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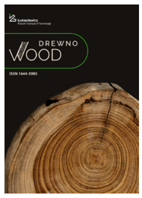

Density distribution in middle-sized silver birch wood (*Betula pendula* Roth)

Ewa Dobrowolska[a] *
Sławomir Krzosek[b]

[a] Department of Wood Science and Wood Preservation, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences, Warsaw, Poland
[b] Department of Mechanical Wood Processing, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences, Warsaw, Poland

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This paper contains a comprehensive analysis of the variability of density in middle-sized specimens of silver birch (Betula pendula Roth). Wood density tests were carried out using transverse and longitudinal sections of five middle-sized silver birch logs harvested from the Czarna Białostocka Forest District. Selected wood characteristics on which the density depends were investigated, namely the proportion of young and mature timber and the impact of defects. Wood density was tested by a non-destructive method, including the use of an MGD-05 densimeter and X-ray tests. Statistical analysis of the test results showed that the mean density of B. pendula timber depends on the position on the longitudinal and transverse sections of the trunk. It does not vary depending on geographical direction (north or south). Middle-sized silver birch wood is practically entirely composed of juvenile wood. The overall average density is much higher than the mean density at breast height, but the density measured at ¼ log height is not statistically significantly different from the mean density of the entire tree log.

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Introduction

Birch accounts for nearly 7% of the forest area of the national forests in Poland [Report on the condition of Polish forests in 2021, Forestry 2021]. It is one of the pioneer and fast-growing species recommended for colonisation of post-agricultural land and cultivation in plantations. It makes a vital contribution at the beginnings of primary and secondary succession, and prepares the soil for colonisation by less robust tree varieties [Bernadzki and Kowalski, 1983; Załęski, 1987].

In Poland, there are two species of birch yielding timber of industrial significance – the silver birch (*Betula pendula* Roth) and the mossy birch (*Betula pubescens* Ehrh), but due to its higher share in the stock of stands, the silver birch is of greater economic importance [Kubiak and Laurow, 1994; Collective work, 2000; Bowyer et al., 2007].

The dimensional requirements for middle-sized coniferous and non-coniferous wood intended for industrial processing or for use in the round state are presented in the standards PN-91/D-95018 and PN-93/D-02002, which refer to diameters measured without bark: upper diameter greater than 5 cm and lower diameter less than 24 cm. The wood may come in the form of logs, sawn logs, rollers, or slivers. Traditional customers for middle-sized timber are primarily the wood panel, pulp and paper industries. Due to the recent considerable progress in wood processing technology (especially in the field of

* Corresponding author: ewa_dobrowolska@sggw.edu.pl

joining and refining), there has been an increase in demand for middle-sized wood, for example in the construction joinery and furniture industries [Appendix no. 9, 2019].

Among the basic material characteristics of wood that are most commonly determined is its density [Kokociński, 2004]. The maximum density of deciduous trees occurs in the zone near the pith and decreases as one moves from the pith towards the circumference [Kubiak and Laurow, 1994]. The density of woody tissue also depends on such factors as the ratio of overripe wood to mature and juvenile wood, whose formation is linked to the following characteristics: species, rate of growth, habitat, stand density, cambium distance and age, environment, and location of the tree in the stand [Hakkila, 1966; Fukazawa, 1984; Kocoń, 1991; Kretschmann, 1998; Niedzielska and Wąsik, 2000; Bao et al., 2001; Hejnowicz, 2002; Fabisiak, 2005; Bowyer et al., 2007; Gryc et al., 2011; Liepinš et al., 2013; Giagli et al., 2019; Dobrowolska et al., 2020]. Previous studies on the density of diffuse-porous wood indicate that this property is not influenced by the width of annual growth [Krzysik, 1957; Kubiak et al., 1994; Zhang, 1995; Helińska-Raczkowska et al., 1995a; Kokociński, 2004] or the zone within the transverse section of the trunk [Krzysik, 1957; Niemz, 1993 after Mette, 1984].

Despite the growing importance of silver birch wood, there is a lack of published studies on the density distribution in middle-sized wood, for example that obtained during conservation procedures. The goal of the present study was to perform a comprehensive analysis of the density variation across a transverse section and longitudinal section of middle-sized silver birch timber, aged about 40 years, harvested in the north-east of Poland. An X-ray method, with an isotope densimeter, was used to assess the density of the tested timber. The analysis considered the influence of the width of annual growth, the size and extent of knots, and the significance of the proportion of juvenile and mature wood for the density distribution.

It is anticipated that the findings of this research will demonstrate the feasibility of expanding the raw material base to encompass medium-sized wood. This is of particular importance for both conventional and innovative wood processing technologies.

Experimental material

Five middle-sized silver birch logs (labelled SI, SII, SIII, SIV and SV), aged approximately 40 years, were harvested from the Czarna Białostocka Forest District for use in the density distribution study. Their characteristics are presented in Table 1.

These were trees from Class I in Kraft's tree position classification, i.e. dominant trees [Assmann, 1968; Obmiński, 1978].

Their height was approximately 15 m, with a crown index of 0.5 and a breast height in bark of 23 cm (Table 1).

The silver birch logs were sawn. Ten uncut balks containing the pith were selected from each log for testing. After drying to 12% (± 1.7%) and planing of the surface, the average balk thickness was 70 mm (± 1.4 mm) and the length 1.5 m (± 0.1 m). The balks were labelled with consecutive numbers from 1 to 14, with the number 1 indicating the butt end balk and the highest numbers (13 or 14) the balks from the top of the logs. The width and length of the sawn timber (average values from two measurements) were determined to the nearest 1 mm.

The density of the wood was measured to the nearest 0.1 kg/m^3, using an MGD-05 isotopic densitometer, with americium (241Am) with a gamma-ray energy of 59.5 keV as the radiation source (Fig. 2). During all measurements, a 5 mm diameter radiation collimator was used at a distance of 150 mm from the detector. The measuring time was 30 seconds, with an error of ± 10 kg/m^3 [Krzosek, 1998; Dobrowolska et al., 2020].

A plotted measurement grid consisting of 150 × 20 mm rectangles was used to examine the density distribution of the individual balks. On the transverse

Table 1. Characteristics of the studied middle-sized silver birch (*Betula pendula*) trees

Characteristic	Log no.				
	SI	SII	SIII	SIV	SV
Tree age * [years]	38	44	42	42	38
Breast height diameter in bark [cm]	23	23	23	23	23
Tree height [m]	15.30	15.15	14.90	15.20	15.20
Crown length [m]	7.65	7,60	7.45	7.60	7.60
Crown index **	0.5	0.5	0.5	0.5	0.5

* On the basis of the number of annual growth rings in the butt end cross-section

** Crown length-to-height ratio

section, the density test consisted of measuring the tested timber in the northern and southern directions, along lines which ran parallel to the longitudinal axis of the wood, 20 mm apart. The first line, marked with the number 0, ran through the pith of each balk. Subsequent lines moving away from the pith were numbered 2, 4, 6, 8, 10, 12, 14 and 16. On the longitudinal section, the distribution of density was tested along measuring lines at distances of 150 mm.

The test results for the density distribution of middle-sized silver birch logs were divided into two groups: for wood 'with defects' – these are the results that were obtained according to the measurement grid – and for 'defect-free' wood, after eliminating significant changes in density caused by defects such as knots, cracks, false heartwood and grown-in bark. The results are summarised in tables and graphs for both groups of measurements. Only the results for wood 'with defects' [Elandt, 1964] were analysed statistically.

The breadth of the growth rings was determined with the use of a Biotronic measuring device, connected to a computer. Measurements were taken with a precision of 0.01 mm on wood strips; prior to testing, their surfaces were aligned using a microtome knife. Samples of macerated wood tissue were prepared from the annual growth rings numbered 3, 6, 9, 12, 15, and 20, and then every fifth growth ring up to the circumference. Microscope preparations were made to assess the length of the wood fibres. Measurements with an accuracy of 0.1 μm were performed using a Microscan Imager 512 computer image analyser.

A statistical analysis including two-segment regression was performed on the mean values of the measurements obtained for all of the logs tested [Elandt, 1964].

Results

1. Distribution of wood density in middle-sized silver birch timber

The basic results of the middle-sized wood density tests of the silver birch are presented in Table 2.

Included are values for mean density, standard deviation, coefficient of variation, then mean densities at breast height and at ¼ log height, minimum and maximum value, range, and number of density measurements taken.

The mean value for wood density in middle-sized silver birch was determined at 580 kg/m^3, a value within the range indicated by previous publications.

Table 2. Results of density distribution study in middle-sized wood of silver birch (*Betula pendula*) at 12% moisture content

Density		
Mean density [kg/m^3]	With defects	580
	Defect-free	573
Standard deviation for mean density [kg/m^3]	With defects	49
	Defect-free	42
Coefficient of variation for average density [%]	With defects	8.5
	Defect-free	7.3
Mean density [kg/m^3] at breast height diameter	With defects	558
	Defect-free	558
Mean density [kg/m^3] at ¼ log height	With defects	584
	Defect-free	581
Minimum measured density value [kg/m^3]	With defects	346
	Defect-free	473
Maximum measured density value [kg/m^3]	With defects	797
	Defect-free	695
Range [kg/m^3]	With defects	451
	Defect-free	219
Number of density measurements	With defects	2638
	Defect-free	2204

Table 3. Two-tailed Student's t-test of mean density values (level of significance a=0.05) for the density distribution in middle-sized silver birch wood

Analysed characteristic	Empirical statistic t	Critical statistic $t_{0.05/2; v}$	Number of degrees of freedom v
Average density over the entire log/ Average density at breast height	**3.384**	2.028	36
Average density over the entire log/ Average density at ¼ log height	-0.636	2.028	36

Table 4. Volume of annual growth rings (average values at breast height) in middle-sized silver birch logs

Characteristic	Middle-sized wood
Number of growth rings	37
Average width of annual growth rings [mm]	2.9
Minimum width of annual growth rings [mm]	0.6
Maximum width of annual growth rings [mm]	6.3
Coefficient of variation [%]	45.7

The presence of defects (mainly knots) was shown to have a statistically significant impact on the mean density of middle-sized silver birch timber. The values obtained for wood with defects were higher (by an average of 7 kg/m^3) than the mean density values for wood without defects.

The middle-sized silver birch wood was characterised by a coefficient of variation in density of 8.5%, and the gap between the obtained coefficients of variation in density for wood with and without defects was 1.2 p.p. The maximum measured value of density for the middle-sized wood was 797 kg/m^3, and the minimum was 346 kg/m^3.

In research by Hakkila [1966, 1979], it was found that in pines, spruces and birches the conventional density at ¼ log height is approximately equal to the average conventional density of the entire log. According to the authors of other density studies [Pazdrowski, 1988; Isaeva, 1978; Velling, 1979; Niedzielska, 1995; Viherä-Aarnio, 2017], measurements made at breast height represent the average conventional density for the whole trunk more appropriately.

Based on a two-tailed Student's test of the difference between mean values assuming unequal variance (significance level a=0.05), it was found that the mean density for the whole log was substantially higher than the mean density at breast height (Table 3). The average density measured at ¼ of the log height was not significantly different from the overall mean density for silver birch timber.

2. Presence of juvenile and mature wood and width of annual growth rings

The characteristics of the annual growth rings of middle-sized silver birch logs (mean values at breast height) are shown in Table 4. The mean width of these annual growth rings was 2.9 mm, with an average coefficient of variation of more than 45%.

Table 5 shows the length of wood fibres (at breast height) for the silver birch logs surveyed. The average fibre length was 1154 µm, with a coefficient of variation of 19.8%.

Fibre length in the juvenile wood zone increased from around 800 to 1220 µm (a change of 53%), while in the mature wood zone, the progression in fibre length was already much smaller (around 11%).

The results obtained are consistent with data found in the literature [Wagenführ et al., 1985; Kokociński, 2005; Galewski and Korzeniowski, 1958; Lachowicz, 2010]. According to Helińska-Raczkowska et al. [1995b], in the entire area occupied by juvenile wood (14 annual growth rings, forming a cylinder with a 12–13 cm diameter), occupying 30% to 60% of the entire cross-section, the length of the fibres at 1/6 of the height of 25-year-old silver birch trees increases by about 60% (from 800 to 1260 µm), while in the mature wood zone, the increase in the length of these anatomical elements is about 10%.

The presence of juvenile and mature wood was assessed using two-segment regression [Abdel-Gadir

Table 5. Wood fibre length characteristics (at breast height) of middle-sized silver birch logs

Characteristic	Middle-sized wood
Average length of wood fibres [μm]	1154
Minimum length of wood fibres [μm]	591
Maximum length of wood fibres [μm]	1792
Coefficient of variation [%]	19.8

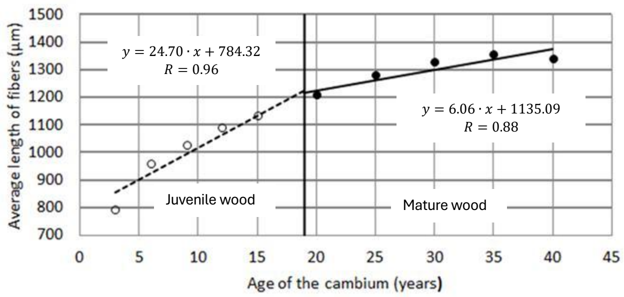


Fig. 1. Juvenile and mature wood in the examined middle-sized silver birch wood

et al., 1993; Stanisz, 2007; Bonham et al., 2001]. The juvenile wood zone was found to comprise 19 annual growth rings (Fig. 1).

The tested juvenile wood from breast height level formed a cylinder with an average diameter of 14 cm.

The ratio of the juvenile wood area at breast height to the entire log cross-section was between 60% and 68% (an average of 65%).

This indicates that young trees are practically entirely made up of juvenile wood. According to Pazdrowski et al. [2000] and Jakubowski [2004], the proportion of juvenile wood decreases over time as mature wood increases.

3. Distribution of density values for cross-section and longitudinal section of silver birch timber

The distributions of the mean density values over a transverse section of the timber and over the length of an entire middle-sized silver birch log are shown in Fig. 2 and 3.

The distributions of mean densities on the transverse section of the whole middle-sized silver birch log without defects and with defects were described by second-degree polynomials with a high coefficient of determination (Fig. 2 A). They show a good match of the regression function and explain 96% of the variation in mean density, analysed in accordance with the adopted model. There was a statistically significant effect of distance from the trunk pith on the distribution of mean densities across the silver birch logs.

A clear increase in the mean density of the wood was observed in the cross-section along the radius of the tree from the pith towards the circumference, from 562 kg/m^3 to 606 kg/m^3. The results appeared to be in agreement with those of Kubiak and Laurow [1994], but in opposition to those obtained by Krzysik [1957] and Kokociński [2004].

The variance analysis indicated that there was no statistically significant impact of north or south direction on the average density spread across the cross-section of the entire silver birch timber.

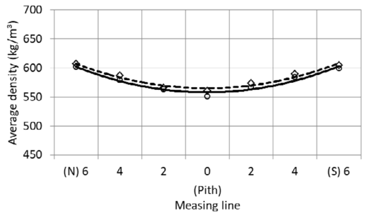
Also, the density measured directly at the radius of the trunk did not depend on the geographical direction. Similarly, Miler [1966], in his study, confirmed the lack of influence of compass points on the density distribution in medium-sized silver birch wood.

The Tukey test was used to check the effect of distance from the pith on density, by making a multiple comparison of mean densities (Table 7). Three similar groups were formed. The highest mean density (606 kg/m^3) was recorded for a measurement line placed 6 cm from the core. The next group had a mean density of 587 kg/m^3 and occurred 4 cm from the core. The lowest average density of 571 kg/m^3 was found for measuring lines placed 2 cm from the core.

Distribution of density values on the cross-section of middle-sized timber free of defects was determined at breast height and at ¼ of the overall height of a silver birch stems (Fig. 2 B and C).

The trend line characterising the changes in the distribution of mean densities on the cross-section of a middle-sized silver birch log, at both heights, took the form of a second-degree polynomial, characterised by high coefficients of determination: 0.94 for the distribution of mean

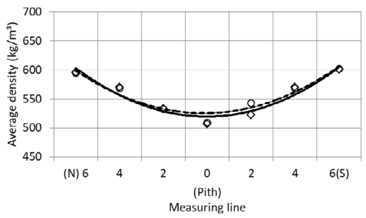
A



Defect-free $y = 5.16 \cdot x^2 - 40.44 \cdot x + 635.70;\ R^2 = 0.96$

With defects $y = 4.52 \cdot x^2 - 35.68 \cdot x + 636.64;\ R^2 = 0.96$

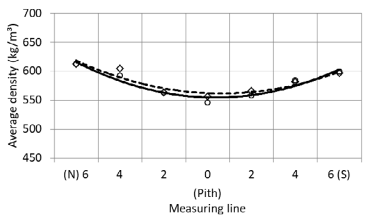
B



Defect-free $y = 8.56 \cdot x^2 - 67.28 \cdot x + 657.63;\ R^2 = 0.92$

With defects $y = 9.18 \cdot x^2 - 72.91 \cdot x + 666.04;\ R^2 = 0.94$

C



Defect-free $y = 6.11 \cdot x^2 - 51.29 + 661.96;\ R^2 = 0.94$

With defect $y = 5.32 \cdot x^2 - 45.63 + 659.65;\ R^2 = 0.86$

Fig. 2. Distribution of mean values of density on a transverse section of middle-sized silver birch timber: whole log (A), at breast height (B), at ¼ log height (C)

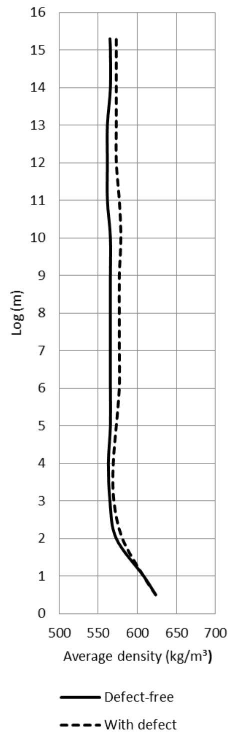


Fig. 3. Distribution of mean values of density on a longitudinal section of middle-sized silver birch timber

densities at breast height, and 0.86 for the distribution of mean densities at ¼ log height (equal to 3.75 m).

On the cross-section of the trunk, in both cases, the average wood density increased along the radius from the pith towards the circumference.

Correlation coefficients were also calculated between the distribution of mean densities over the trunk cross-section of an entire middle-sized silver birch log and the distributions of mean densities at breast height and at ¼ log height.

Two-sided significance tests of the correlation coefficients showed (at a significance level of $\alpha=0.05$) that the correlation was statistically significant in both cases (Table 8). The density distribution determined both at breast height and at ¼ log height corresponds to the density distribution for the whole trunk of middle-sized silver birch logs.

Figure 4 presents the distribution of the mean values of density on the longitudinal section of a middle-sized silver birch timber, with defects and without, for two zones – from the butt of the timber to the crown base, and between the crown base and the top of the tree.

One-way analysis of variance (Table 9) showed that the height of the wood on the trunk had a statistically significant effect on the mean density of middle-sized silver birch wood.

By determining the correlation coefficients and carrying out a two-sided significance test of the correlation coefficients (Table 10), the statistical significance of the relationship between the average wood densities for the two zones, from the butt to the crown base and between the crown base and the top of the tree, was established.

The obtained results showed that in the section from the butt of the log to the crown base, the correlation was statistically significant, while in the section between the crown base and the top of the tree the correlation was statistically insignificant.

In addition, the distributions of average densities at 0.2 log height (from the butt to 3.30 m) and above from 3.30 m to the top of the tree were analysed on the longitudinal section. The average density on the longitudinal section of the middle-sized silver birch log below 0.2 log height varied between 540 kg/m³ and

Table 6. Two-factor ANOVA (at significance level a=0.05) for the distribution of mean density values over a transverse section for entire middle-sized silver birch logs

Source of variation	Sum of squares of deviations	Number of degrees of freedom	Mean square of deviations	F empirical	p – test similarity
Free expression	663 214 832	1	663 214 832	303 603.531	0.000
Geographical direction	6 564	1	6 564	3.005	0.083
Distance from the pith	372 186	2	186 093	85.189	**0.000**
Direction * Distance	6 191	2	3 095	1.417	0.243
Error	4 661 673	2 134	2 184		

Table 7. Tukey's test of the 'pith distance' factor for the distribution of mean values of density on a cross-section of middle-sized silver birch timber

Distance from the pith [cm]	Mean density [kg/m^3]	Level of significance p		
		2	4	6
2	571		**0.000**	**0.000**
4	587	**0.000**		**0.000**
6	606	**0.000**	**0.000**	
Homogeneous group number		1	2	3

Table 8. Two-sided significance tests of correlation coefficients for the relations between the average density values on the cross-section of entire middle-sized silver birch timber and the average density values on the cross-section at breast height and at ¼ of the height of middle-sized silver birch stem (confidence level a = 0.05)

Area	Coefficient of correlation R	Critical value $R_{0.05; v; k+1}$	Number of degrees of freedom v
Distribution at breast height	0.994	0.950	2
Distribution at ¼ log height	0.977	0.950	2

Table 9. One-factor analysis of variance (at a significance level of α=0.05) for the distribution of mean densities on the longitudinal section of a middle-sized silver birch log

Empirical statistic F	Critical statistic $F_{0.05; u; v}$	Number of degrees of freedom v
4.103	1.250	100; 2 537

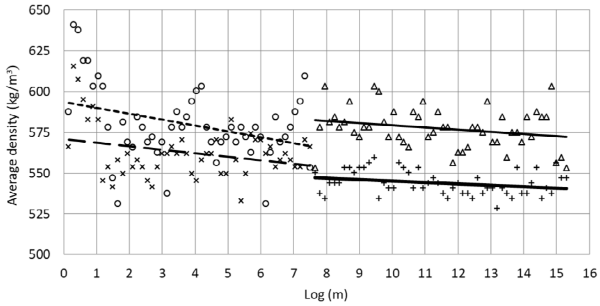
640 kg/m^3, while above that height it ranged between 540 kg/m^3 and 600 kg/m^3 (Fig. 5).

The results showed a statistically significant correlation for the first part of the log, while above 3.30 m the correlation was statistically insignificant, as there was little change in density in this area (Table 11).

Conclusions

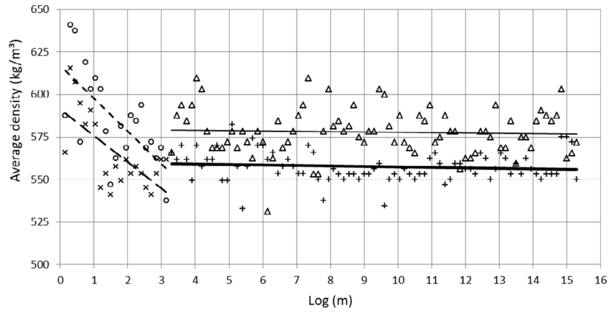
Based on the results of the tests and analyses performed, the following conclusions were drawn:

1. The position of wood in the transverse section and longitudinal section of a tree trunk had a statistically significant impact on the mean values of



Trunk	With defects	- - - - - -○	$y = -3.35 \cdot x + 592.90; R = -0.35$
	Defect-free	▬ ▬ ▬ ×	$y = -4.19 \cdot x + 590.94; R = -0.48$
Crown	With defects	——△	$y = -0{,}68 \cdot x + 584{,}97; R = -0.12$
	Defect-free	▬▬ +	$y = -0.03 \cdot x + 567.86; R = -0.01$

Fig. 4. Density distribution for wood with and without defects on longitudinal section of middle-sized silver birch logs



Below 0.2 log height	With defects	- - - - - -○	$y = -22.48 \cdot x + 622.28; R = -0.76$
	Defect-free	▬ ▬ ▬ ×	$y = -21.95 \cdot x + 618.80; R = -0.78$
Above 0.2 log height	With defects	——△	$y = 0.14 \cdot x + 575.35; R = 0.03$
	Defect-free	▬▬ +	$y = -0.09 \cdot x + 568.92; R = -0.03$

Fig. 5. Density distributions for wood with and without defects on the longitudinal section of a middle-sized silver birch log below and above 0.2 log height

Table 10. Significance test of correlation coefficients between the average density of middle-sized silver birch wood and its height on the trunk (at significance level α=0.05)

Area	**Coefficient of correlation R**	**Critical value $R_{0,05; v; k+1}$**	**Number of degrees of freedom v**
From the butt to the crown base (to 7.50 m)	**-0.348**	0.279	48
Between the crown base and the top of the tree	-0.124	0.276	49

Table 11. Significance test of correlation coefficients between the average density of middle-sized silver birch wood and its position on the trunk below and above 3.15 m height (at significance level α=0.05)

Area	**Coefficient of correlation R**	**Critical value $R_{0,05; v; k+1}$**	**Number of degrees of freedom v**
Below 3.30 m height	-0.762	0.433	19
Above 3.30 m height	-0.029	0.220	78

wood density in the tested middle-sized silver birch timber.

2. The direction (north or south) in which the density tests were performed had no statistically significant impact on the distribution of the mean density values in the transverse section of the entire tested silver birch timber.
3. The distribution of the density values in the transverse section of the entire tested timber could be described by a quadratic polynomial – the mean value of wood density clearly rises along the radius of the tree, from the pith outwards.
4. In the longitudinal section of the studied timber, the mean value of wood density become lower when moving away from the log butt in the direction of the base of the crown (a statistically significant correlation was recorded). No correlation was observed between the mean density value and the level of wood on the trunk.
5. For the middle-sized silver birch logs tested:
   - the mean value of wood density was statistically much higher than the mean density of wood at breast height;
   - the difference between mean density values for the wood at ¼ log height and for the entire log was statistically insignificant;
   - the distribution of the mean values for wood density at breast height and at ¼ log height accurately reflected the distribution of the mean values for density of wood in the transverse section assessed for the entire log length;
   - the height up to which the mean wood density value decreased as the measurement point moved from the log butt to the crown root was 0.2 log height.
6. The mean value of the wood density and its distribution in the longitudinal and transverse sections of middle-sized logs of silver birch confirm the possibility of expanding the base of raw materials to be used in both traditional and new technologies of wood processing.

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Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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PN–93/D–02002 – Surowiec drzewny. Podział, terminologia i symbole

PN–91/D–95018 – Surowiec drzewny. Drewno średniowymiarowe. Wspólne wymagania i badania.

Appendix no. 9 to Regulation no. 51 of the Directorate-General for Forestry of 30/09/2019. Technical terms. Middle-sized timber (Załącznik nr 9 do Zarządzenia nr 51 DGLP z dnia 30.09.2019 r. Warunki techniczne. Drewno średniowymiarowe iglaste).