameter of the vessel lumina at a height of 9 m was significantly different than at a height of 1 m from the stem base. The difference between the radial and tangential diameters of the vessel lumina at the same height of the trunk was more significant in the base and top zones.

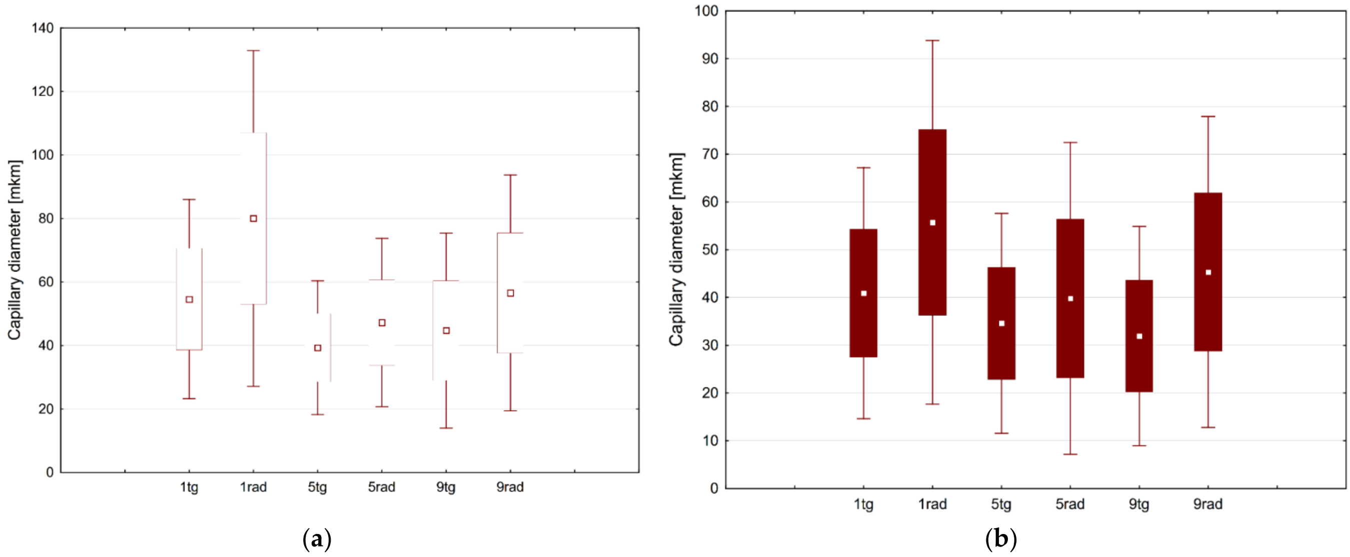


Figure 4. Boxplot visualizations of the effect of different trunk heights on stemwood vessel diameters of (**a**) *Betula pendula* Roth. and (**b**) *Populus tremula* L. transverse sections.

4. Discussion

4.1. How Does the Microstructure of Birch and Aspen Stemwood Differ along the Height of the Trunk?

The microstructure of deciduous diffuse-porous species is characterized by a uniform distribution of thin-walled elements (vessels) in the growth ring. Wood compaction in these species occurs due to the compression of the lumina of thin-walled cells lying between the vessels (intercellular space) and lumina of the vessels themselves. The cell walls are not destroyed.

In our study of wood microstructure variability, it was found that (in percentage terms) a decrease in the diameters of the vessel lumina per meter of stem height could be measured at 2.4% for birch (Table 2) and 2.2% for aspen (Table 3). These data were in good agreement with the density changes. The decrease in the birch wood density per meter of stem height was 2.12%; for aspen, it was 2.2% [33]. The decrease in the wood density from the base to the top of the trunk was due to a change in the anatomical structure [17–19,27,29,34–36]. There was also an observed increase in the vessels per square millimeter from the base to the top [33].

Comparing the data on the wood density changes per meter of birch and aspen stem heights as well as the change in the diameters of the vessel lumina of these species per meter of height, we concluded that there was a correlation between the microscopic structure of the wood and its density. A similar gradient of decreasing density with an increasing relative height of pine, spruce, birch and aspen trees was presented by Poluboyarinov [37]. Our presented study on the influence of microstructures in birch and aspen wood on the density along the height of the trunk complements the scant available data, especially relating to the stands of Central Russia where it contributes to a unique source of information.

The presence of a correlation between the variability of the microstructures and the change in the density of the wood along the height of the trunk must be taken into account in the production of compressed wood. To obtain compressed wood that is homogeneous in density and quality, it is necessary to determine the wood compaction and the initial dimensions of the raw material, depending on its initial density and its location in the trunk. The given density of the compressed wood and the initial density of the raw material are the basis for the calculation of compaction. The degree of compaction determines the initial size of the blanks before compacting [33].

Comparing the data on the change in wood density per meter of stem height of the birch and aspen species as well as the change in the diameters of the vessel lumina for each meter of stem height, we concluded that there was a correlation between the microscopic structure of the wood and its density.

4.2. What Effect Does the Wood Species Have on the Wood Microstructure?

The location, growing conditions and age of trees as well as the interaction of these factors had a statistically significant effect on the microstructure of birch wood. The mean basic density of birch wood increased with the age of the tree [27]. For the age of technical maturity, the density at a normalized moisture content along the height of the birch trunk varied from 657.6 kg m^{-3} at a height of 1 m to 611.5 kg m^{-3} at a height of 5 m and 531 kg m^{-3} at a height of 9 m [33]. Research has shown a similar gradient of decreasing density from 500 to 475 kg m^{-3} with an increase in the relative height of the tree [31]. Different values of absolute density can be explained by different geographic locations. At the same time, it was found that the radial diameter of the vessel lumina were almost halved when moving from the base to the top of the birch trunk. The sharpest gradient was observed at a height of 5 m in the middle part of the trunk. A gradual decrease in the radial diameter of the vessel lumina occurred when the stem height increased to 9 m. It is noteworthy that the average density values for an entire trunk were 454.5 kg m^{-3} in the case of plantation cultivation of birch and 507 kg m^{-3} in the case of a natural stand [29].

The study of the aspen microstructure along the height of the trunk complements the scant available data and is particularly important for the stands of Central Russia. The character of the diameter of the vessel lumina gradient relative to the trunk height was similar to the gradient seen in the birch stemwood and proceeded downwards in its absolute value. It is, therefore, advisable to take into account the static and dynamic loads of a standing tree in further studies in addition to the main factors that determine the patterns of changes in the wood microstructure of birch and aspen relative to the height along the trunk.

4.3. How Can We Rationally Use Knowledge about the Wood Microstructure to Improve the Wood Quality?

The presence of a correlation between the variability of the microstructure and changes in the density of wood relative to the height of the trunk should be taken into account in production.

The quality of wood depends on its density [13,18,19,23,27–31,33,37–40]. The higher the density of wood, the higher its quality indicators. Hardwoods have the highest density. In the forests of Russia, the timber stock is about 80–81 billion m^3, of which 75% is coniferous wood and 19.6% softwood stands. Hardwoods account for 2.4%; 9.8% are taken by other types.

Compressed and modified softwoods can be used to replace an insufficient volume of the most valuable hardwood. The forest structure of Russia has seen a decrease in the hardwood reserves over the past decade. Furthermore, the demand for soft hardwood is low and so contributes to the accumulation of the stock of this type of wood.

Existing technologies for pressing and modifying wood do not take into account the factor of changes in the density of the starting material depending on the changes seen in its microstructure along the height of the tree trunk [39]. Therefore, in existing technologies, the wood compaction is set to be the same for all raw materials. However, this does not allow for compressed wood, which is homogeneous in its density and quality [26].

In the future, from the parts of the trunk of birch and aspen located at different distances from the base of the trunk, it will be possible to obtain compressed wood [41] that is homogeneous in density and hardness.

5. Conclusions

The microstructure of birch and aspen stemwood varied from the base to the top. The decrease in the diameters of the vessel lumina per meter of trunk height was 2.4% for birch and 2.2% for aspen wood. The change in the gradient of the diameters of the vessel lumina in the aspen microsections was similar in the trunk height to the gradient seen in the birch stemwood.

Knowledge of the peculiarities of microstructure changes will improve the implementation of forest inventory and ensure a more rational cutting of stemwood for future compressing.

The established difference between the radial and tangential diameters of the vessel lumina in the stemwood microsections along the height of the trunk was not final in itself. However, in the future, it will add valuable information that can be used in the study of the changes in wood properties and predict the production of a uniform quality of compressed wood from the entire trunk.

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