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Variation of Selected Macrostructure Features and Density Wood of the European Spruce (*Picea abies* (L.) Karst.) in the Cross-Section of Trees over 90-Years-Old in Poland

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Abstract: In the present study, the following features were investigated: the variability of selected macrostructure features (width of the annual growth ring and share of latewood) and wood density of the European spruce (*Picea abies* (L.) Karst.) in a cross-section of the trunk. The study was conducted in locations of the northeastern range (12 research plots) and the southwestern range (20 research plots) of spruce in Poland. On the testing plots, Pressler drill borehole samples were taken from 15 selected trees. Then, the borehole samples were divided into 2 cm long sections and, for each section, the average width of the annual growth ring, the average share of latewood, and the relative wood density were calculated. In conclusion, it was found that the width of the annual growth rings in the tested material was increasing constantly from the outer circumference (the perimeter) of the trunk towards the pith. The greatest share of latewood was found not only in the perimeter zones of the tree trunk but also in the zones close to the pith. It was also discovered that the highest wood densities occur in the perimeter zones, and that these densities decrease towards the pith. It was only in the sections next to the pith that an increase in wood density was noted. Having analysed the relationships between the examined features, it can be concluded that the width of annual growth rings affects both the share of latewood and the wood density. The aforementioned were negative correlations, whereas the increase in the share of latewood also impacts the increase in wood density and was determined to have a positive correlation.

Keywords: width of the annual growth ring; share of latewood; cross-section of the trunk; Pressler drill

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1. Introduction

The European spruce (*Picea abies* (L.) Karst.) has a 5.3% volume share in Poland, ranking fourth in this respect after pine, oak, and beech [1]. The main natural center of its occurrence is found in the mountain areas (in southern Poland); however, spruce also occurs in the Warmia and Mazury region (in northern Poland). This area in Poland is within the northeastern range of spruce, while mountain stands are in the southwestern range [2]. Research has shown that the wood from mountain spruce stands has different properties from the wood found in lowland stands [3].

The characteristics of wood depend on many internal and external factors. In conifers, a clear correlation was observed between the width of annual growth rings, the share of latewood, and the density and strength of the wood. The share of latewood increases with narrower annual growth rings, resulting in an increase in wood density and strength [4–9]. Some researchers, however, found inverse correlations, especially regarding the density of spruce wood of various provenances, in studies conducted within experimental plots [10–12]. The structure and density of wood are often influenced by its location on the trunk, both along the length of the trunk and within its cross-section [4,13]. The widest growth rings are found in the root collar because it is necessary for the formation of the butt swell at the base of the trunk, where the wind produces the greatest bending moment.

Above the butt swell, the growth ring width decreases and then increases again in the apex. In turn, in the cross-section, the width of the annual growth rings decreases from the pith to the periphery [14]. Such a phenomenon is due to the fact that as the tree grows in thickness, the rings overlap on the trunk in an increasingly larger diameter.

The width of annual growth rings depends to a large extent on the average annual temperature, which in turn affects the length of the growing season [4,15]. Therefore, wood of the same species, for instance, spruce from lowland areas (with milder climate) has wider annual growth rings than spruce wood from mountainous and high-mountain areas [16–20]. Some authors point out that the structure of wood (the width of the annual growth rings, the proportion of latewood, and wood density) depends not only on the air temperature but also on the amount of water in the soil [9], habitat conditions [21], and tree growth conditions [22–25]. In turn, Nabais et al. [26], who analysed the impact of climate on wood density in different tree species, found that in the case of spruce, climatic conditions do not affect this feature of wood.

The aim of this study was to determine the variability of selected macrostructure features (the width of the annual growth rings and the share of latewood) and the density of spruce wood along the trunk's cross-section and to determine the relationship between the studied features in trees over 90-years-old growing in Poland.

2. Materials and Methods

The preliminary selection of stands for the present study was made on the basis of descriptions contained in the forest management reports from individual forest districts. Only such stands were taken into account in which spruce trees have reached the age of 90 years or more, with a minimum area exceeding 3 hectares (Table 1). This was linked to the feasibility of locating a trial area of the designated size of 1 ha therein. At this stage, the following factors were taken into account: species composition (single species spruce stands or those in which the share of spruce was greater than that of other species); the stocking index (comparison of the volume of wood actually existing in a stand per 1 hectare to that given in the tables, which the same stand could show at a given age and in a given habitat under optimal conditions); valuation; forest habitat type; the height above sea level and the exposure, in the case of the southwest range; and finally, the diversification of stands in terms of survey features. In each forest district, several stands were designated; then, based on the site inspection, 1 or 2 of those most suited to the required criteria were selected. Finally, the following stands were selected: the ones in which the age of spruce ranged from 90 to 128 years, growing in the following forest sites: BMw—humid mixed coniferous forest, BMsw—fresh mixed coniferous forest, LMsw—fresh mixed forest, Lsw—fresh forest (lowland areas), BWG—alpine coniferous forest, BG—mountain coniferous forest, LMG—mountain mixed forest, and LG—mountain forest (mountain areas), and the stocking index ranged from 0.3 to 1.3 (Table 1). Research plots located in mountain areas (No. 13–28) were located at an altitude of 400 to 1200 m above sea level.

Finally, in the northeastern range of spruce in Poland (Mazury—the Masuria region), 12 research plots were designated (located in 12 forest districts), whereas within the south-western range (in the mountains)—7 plots were established in the Sudetes (in 6 forest districts) and 9 in the Carpathians (in 7 forest districts) (Figure 1).

The plots were located in the areas most representative of the conditions within the tree stand, in terms of the tree cover index (type and degree of space filling with tree canopy in the stand), stocking index, and quality of spruce wood. In the case of stands with a species composition other than a 100% share of spruce, the research plot was designated in such a way that 100% of spruce was within its boundaries. The plots were 1 hectare in size and square in shape (100 × 100 m). Within the research plots, the diameter at breast height (DBH) of each spruce with a thickness of at least 7 cm was measured, and borehole samples were taken with a Pressler drill from 15 selected trees. The selection of test trees for drill sampling was conducted according to the Draudt method [27] which consists of assigning the number of sample trees proportionally to the number of trees in their

respective thickness classes. The borehole was made into the pith at a height of about 30 cm from the ground surface, up to a maximum depth of 40 cm.

Table 1. General characteristics of the research plots (the national forest inventory data from Poland).

Regional Directorate of the State Forests, Forest District, Subdistrict, Number of Plot	Forest Site	Species Composition	Age (Year)	Stocking Index	Regional Directorate of the State Forests, Forest District, Subdistrict, Number of Plot	Forest Site	Species Composition	Age (Year)	Stocking Index
Olsztyn Młynary Srebrny Potok No. 1	Lsw	7 Spruce 1 Beech 1 Spruce 1 Beech	101 101 76 76	0.7	Wrocław Śnieżka Karpacz No. 15	BG	10 Spruce	128	0.7
Olsztyn Wichrowo Piotraszewo No. 2	LMsw	6 Spruce 2 Pine 2 Spruce	120 120 83	0.6	Wrocław Kamienna Góra Jarkowice No. 16	BMG	10 Spruce	114	1.0
Olsztyn Zaporowo Borek No. 3	BMw	7 Spruce 1 Birch 1 Spruce 1 Pine	93 73 53 133	0.4	Wrocław Zdroje Piekiełko No. 17	LG	9 Spruce 1 Larch	128 128	0.9
Olsztyn Górowo Iławeckie Gałajny No. 4	BMsw	6 Spruce 2 Birch 1 Pine 1 Oak	95 70 70 95	0.9	Wrocław Lądek Zdrój Kamienica No. 18	BMG	10 Spruce	106	0.9
Olsztyn Bartoszyce Kamieniec No. 5	Lsw	6 Spruce 3 Spruce 1 Birch	96 66 66	0.6	Wrocław Lądek Zdrój Kamienica No. 19	BMG	10 Spruce	101	1.1
Olsztyn Mrągowo Dębowo No. 6	Lsw	9 Spruce 1 Birch	98 98	0.9	Katowice Wisła Przysłup No. 20	BWG	7 Spruce 3 Spruce	90 70	0.9
Olsztyn Srokowo Kronowo No. 7	LMsw	7 Spruce 2 Pine 1 Birch	100 100 100	0.7	Katowice Węgierska Górka Zielona No. 21	LMG	10 Spruce	120	0.9
Białystok Giżycko Zielony Dwór No. 8	Lsw	6 Spruce 2 Oak 2 Hornbeam	94 94 94	0.9	Katowice Węgierska Górka Skrzyczne No. 22	LMG	5 Spruce 4 Fir 1 Beech	90 60 30	0.8
Białystok Borki Diabla Góra No. 9	BMw	10 Spruce	107	0.5	Katowice Jeleśnia Ślemień No. 23	LG	6 Spruce 3 Fir 1 Beech	90 60 40	0.8
Białystok Olecko Dąbrówki No. 10	BMsw	9 Spruce 1 Oak	100 100	0.5	Katowice Bielsko Biła No. 24	BMG	6 Spruce 3 Spruce 1 Beech	111 91 61	1.3
Białystok Suwałki Pijawne No. 11	BMsw	7 Spruce 1 Pine 2 Spruce	120 120 94	0.5	Tatrzański Park Narodowy Morskie Oko No. 25	BWG	10 Spruce	125	1.2
Białystok Augustów Zyliny No. 12	BMw	6 Spruce 4 Spruce	120 76	0.3	Tatrzański Park Narodowy Łysa Polana No. 26	LG	7 Spruce 2 Spruce 1 Spruce	110 85 130	0.8
Wrocław Szklarska Poręba Szronowiec No. 13	LMG	9 Spruce 1 Birch	94 94	0.8	Kraków Krościenko Czarna Woda No. 27	LMG	7 Spruce 1 Fir 1 Beech 1 Beech	105 105 105 75	0.7
Wrocław Śnieżka Karpacz No. 14	BWG	10 Spruce	128	0.8	Kraków Gorlice Małastów No. 28	LG	5 Spruce 4 Fir 1 Pine	92 92 92	0.3

Explanations: BMw—humid mixed coniferous forest, BMsw—fresh mixed coniferous forest, LMsw—fresh mixed forest, Lsw—fresh forest, BWG—alpine coniferous forest, BG—mountain coniferous forest, LMG—mountain mixed forest, and LG—mountain forest.

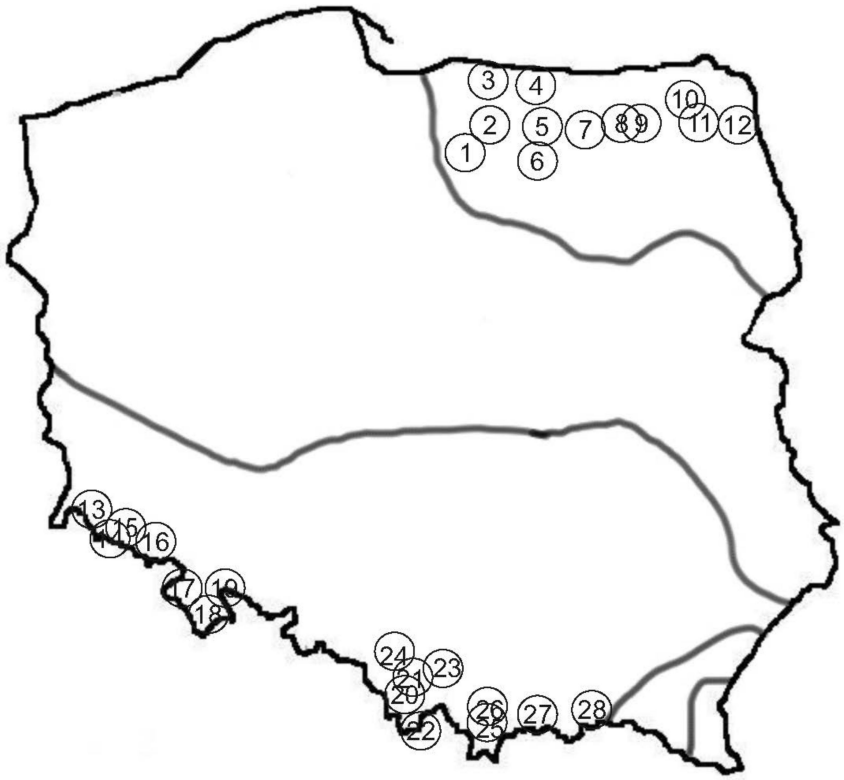


Figure 1. Location of research plots. Explanations: 1–28—number of plot.

The surfaces of the borehole samples were smoothed and then scanned. After scanning the borehole samples, measurements were taken of the following: the width of annual growth rings, the width of latewood zones, and the share of latewood. Measurements with an accuracy of 0.01 mm were conducted on an electronic image with the use of the specialised software application "Przyrost WP" [28]. Following that, the borehole samples were divided into 2 cm long sections. Subsequent sections were numbered from I to XI, with the first section located at the outer circumference of the trunk. For individual sections, the average width of the annual growth ring, the average share of latewood, and the relative basic density of the section were calculated. The relative basic density of the wood was calculated according to the following formula:

$$\gamma_w = \frac{m_0}{V_{max}}$$

where: γ_w—relative basic density, m_0—mass of absolutely dry wood (0% moisture), and V_{max}—wood volume in the state of maximum swelling.

The volume of wood was measured using the hydrostatic method (water displacement) [29]. After the volume was measured, the wood samples were dried, and then their dry weight was determined.

Next, depending on their thickness, tree trunks were divided into groups with 4, 5, 6, 7, 8, 9, 10, and 11 sections, respectively. Such a division was necessary because the studied groups included stands that differed in terms of survey features that may affect the growth of trees. This may be influenced, in particular, by age and habitat (lowlands) as well as altitude and climatic conditions (mountain areas).

Due to the fact that after the application of the Shapiro–Wilk test, the null hypothesis of the normality of data distributions was rejected, the Kruskal–Wallis test and the post-hoc multiple comparison tests were used to analyse the statistical significance of the differences, whereas the Spearman rank correlation test (R Spearman) was used to determine correlations between different features [30,31]. The significance level of $\alpha = 0.05$ was adopted in the statistical analyses.

3. Results

3.1. The Widths of Annual Growth Rings

Having analysed the studied material, it was found, in most cases, that the widths of annual growth rings increased initially starting from the outer circumference (section I) towards the interior of the trunk (Figure 2). However, it has been observed that after reaching the half-length of the trunk radius, the differences in the widths of annual growth rings of subsequent sections decreased and, in most cases, they tended to remain at a similar level all the way to the pith. This is also confirmed by statistical characteristics (Table 2) which show that the smallest widths of annual growth rings (less than 1 mm in width) were found at the trunk's outer circumference (section I), while further inwards, both the minimum and maximum values remained at similar levels. Statistical analyses (Table 2) showed that significant differences between the widths of annual growth rings in individual sections occurred in all groups of trees and were mostly differences between the sections located at the trunk's outer circumference (sections I, II, and III) and the sections located in the middle and at the end of the radius (sections at the pith of the trunk).

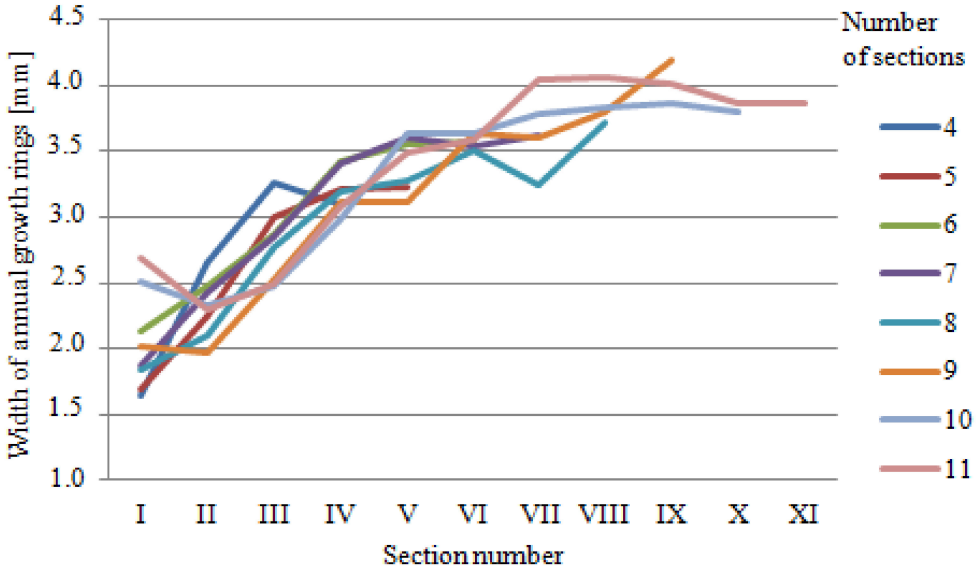


Figure 2. Distribution of the width of annual growth rings along the radius in the cross-section of the examined trees. Explanations: 4–11—refer to trees with a certain number of sections along the radius of the trunk cross-section.

Table 2. Statistical characteristics of the width of annual growth rings for the tested material.

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
4	Average	1.64	2.65	3.27	3.09							
	Median	1.44	2.52	2.98	2.92							
	Min	0.34	0.58	0.46	0.90							
	Max	3.86	5.76	6.98	6.14							
	Standard deviation	0.89	1.34	1.67	1.32							
	Coefficient of variation	54.50	50.65	51.22	42.80							
	Significant differences	a	a	a	a							

Table 2. *Cont.*

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
5	Average	1.69	2.24	3.00	3.21	3.22						
	Median	1.14	1.96	2.75	2.97	3.08						
	Min	0.38	0.64	0.63	1.13	0.71						
	Max	7.37	6.01	6.35	8.02	11.89						
	Standard deviation	1.37	1.30	1.40	1.45	1.65						
	Coefficient of variation	80.56	58.08	46.58	45.21	51.10						
	Significant differences	a	b	ab	ab	ab						
6	Average	2.13	2.47	2.87	3.43	3.56	3.57					
	Median	1.79	2.24	2.62	3.05	3.19	3.17					
	Min	0.37	0.50	0.82	0.65	1.25	1.20					
	Max	6.53	7.64	6.86	7.96	7.70	7.98					
	Standard deviation	1.43	1.43	1.47	1.63	1.43	1.61					
	Coefficient of variation	67.23	57.84	51.30	47.64	40.23	44.99					
	Significant differences	a	b	a	ab	ab	ab					
7	Average	1.88	2.43	2.86	3.41	3.61	3.54	3.62				
	Median	1.48	2.08	2.69	3.01	3.46	3.23	3.32				
	Min	0.34	0.56	0.64	1.08	1.11	0.92	0.82				
	Max	7.29	8.14	7.42	11.45	10.64	12.43	13.10				
	Standard deviation	1.36	1.39	1.47	1.78	1.73	1.85	2.07				
	Coefficient of variation	72.50	57.35	51.49	52.22	47.99	52.12	57.26				
	Significant differences	a	b	a	ab	ab	ab	ab				
8	Average	1.84	2.10	2.77	3.20	3.28	3.51	3.25	3.72			
	Median	1.46	1.88	2.18	2.81	3.00	3.48	3.19	3.45			
	Min	0.49	0.48	0.89	1.03	0.80	1.10	0.57	0.50			
	Max	5.06	4.35	9.52	8.25	7.05	8.11	8.18	15.78			
	Standard deviation	1.19	0.99	1.73	1.85	1.69	1.74	1.55	2.33			
	Coefficient of variation	64.88	47.16	62.43	57.76	51.58	49.72	47.73	62.62			
	Significant differences	a	b	-	a	ab	ab	ab	ab			

Table 2. *Cont.*

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
9	Average	2.01	1.97	2.52	3.11	3.12	3.64	3.61	3.51	3.70		
	Median	1.61	1.72	2.29	2.73	2.95	3.52	3.38	3.27	3.31		
	Min	0.52	0.69	0.91	0.79	0.71	0.84	0.88	1.17	1.56		
	Max	9.44	4.96	5.43	8.86	7.12	7.61	7.90	6.20	7.96		
	Standard deviation	1.65	0.96	1.09	1.67	1.28	1.55	1.57	1.46	1.57		
	Coefficient of variation	81.98	48.74	43.44	53.64	40.94	42.65	43.53	41.59	42.45		
	Significant differences	a	b	c	ab	ab	abc	ab	ab	abc		
10	Average	2.51	2.34	2.48	2.99	3.64	3.64	3.79	3.83	3.87	3.79	
	Median	2.30	2.06	1.96	2.32	3.27	3.08	3.68	3.94	3.83	3.48	
	Min	0.43	0.77	1.04	1.14	1.06	1.19	1.68	2.25	2.38	0.99	
	Max	6.46	4.92	5.68	6.97	9.60	8.55	6.93	5.79	6.37	7.41	
	Standard deviation	1.42	1.25	1.28	1.67	1.81	1.72	1.43	1.08	1.05	1.61	
	Coefficient of variation	56.58	53.48	51.53	55.75	49.63	47.15	37.66	28.21	27.12	42.53	
	Significant differences	a	b	c	-	-	-	b	abc	abc	b	
11	Average	2.68	2.29	2.49	3.09	3.50	3.60	4.04	4.06	4.01	3.86	3.86
	Median	2.77	1.89	2.17	2.67	3.01	2.91	3.59	3.69	3.46	3.60	3.56
	Min	0.41	0.72	1.04	1.36	1.30	1.38	1.63	1.81	2.05	1.43	0.70
	Max	7.84	5.58	5.19	6.42	10.16	9.02	9.92	10.54	9.45	11.08	11.74
	Standard deviation	1.80	1.16	1.14	1.40	1.83	1.86	2.03	1.83	1.83	1.76	1.93
	Coefficient of variation	66.89	50.68	45.75	45.25	52.29	51.74	50.26	45.03	45.59	45.69	50.07
	Significant differences	a	b	c	-	-	-	bc	bc	bc	abc	-

Explanations: sections with the same letter designation: a–c differ significantly, but successive sections with the same letter designation are compared to the first section with the same such designation, for example, for 4 sections-sections: I and II, I and III, I and IV differ significantly, while sections: II and III, II and IV, III and IV do not differ significantly; "-"—means: no significant differences.

3.2. The Share of Latewood

Having analysed the share of latewood along the cross-sections of trees from the lowlands, it was found that the highest shares occurred in the perimeter zones of trunks (section I) (Figure 3, Table 3). Staring from the circumference, these shares gradually decreased, stabilizing in the central parts of the trunk's radius at the level of approximately 20%. On the other hand, this share increased again in the zones adjacent to the pith. It was also found that the highest values, in some cases, showed over 70% share of latewood. Statistical analyses (Table 3) have demonstrated that significant differences in the share of latewood in individual sections occurred in almost all groups of trees (except trees with 10 sections) and they were mostly differences between the sections at the trunk's outer

circumference (sections I, II, III) and sections located in the central part of the radius, and at the pith.

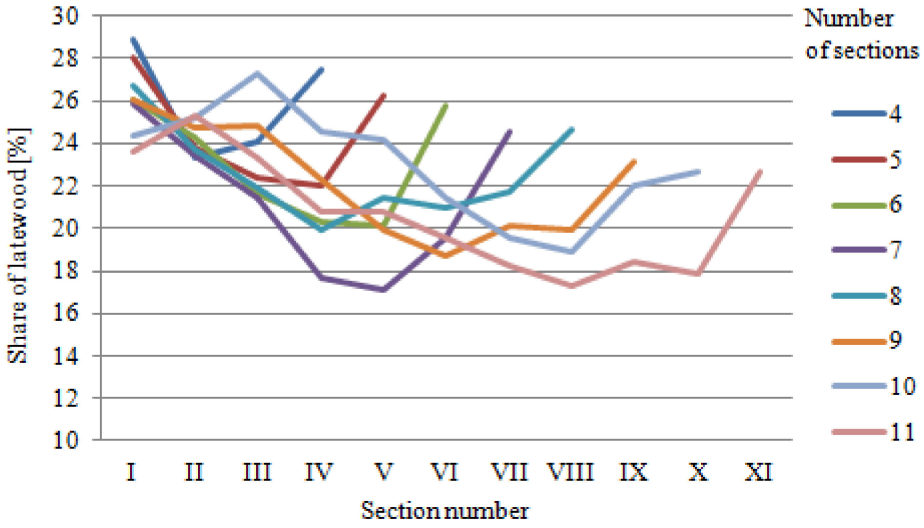


Figure 3. Distribution of latewood share along the radius of the cross-section of the examined trees. Explanations: 4–11—refer to trees with a certain number of sections along the radius of the trunk cross-section.

Table 3. Statistical characteristics of the share of latewood for the tested material.

Number of Sections	Section Number	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
	Statistics											
4	Average	28.89	23.34	24.11	27.44							
	Median	27.33	21.43	23.41	28.01							
	Min	10.57	8.90	8.60	11.87							
	Max	51.63	56.47	43.74	51.86							
	Standard deviation	9.15	10.17	8.64	10.64							
	Coefficient of variation	31.68	43.59	35.82	38.78							
	Significant differences	a	a	-	-							
5	Average	28.02	23.83	22.42	21.96	26.29						
	Median	27.68	22.63	21.93	21.31	26.65						
	Min	8.05	7.59	7.43	3.90	5.15						
	Max	64.95	57.57	51.60	49.79	56.73						
	Standard deviation	8.81	9.37	8.84	9.70	10.69						
	Coefficient of variation	31.43	39.31	39.44	44.19	40.67						
	Significant differences	a	a	a	a	-						

Table 3. *Cont.*

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
6	Average	26.10	24.24	21.66	20.34	20.15	25.80					
	Median	27.02	23.97	21.30	20.93	19.96	25.92					
	Min	7.64	7.20	4.70	2.97	3.17	5.80					
	Max	47.38	58.14	58.44	42.65	70.28	74.80					
	Standard deviation	8.55	10.30	9.72	9.63	9.75	11.41					
	Coefficient of variation	32.75	42.48	44.88	47.35	48.42	44.21					
	Significant differences	a	-	a	ab	ac	bc					
7	Average	25.87	23.42	21.45	17.67	17.15	19.54	24.58				
	Median	26.01	23.54	20.48	17.69	17.35	19.24	24.73				
	Min	9.47	11.00	6.42	3.85	5.36	3.83	3.37				
	Max	44.54	43.79	44.86	36.58	32.93	44.98	56.82				
	Standard deviation	7.72	7.31	8.72	8.05	7.30	9.05	11.15				
	Coefficient of variation	29.83	31.24	40.64	45.58	42.56	46.31	45.37				
	Significant differences	a	b	a	abc	abd	a	cd				
8	Average	26.68	23.71	21.88	19.98	21.49	21.00	21.70	24.60			
	Median	25.01	24.21	22.36	18.81	21.98	21.27	20.10	25.20			
	Min	10.43	12.79	4.00	4.33	4.25	4.30	7.23	5.17			
	Max	45.68	43.71	53.37	46.15	45.88	57.02	36.68	47.90			
	Standard deviation	8.06	7.52	9.74	9.63	9.25	10.85	8.69	10.73			
	Coefficient of variation	30.23	31.71	44.52	48.18	43.04	51.67	40.07	43.60			
	Significant differences	a	-	-	a	-	-	-	-			
9	Average	26.05	24.78	24.87	22.33	19.90	18.68	20.09	19.91	23.14		
	Median	26.07	24.62	22.22	21.46	19.72	17.76	18.15	19.12	21.53		
	Min	8.50	6.74	8.89	4.62	5.22	4.73	5.67	6.15	6.20		
	Max	43.91	47.79	49.20	40.03	35.29	38.43	34.50	37.55	49.85		
	Standard deviation	7.14	8.49	8.85	9.50	7.36	8.70	7.58	8.32	10.58		
	Coefficient of variation	27.42	34.26	35.59	42.56	36.98	46.59	37.73	41.78	45.70		
	Significant differences	a	-	-	-	a	a	a	a	-		

Table 3. *Cont.*

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
10	Average	24.34	25.17	27.29	24.55	24.22	21.40	17.87	17.92	21.20	21.91	
	Median	23.47	23.32	25.32	22.68	19.23	18.13	17.93	16.24	16.90	18.90	
	Min	12.38	9.70	7.55	11.10	8.10	5.40	4.88	3.45	5.12	6.90	
	Max	48.06	57.12	77.49	71.86	64.92	59.26	43.71	45.22	49.48	44.10	
	Standard deviation	8.14	11.23	14.05	13.20	14.10	13.14	9.66	10.54	12.09	10.39	
	Coefficient of variation	33.45	44.63	51.51	53.76	58.22	61.38	54.07	58.80	57.02	47.42	
	Significant differences	-	-	-	-	-	-	-	-	-	-	
11	Average	23.61	25.27	23.36	20.75	20.80	19.51	18.21	17.32	18.45	17.86	22.65
	Median	23.37	25.76	24.78	23.76	20.61	17.99	17.00	15.95	18.63	17.68	18.16
	Min	10.23	10.45	7.88	3.43	2.60	4.17	2.70	2.35	4.25	7.05	3.40
	Max	31.49	43.91	34.83	37.62	44.72	41.54	44.14	35.52	36.56	28.42	69.06
	Standard deviation	5.69	6.89	7.24	8.13	8.53	8.86	8.68	8.22	7.24	5.31	13.17
	Coefficient of variation	24.12	27.26	30.97	39.18	40.99	45.42	47.67	47.48	39.21	29.72	58.14
	Significant differences	a	b	-	-	-	-	b	ab	-	b	-

Explanations: sections with the same letter designation: a–d differ significantly, but successive sections with the same letter designation are compared to the first section with the same such designation; "-"indicates no significant differences.

3.3. Wood Density

When analysing the distribution of wood density along the trunk cross-section, similar trends can be observed in all data groups (Figure 4, Table 4). It was found that the highest wood densities occur in the perimeter zones (section I) and decreases towards the pith. Only in the sections immediately next to the pith was an increase in wood density noted. Statistical analyses showed (Table 4) that significant differences in wood density occurred in almost all groups of trees, and that these were mostly differences between the sections located at the trunk's outer circumference (sections I, II, and III) and those located in the middle part of the radius and at the pith. In trees with 5, 6, and 7 sections, it was also found that the sections located in the middle part of the radius differed significantly from the sections at the pith. However, no significant differences were found in trees with 10 sections.

3.4. Correlations

In order to determine the correlation between the features (Table 5), Spearman's rank correlation coefficient test (R Spearman) was used. As a result of the conducted analysis, it was found that the width of annual growth rings affects both the share of latewood and the wood density. Furthermore, it was found that these were high negative correlations (according to the Guilford classification), amounting to $r = -0.618$ for the share of latewood and $r = -0.507$ for the density of the wood. By contrast, the increase in the share of latewood affects the increase in wood density and has a high positive correlation ($r = 0.603$).

Table 4. Statistical characteristics of wood density for the tested material.

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
4	Average	0.380	0.343	0.326	0.359							
	Median	0.371	0.335	0.323	0.350							
	Min	0.270	0.254	0.248	0.235							
	Max	0.530	0.522	0.486	0.569							
	Standard deviation	0.051	0.053	0.044	0.059							
	Coefficient of variation	13.43	15.53	13.61	16.54							
	Significant differences	a	a	ab	b							
5	Average	0.389	0.353	0.336	0.344	0.377						
	Median	0.395	0.345	0.332	0.331	0.364						
	Min	0.271	0.254	0.261	0.240	0.251						
	Max	0.535	0.593	0.519	0.602	0.659						
	Standard deviation	0.058	0.055	0.058	0.062	0.075						
	Coefficient of variation	14.95	15.47	17.28	18.07	19.89						
	Significant differences	a	a	ab	ac	bc						
6	Average	0.386	0.366	0.346	0.339	0.350	0.365					
	Median	0.379	0.356	0.335	0.322	0.334	0.351					
	Min	0.267	0.255	0.252	0.252	0.265	0.271					
	Max	0.532	0.650	0.536	0.524	0.575	0.587					
	Standard deviation	0.058	0.064	0.059	0.060	0.065	0.059					
	Coefficient of variation	14.98	17.50	16.94	17.64	18.44	16.29					
	Significant differences	a	b	a	abc	a	c					
7	Average	0.376	0.352	0.340	0.325	0.319	0.333	0.385				
	Median	0.378	0.347	0.324	0.314	0.311	0.326	0.372				
	Min	0.283	0.247	0.225	0.239	0.222	0.263	0.266				
	Max	0.516	0.574	0.631	0.608	0.487	0.512	0.628				
	Standard deviation	0.054	0.059	0.065	0.063	0.051	0.046	0.080				
	Coefficient of variation	14.43	16.79	19.26	19.40	15.85	13.72	20.84				
	Significant differences	a	b	ac	abd	abe	af	cdef				

Table 4. *Cont.*

Number of Sections	Section Number / Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
8	Average	0.381	0.362	0.354	0.349	0.342	0.339	0.355	0.370			
	Median	0.371	0.349	0.334	0.337	0.322	0.327	0.341	0.359			
	Min	0.258	0.285	0.275	0.258	0.251	0.238	0.260	0.262			
	Max	0.524	0.530	0.491	0.520	0.524	0.451	0.526	0.636			
	Standard deviation	0.058	0.055	0.056	0.056	0.064	0.052	0.068	0.079			
	Coefficient of variation	15.21	15.12	15.73	16.13	18.75	15.20	19.28	21.23			
	Significant differences	a	-	-	-	a	a	-	-			
9	Average	0.378	0.364	0.358	0.348	0.337	0.321	0.322	0.335	0.351		
	Median	0.370	0.351	0.350	0.329	0.326	0.316	0.317	0.316	0.348		
	Min	0.307	0.266	0.278	0.254	0.264	0.260	0.242	0.281	0.262		
	Max	0.455	0.456	0.459	0.648	0.447	0.416	0.391	0.465	0.459		
	Standard deviation	0.041	0.044	0.047	0.068	0.042	0.041	0.040	0.043	0.049		
	Coefficient of variation	10.95	12.15	13.10	19.38	12.50	12.69	12.30	12.84	13.83		
	Significant differences	a	b	c	a	a	abc	abc	a	-		
10	Average	0.366	0.363	0.358	0.346	0.341	0.328	0.331	0.328	0.335	0.346	
	Median	0.354	0.364	0.351	0.338	0.331	0.318	0.322	0.322	0.315	0.333	
	Min	0.286	0.290	0.280	0.277	0.277	0.253	0.263	0.265	0.287	0.276	
	Max	0.507	0.524	0.502	0.443	0.502	0.460	0.441	0.424	0.506	0.437	
	Standard deviation	0.052	0.048	0.051	0.040	0.050	0.047	0.049	0.047	0.051	0.045	
	Coefficient of variation	14.28	13.33	14.37	11.48	14.71	14.49	14.77	14.29	15.10	13.05	
	Significant differences	-	-	-	-	-	-	-	-	-	-	
11	Average	0.362	0.355	0.344	0.334	0.331	0.328	0.321	0.320	0.321	0.328	0.368
	Median	0.358	0.357	0.348	0.330	0.338	0.320	0.309	0.324	0.319	0.326	0.339
	Min	0.285	0.274	0.275	0.257	0.263	0.261	0.260	0.232	0.251	0.255	0.234
	Max	0.465	0.426	0.408	0.398	0.401	0.447	0.426	0.424	0.427	0.396	0.637
	Standard deviation	0.042	0.042	0.037	0.040	0.042	0.046	0.043	0.040	0.038	0.034	0.086
	Coefficient of variation	11.56	11.83	10.69	11.91	12.71	14.11	13.51	12.38	11.87	10.45	23.32
	Significant differences	a	-	-	-	-	-	a	a	a	-	-

Explanations: sections with the same letter designation: a–f differ significantly, but successive sections with the same letter designation are compared to the first section with the same such designation; "-" indicates no significant differences.

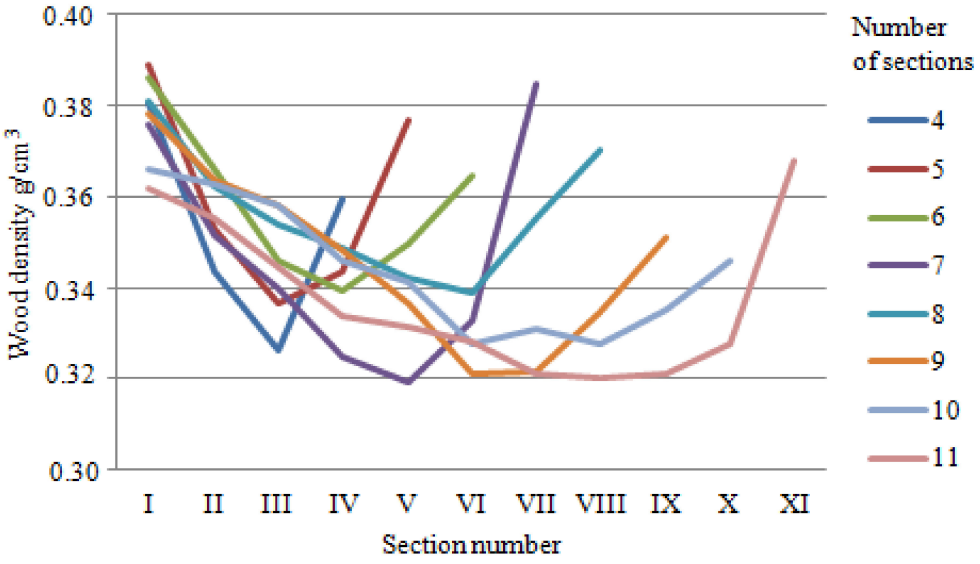


Figure 4. Distribution of wood density along the radius of the cross-section of the examined trees. Explanations: 4–11 refer to trees with a certain number of sections along the radius of the trunk cross-section.

Table 5. Correlation test results.

Features of Wood	R (Spearmann)	*t* (N-2)	*p*	Equations of Regression Models
Annual growth rings and share of latewood	−0.618	−41.400	0.000	y = 31.6972 − 2.9754xx
Annual growth rings and wood density	−0.507	−31.028	0.000	y = 0.3908 − 0.0133xx
Share of latewood and wood density	0.603	39.893	0.000	y = 0.2757 + 0.0033xx

4. Discussion

The present research has shown that the width of the annual growth rings increases from the outer circumference towards the pith. Such a tendency in coniferous species had been found before [4,14,15]. In turn, the highest shares of latewood were found both in the outer (perimeter) zones and in the zones immediately adjoining the pith. This resulted in a similar distribution of wood density. Here, too, the highest densities were recorded in the outermost and pith zones of the trunk. Wąsik et al. [32], while conducting research on giant fir wood, observed an increase in annual growth rings from outer circumference towards the pith, with a simultaneous decrease in the share of latewood and density. However, cases have also been observed where the wood density exhibited the highest values both in the outer perimeter zone and at the pith. Hapla et al. [33] reported similar regularities in giant firs from Germany. The aforementioned authors stated that the wood density of the rings adjacent to the pith was slightly higher compared to the density of the subsequent rings directly surrounding the previous ones. Then, the density value gradually increased towards the cortex. A similar phenomenon was observed in the black spruce (*Picea mariana* (Mill.) B.S.P.) in Canada [34]. Here, too, the highest wood densities, as well as the highest shares of latewood, were found in the zone adjoining the pith, and, subsequently, the values of these features decreased and then increased again towards the trunk's outer circumference. In turn, the width of annual rings increased from the outer circumference towards the pith.

In the present study, a decrease in the share of latewood and wood density was found with the increasing width of annual growth rings, while an increase in the share

of latewood resulted in an increase in wood density. Such correlations were previously noted in spruce and were explained by a different structure of tracheids in latewood [9]. Latewood tracheids have a lesser lumen diameter and thicker cell walls than early wood tracheids. Therefore, a greater proportion of latewood in the annual growth ring results in a greater wood density.Furthermore, Jyske et al. [7], who investigated spruce wood, found that the share of latewood and wood density increased from the pith towards the outer perimeter. They also observed that the width of annual growth rings affects the share of latewood and wood density, which are negative correlations, whereas the share of latewood affects wood density, which is a positive correlation. The correlation between the decrease in the density of spruce wood and the increase in the width of annual growth rings was also noted by Gryc and Horáček [35] who found that the widest annual growth rings occurred in the middle part of the trunk. In turn, the wood density increased from the pith towards the outer circumference, yet these differences were not statistically significant.

5. Conclusions

1. The width of the annual growth rings in the tested material was constantly increasing from the outer circumference towards the pith.
2. The greatest share of latewood was found not only in the perimeter zones of the trunk but also in the zones immediately adjacent to the pith.
3. It was found that the highest wood densities occur in the perimeter zones and that these densities decrease towards the pith. Only in the sections immediately at the pith, was an increase in wood density noted.
4. Having analysed the correlations between the examined features, it was found that the width of annual growth rings affects both the share of latewood and the wood density. Furthermore, these were negative correlations, whereas the increase in the share of latewood affected the increase in wood density, exhibiting a positive correlation.

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