Relationship of Tracheid Length, Annual Ring Width, and Wood Density in Scots Pine (*Pinus sylvestris* L.) Trees from Different Social Classes of Tree Position in the Stand

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This study investigated the relationship between the length of the tracheids, the width of annual rings, and the wood density of Scots pine (*Pinus sylvestris* L.) obtained from the dominant, intermediate, and suppressed classes of a 60-year-old stand. Measurement of tracheid length was performed on the material macerated from the following annual rings: 3, 6, 9, 12, 15, and thence every 5 annual rings. Basic density was determined on samples that included five annual rings from the core to bark. Tree position in the stand had a significant impact on the examined properties of wood. In a given biosocial class, tracheid length decreased as the width of annual rings increased. As the biosocial position of a tree in the stand improved, the length of the tracheids increased, and wood density decreased. In wood of the same density range, the increment in tracheid length was the greatest in wood of dominant trees and the lowest in wood of suppressed trees.

Keywords: Scots pine; Dominant; Intermediate and suppressed trees; Basic density; Tracheid length; Ring width

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INTRODUCTION

In Poland, Scots pine (*Pinus sylvestris* L.) is a dominant species in forest stands. Scots pine (*Pinus sylvestris* L.) is found under a wide range of ecological conditions and in different soils and climates (Martín *et al.* 2010); thus, there is considerable variability in wood properties (Verkasalo and Leban 2002; Peltola *et al*. 2009; Auty *et al*. 2014).

The properties of wood are determined by its microscopic structure (cell shape and dimensions), the submicroscopic structure (the layer structure and the distribution of basic compounds in the cell wall), and wood density (packing of wood mass per unit volume). Due to the structural variation of wood (both inter- and intraspecific), its properties vary across a broad range of values. Despite the variability of wood properties, it is a valuable structural material, and it is a useful raw material for the production of wood-based materials and use in the pulp and paper industry (Wegner *et al*. 2010).

For products manufactured both from solid wood and pulps, tracheid length is the primary wood microstructure characteristics that is related to final product quality. Tracheid length is not constant within a single species. Tracheid length varies with the cambial age and width of annual rings (Hannrup and Ekberg 2011; Mvolo *et al*. 2015).

The width of annual rings and the proportion of late wood are wood macrostructure properties that are used as indicators of wood quality in many branches of the wood industry. The width of annual rings reflects radial growth dynamics, and the proportion of late wood is related to wood density. For softwoods, the proportion of late wood in the narrow annual rings is greater than in the wide annual rings (Adamopoulos *et al.* 2009). Therefore, such wood exhibits higher strength parameters than wood with wide annual rings (Rozenberg *et al.* 1999). Because density is strongly related with mechanical strength properties of wood (Mankowski *et al*. 2020) and is relatively easy to measure, it is recommended as an indicator of wood technological properties (Panshin and de Zeeuw 1980; Armstrong *et al*. 1984).

The above-mentioned wood properties depend on many internal factors, such as genetic predispositions (Pot *et al*. 2002), physiological irregularities, growth hormone activity (Buttò *et al*. 2020), and external factors related to climatic and habitat conditions (Wimmer and Grabner 2000; Mäkinen and Hynynen 2014; Sopushynskyy *et al*. 2017). These properties show diverse variability in wood of individual softwood species, within individual trees, and between trees in even-aged stands depending on the social class of tree position in the stand (Lindström 1996a; Koga and Zhang 2004).

During the vegetation season, seasonal differences have been observed in the activity of cambium, which are reflected in the intensity of divisions and the type of wood produced (Larson 1994). Therefore, wood density, annual ring width, and cell length change with tree age (Franceschini *et al*. 2013), stem height, and tissue position at the stem cross-section (Gartner *et al*. 2002).

The width of annual rings influences the formation of anatomical element length. Findings on the effect of growth rate on changes in cell length vary. For example, 7 of the 16 publications cited by Zobel and van Buijtenen (1989) reported a reduction in tracheid length as annual ring width increased in species such as *Pinus radiata*, *Pinus echinata*, *Pinus ponderosa*, *Pinus taeda*, and *Picea abies.* In three studies on the wood of *Pinus sylvestris*, *P. glabra*, and *Picea abies*, an opposite relationship was shown; however, in the remaining 6 of the 16 studies, no relationship was reported between annual growth increment and tracheid length in wood of *Pinus sylvestris*, *P. echinata*, *P. strobus*, *Picea abies*, *Larix decidua*, *Pseudotsuga menziesii*, and *Tsuga heterophylla*.

In trees that are weakened, which is characterised by a rapid decrease in diameter increment, tracheid length drops drastically (de Kort 1990; Niedzielska 1995). In contrast, in vital trees, tracheid length declines as annual rings width increases (de Kort 1990). In addition, Fujiwara and Yang (2000) reported a negative relationship between tracheid length and ring width for wood of *Pinus banksiana*, *Abies balsamea*, and *Picea mariana*, but no such dependence was found for *Picea glauca*.

Though researchers generally agree on the variation in wood density on the transverse section of the stem (along the radius of the tree) within a single tree, there is much controversy over the variability of the value of wood density between trees from different biosocial classes in even-aged stands, particularly softwoods. Studies by Fabisiak and Moliński (2002a,b) on trees in Poland in various tree positions in the stand indicate considerable differences in wood properties. Jachontow (1913), who investigated wood density in pines growing in the Vistula basin, reported this finding. He stated that wood density increases as site class deteriorates. In addition, the variation in wood density depending on the location of xylem within a single tree is equally problematic. This variation is essential to the determination of pulp yield and technological quality of wood obtained from different parts of the stem.

Due to the above-stated findings and the fact that wood properties within the same species vary from site to site (Aleinikovas and Grigaliûnas 2006; Fernandes *et al.* 2017), it was decided that the aim of this study would be the determination of the properties of pine wood originating in Poland from the vicinity of Zielonka near Poznań. The research is a part of a series of tests concerning the recognition of the properties of pine wood from various regions of Poland. Comparing those properties with the properties of wood from other regions of the world, it is possible to compare the quality of wood raw material. Moreover, the aim of this study is to determine the dependence between tracheid length, annual ring width, and wood density in Scots pine (*Pinus sylvestris* L.) trees that came from different biosocial classes of tree positions in the stand.

EXPERIMENTAL

Analyses were conducted on wood of Scots pine (*Pinus sylvestris* L.) that was collected from a 60-year-old, even-aged pure stand of stand quality class I located in the Zielonka Forest District near Poznań (N 52°37´, E17°03´). Dominant, intermediate, and suppressed trees were selected for the analyses. Three trees were selected from each biosocial class. The mean diameters at breast height (at 1.3 m from ground level) were 28 cm, 22 cm, and 14 cm, for the 3 trees selected from each respective biosocial class. The trees were characterised by a cylindrical straight stem and a uniformly developed crown. Discs of 5 cm in height were cut from the breast height diameter of the trees. Three strips of 20 mm in thickness measured in the tangential direction were cut from the disks in the north-south direction. The first strip after planing was used to determine the width of annual rings and the proportion of late wood along the north radius of the analysed trees. From the second strip, the samples, each of which comprised of 5 annual rings counting from the pith to bark, were used to determine the basic density of wood. The basic density was determined on fresh wood (W>30%). Immediately after extracting the samples, their volume (V_w) was determined based on the Archimedes principle. The next step was to determine the weight of these samples when absolutely dry. For this purpose, the samples were dried at 105 °C for 48 h. The mass of the samples was determined on the electronic balance with an accuracy of 0.001 g. The basic density was calculated according to the formula (1),

$$\mathrm{BD} = m_d/V_w \quad (1)$$

where BD is the basic density (kg/m^3), m_d is the mass of oven-dry sample (kg), and V_w is the volume of sample of maximum swelling m^3, W>30%).

The third strip was used to prepare macerates for measurements of tracheid length. The measurements were taken for the following annual rings: 3, 6, 9, 12, 15, and thence every 5 annual rings. To prepare samples for tracheid length measurement, the early and late wood zones were collected separately from the investigated annual rings, and they were then subjected to tissue maceration. For this purpose, a 1 : 1 acetic acid : hydrogen peroxide mixture was used. Maceration was run in an incubator at 60 °C for 24 h. From each annual ring, lengths of 30 tracheids each were measured in the early wood and late wood, and the mean tracheid lengths were calculated for each annual ring.

The widths of the annual rings and late wood zones were measured under a stereoscope microscope (SZX7, Olympus, Hamburg, Germany) (accurate to 0.01 mm), and tracheid lengths were measured using a Primo Star light microscope (Carl Zeiss Microscopy, Oberkochen, Germany) (accurate to 0.1 µm). Both microscopes were equipped with Moticam®3+ cameras (Motic Incorporation Ltd., Hong Kong, China) and coupled with a Motic Images Plus 2.0 software computer image analyser (Motic Asia, Hong Kong, China). Statistical analysis was performed using Statistica 10.0 software (Dell, Round Rock, TX, USA). The descriptive statistics were determined, and single factor analysis of variance (ANOVA) tests were applied. All tests were carried out for the significance level of $p < 0.05$.

RESULTS AND DISCUSSION

Changes in annual rings width along the radius in Scots pines trees that differ in their growth dynamics in an even-aged stand are presented in Fig. 1.

The mean annual ring width was 3.4 mm in dominant trees, 2.4 mm in intermediate trees, and 1.5 mm in suppressed trees (Table 1). Analysis of variance showed that differences in the width of annual rings in trees from different social classes of tree position in the stand were statistically significant, as the calculated value of the test statistic (F) was 14.876, and the table value at the significance level of 0.05 was 3.114.

Table 1. Descriptive Statistics and Analysis of Variance of Annual Rings Width (RW) (mm) of Pine Wood of Dominant (D), Intermediate (I), and Suppressed (S) Trees

<table>
<tr><td>Biosocial Tree Class</td><td>Mean Value</td><td colspan="3">Min</td><td colspan="2">Max</td><td>Std. Deviation</td><td colspan="2">Std. Error</td></tr>
<tr><td>D</td><td>3.44</td><td colspan="3">1.75</td><td colspan="2">6.40</td><td>1.456</td><td colspan="2">0.297</td></tr>
<tr><td>I</td><td>2.39</td><td colspan="3">1.00</td><td colspan="2">4.53</td><td>1.001</td><td colspan="2">0.206</td></tr>
<tr><td>S</td><td>1.54</td><td colspan="3">0.53</td><td colspan="2">4.10</td><td>1.016</td><td colspan="2">0.207</td></tr>
<tr><td colspan="2" rowspan="2">Source of Variation</td><td colspan="8">Results of Variance Analysis</td></tr>
<tr><td>SSB</td><td>df</td><td>MSB</td><td>SSE</td><td>df</td><td>MSE</td><td>F</td><td>p</td></tr>
<tr><td colspan="2">Biosocial Tree Class</td><td>50.477</td><td>2</td><td>25.238</td><td>132.331</td><td>78</td><td>1.696</td><td>14.876</td><td>0.000*)</td></tr>
</table>

SSB – sum squares between groups; MSB – mean squares between groups; SSE – sum squares within groups; MSE – mean squares within groups; df – degrees of freedom; p – level of significance; F – value of test function F; *) significant differences

Radial variability of the share of late wood in trees belonging to different biosocial classes is presented in Fig. 2, and descriptive statistics in Table 2.

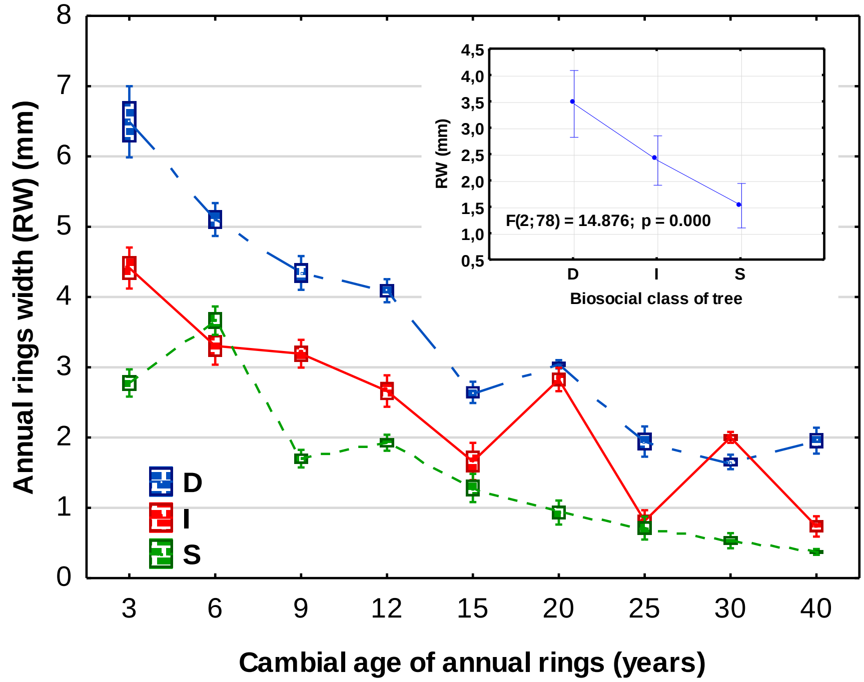

Fig. 1. Annual rings width of pine wood from dominant (D), intermediate (I) and suppressed (S) trees and the results of the ANOVA analysis

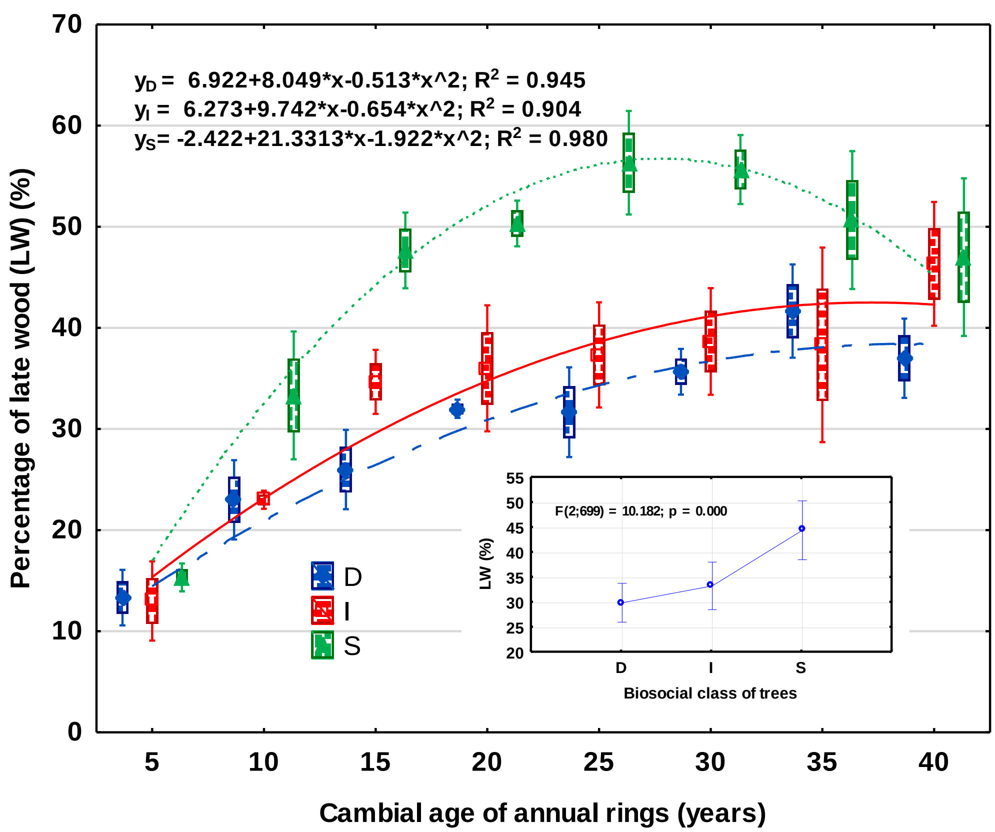

Fig. 2. The effect of cambial age of annual rings on the percentage of late wood (LW) in wood of dominant (D), intermediate (I), and suppressed (S) pine trees

Table 2. Descriptive Statistics and Analysis of Variance of Percentage of Late Wood (LW) (%) of Pine Wood of Dominant (D), Intermediate (I), and Suppressed (S) Trees

Biosocial Tree Class	Mean	Min	Max	Std. Deviation	Std. Error
D	30.04	10	46	9.205	1.879
I	33.41	10	54	11.267	2.299
S	44.54	14	61	13.978	2.853

Source of Variation	Result of Variance Analysis (significant p < 0.05)							
	SSB	df	MSB	SSE	df	MSE	F	p
Biosocial Class	2763.250	2	1381.625	9362.750	69	135.692	10.182	0.0001*)

In the first 5 annual rings, the mean percentage of late wood was comparable for all trees and ranged from 13% to 15%. As distance from the pith increased, increasingly larger differences were observed in the percentages of late wood in individual tree development groups. The highest percentage of late wood (61%) was observed in suppressed trees. For intermediate and dominant trees, the percentages of late wood were 54% and 46%, respectively. Differences in percentage of late wood in the trees originating from different biosocial classes are statistically significant (Table 2) at a lower level of p = 0.0001.

A similar relationship was found between the age of annual rings and the basic density of wood (Fig. 3).

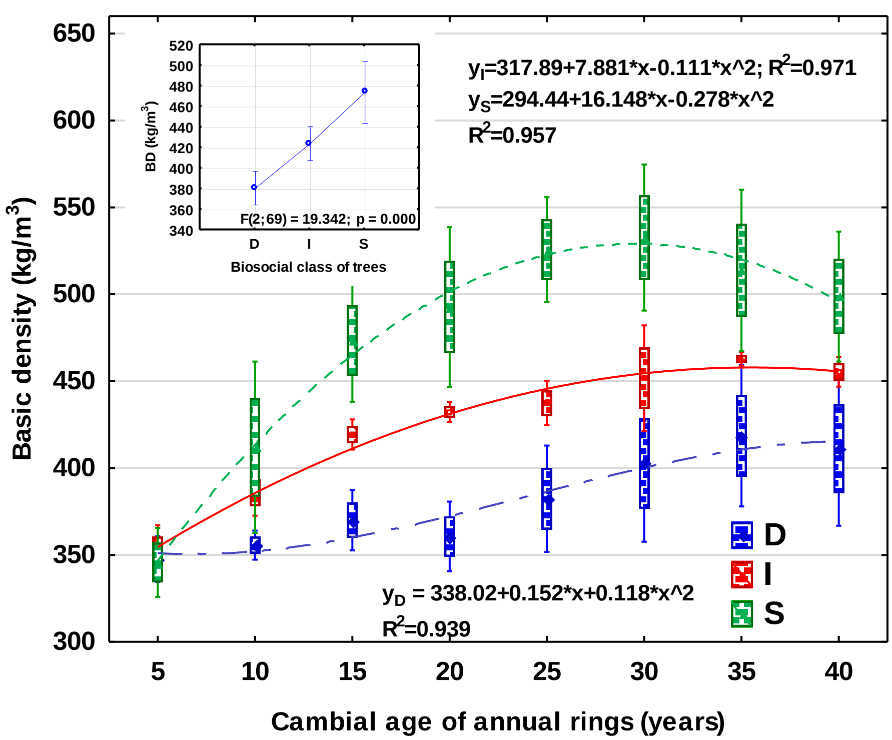

Fig. 3. The effect of cambial age of annual rings on basic density of wood in dominant (D), intermediate (I), and suppressed (S) pine trees

Figure 3 shows that, as the cambial age of annual rings increased, the wood density of suppressed trees increased faster than in dominant trees. The social class of tree position was related to an increase in wood density along the radius in trees, *i.e.*, from the pith to the bark. Analogous conclusions were reached by Lindström (1996b) and Peltola *et al.* (2007).

The results showed that wood density increased as the distance from the pith increased until it reached the maximum value, after which it showed a largely downward trend. Niedzielska (1995) reported that wood density in coniferous trees increases until approximately the 50th annual ring to 60th annual ring, and a certain decrease may be found in the circumferential zone in especially old trees. Similar results to those of this study were presented by Auty *et al.* (2014), who observed a reduction in wood density for Scots pine beyond the 60th annual ring. Within the first 10 annual rings counting from the pith, the average difference in the wood density of suppressed and dominant wood was found to be the smallest compared to the density from further annual rings. However, as the distance from the pith increased, differences were evident in values of wood density of individual trees. The greatest density was recorded in suppressed trees, and the lowest density was recorded in dominant trees.

The relationships investigated could be described relatively accurately by quadratic equations. The analysis of variance indicated that there was a significant effect of cambial age of annual rings on basic density of wood (Table 3). The cambial age of annual rings explained approximately 94%, 97%, and 96% of the change in wood density for dominant trees, intermediate trees, and suppressed trees, respectively. The effect of other factors on wood density was slight, as it ranged from 4% to 6%. In addition, a significant effect of cambial age on wood density for Norway spruce was shown by Franceschini *et al*. (2013).

The dispersion of mean wood densities within a given social class of tree position in the stand was relatively limited. In the group of dominant trees, it ranged from 331 to 455 kg/m^3. In the group of intermediate trees, it ranged from 335 to 488 kg/m^3. In the suppressed trees, it ranged from 331 to 574 kg/m^3.

Table 3. Descriptive Statistics of Wood Basic Density (BD) (kg/m^3) for Dominant (D), Intermediate (I), and Suppressed (S) Pine Trees and Results of Analysis of Variance

Biosocial Tree Class	Mean	Min	Max	Std. Deviation	Std. Error
D	381	331	455	38.343	7.827
I	425	335	488	38.977	7.956
S	474	331	574	71.469	14.588

Source of Variation	Result of Variance Analysis (significant p < 0.05)							
	SSB	df	MSB	SSE	df	MSE	F	p
Biosocial Tree Class	104416.1	2	52208.0	186238.8	69	2699.1	19.343	0.000*)
Cambial Age of Annual Rings	107841.8	7	15405.97	182813.1	64	2856.4	5.393	0.000*)

When comparing mean wood basic density in trees from different social classes of tree position in the stand, the lowest density was recorded in wood of dominant trees (381 kg/m^3), whereas it was highest in suppressed trees (474 kg/m^3). The analysis of variance indicated that the differences in wood density in the investigated trees varying in the position of trees in the stand were statistically significant (p = 0.001), as the value of the calculated test statistic F_{cal} (19.343) was greater than F_{tab} (7.64) (Table 3).

The obtained results were consistent with those presented by Molteberg and Høibø (2006) and Johansson (1993), who reported that wood of suppressed trees exhibited higher density than dominant trees. Further, Lindström (1996a) showed that crown development is the main regulator of basic density for coniferous trees. A similar conclusion was given by Kärkkäinen (1984) and Deng *et al.* (2014), who stated that prediction of wood density may be improved by considering the social class of tree position in the stand.

Similar to the features of wood presented above, also the length of the tracheids varies depending on the position of the annual rings on the cross-section and the position of the tree in the stand (Fig. 4). In all test trees, the length of the tracheids increases with the increase of the cambial age, in accordance with Sanio's law (1872). In the first dozen or even several dozen annual rings, the length of the tracheids increases rapidly, then it reaches a more or less constant value, showing slight fluctuations.

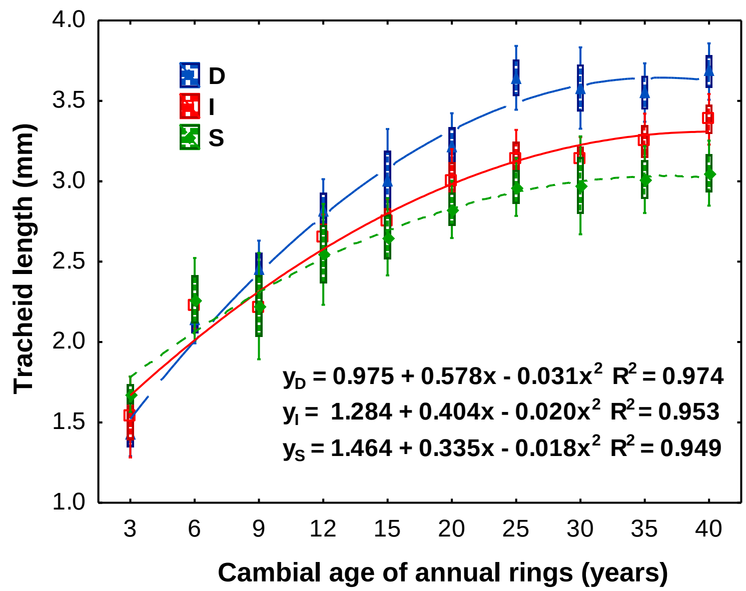

Fig. 4. The effect of cambial age of annual rings on tracheids length of wood in dominant (D), intermediate (I), and suppressed (S) pine trees

As the position of the tree in the stand improves, the length of the tracheids increases. The above observation is consistent with the results of similar studies on Douglas fir (*Pseudotsuga menziesii* Franco) (Fabisiak and Moliński 2002b) and Scots pine (*Pinus sylvestris* L.) (Fries *et al.* 2003). Tracheid lengths ranged from 1.42 mm to 3.68 mm in the case of the dominant tree, from 1.53 to 3.39 mm in the intermediate tree, and from 1.68 to 3.05 mm in the suppressed tree. These sizes are similar to published tracheids length data for *Pinus sylvestris* (*e.g.*, Irbe *et al.* 2013; Mäkinen and Hynynen 2014).

Correlations between annual ring width, tracheid length, the proportion of late wood in the annual ring, and wood density were determined based on the mean values from three trees in a given social class of tree position in the stand. The matrixes presented in Tables 4 to 6 illustrate that all the obtained correlation coefficients were significant. Annual ring width was strongly, negatively correlated with cambial age, wood density, late wood proportion, and tracheid length. The correlation between the width annual rings and their cambial age increased as the biosocial position of the trees in the stand improved. A similar relationship was found between the width of annual rings and tracheid length. Percentage of late wood was positively correlated with basic density. This correlation increased as the biosocial class of the trees in the stand deteriorated. Therefore, the dependence between these characteristics was stronger in wood with narrower annual rings. Tracheid length was strongly, positively correlated with cambial age of annual rings and this correlation increased as the biosocial class of the trees in the stand improved. Similar results were obtained by Molteberg and Høibø (2006) for the wood of Norway spruce, in which tracheids from dominant trees were longer than those from suppressed trees.

The presented correlation matrixes indicate that the length of tracheids was dependent on the dynamics of the growth of the width of annual rings. Thus, tracheids length decreased as the width of rings increased. A strong negative correlation was found between these values (correlation coefficients of r = -0.937, r = -0.905, and r = -0.901 were observed for dominant, intermediate, and suppressed trees, respectively) (Fig. 5). In addition, a strong negative correlation between annual ring width and tracheid length was shown by Dutilleul *et al*. (1998).

Table 4. Correlation Matrix of Annual Rings Width (RW), Basic Density (BD), Percentage of Late wood (LW), Cambial Age of Annual Rings (CA), and Tracheid Lengths (TL) of Pine Wood of Dominant (D) Trees

	RW_D	BD_D	LW_D	CA	TL_D
RW_D	1.000	-0.896	-0.897	-0.908	-0.936
		p=0.001	p=0.001	p=0.001	p=0.000
BD_D		1.000	0.893	0.963	0.953
			p=0.000	p=0.000	p=0.000
LW_D			1.000	0.851	0.946
				p=0.004	p=0.000
CA				1.000	0.948
					p=0.000
TL_D					1.000

Table 5. Correlation Matrix of Annual Rings Width (RW), Basic Density (BD), Percentage of Late wood (LW), Cambial Age of Annual Rings (CA), and Tracheid Lengths (TL) of Pine Wood of Intermediate (I) Trees

	RW_I	BD_I	LW_I	CA	TL_I
RW_I	1.000	-0.943	-0.991	-0.896	-0.905
		p=0.000	p=0.000	p=0.000	p=0.001
BD_I		1.000	0.965	0.937	0.972
			p=0.000	p=0.000	p=0.001
LW_I			1.000	0.911	0.935
				p=0.000	p=0.000
CA				1.000	0.941
					p=0.000
TL_I					1.000

Table 6. Correlation Matrix of Annual Rings Width (RW), Basic Density (BD), Percentage of Late wood (LW), Cambial Age of Annual Rings (CA), and Tracheid Lengths (TL) of Pine Wood of Suppressed (S) Trees

	RW_S	BD_S	LW_S	CA	TL_S
RW_S	1.000	-0.918	-0.946	-0.806	-0.901
		p=0.000	p=0.000	p=0.009	p=0.000
BD_S		1.000	0.978	0.676	0.877
			p=0.000	p=0.046	p=0.002
LW_S			1.000	0.669	0.835
				p=0.049	p=0.005
CA				1.000	0.917
					p=0.000
TL_S					1.000

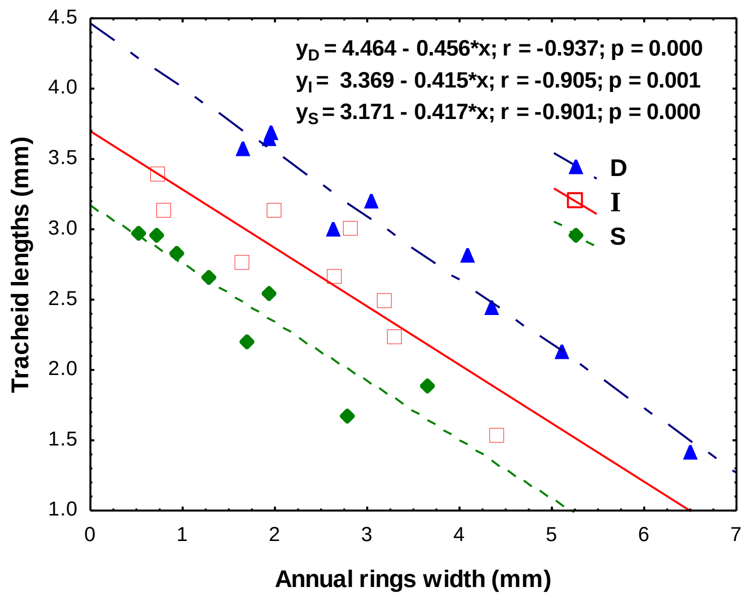

Fig. 5. The effect of annual ring width on tracheid lengths in wood from dominant (D), intermediate (I), and suppressed (S) pine trees

Tracheids of dominant trees were over 1 mm longer than those from suppressed trees, and the observed relationship was independent of annual ring width. At identical annual ring widths, tracheid length increased as the social class of tree position in the stand increased. Similar results were obtained by Irbe *et al.* (2013), as their investigation of the wood of Scots pine and Lodgepole pine showed that, for trees of the same age, longer tracheids are found in trees with greater diameters. In this study, the maximum tracheid length was recorded in annual rings of approximately 2 mm in dominant trees, whereas the maximum tracheid length for intermediate and suppressed trees was at the annual ring width of approximately 0.8 mm. A similar result was reported by Sudo (1973) in the study on *Pinus densiflora*, in which the maximum tracheid length was found for annual rings with widths of 1 mm to 2 mm.

Because there is a strong relationship between annual ring width and tracheid length, the average length of anatomical elements may be estimated based on the determined annual ring widths; thus, the suitability of wood for specific applications may be inferred. Such a potential was reported for Scots pine by Mäkinen and Hynynen (2012).

The relationship of basic density and the width of annual rings in individual pine trees is presented in Fig. 6. Figure 6 shows that wood density decreased as the annual ring width increased. Similar observations were reported by Johansson (1993), Franceschini *et al*. (2013), Auty *et al*. (2014), and Dobner *et al*. (2018). This relationship is best described by cubic polynomial functions, for which the coefficients of determination were $R^2 = 0.836$, $R^2 = 0.893$, and $R^2 = 0.903$ for dominant trees, intermediate trees, and suppressed trees, respectively. In suppressed trees, the maximum density was recorded in wood when the annual ring width was approximately 0.5 mm. In contrast, in intermediate trees, the optimum width of annual rings was 1.0 mm. Karlman *et al*. (2005) showed that, in 100-year-old pine trees that came from naturally regenerated stands in Sweden, the greatest density was recorded for annual rings that ranged in width from 1 mm to 2 mm. Figure 6 shows that for annual rings wider than 3 mm, the differences in wood density of analysed trees decreased.

Figure 7 presents the effect of the percentage of late wood on the density of wood that came from trees from different social classes of tree position in the stand. Figure 7 confirms that the density of the entire xylem increased linearly as the percentage of late wood in annual rings increased (Antonova and Stasova 1993). When investigating the wood of Douglas firs with different crown vitality, de Kort and Baas (1991) showed that the percentage of late wood explained approximately 60% of the variation in wood density. Nevertheless, Fig. 7 shows that at the same percentage of late wood, poorer tree growth conditions were related to greater solid wood density. Thus, deterioration of the social position of a tree in the stand resulted in an increase in the wood density of the late portion of the annual ring. Through extrapolating the linear relationships presented in Fig. 7 for the percentage of late wood that equals 100%, the obtained density values for the late wood of dominant trees, intermediate trees, and suppressed trees were 600, 670, and 700 kg/m^3, respectively.

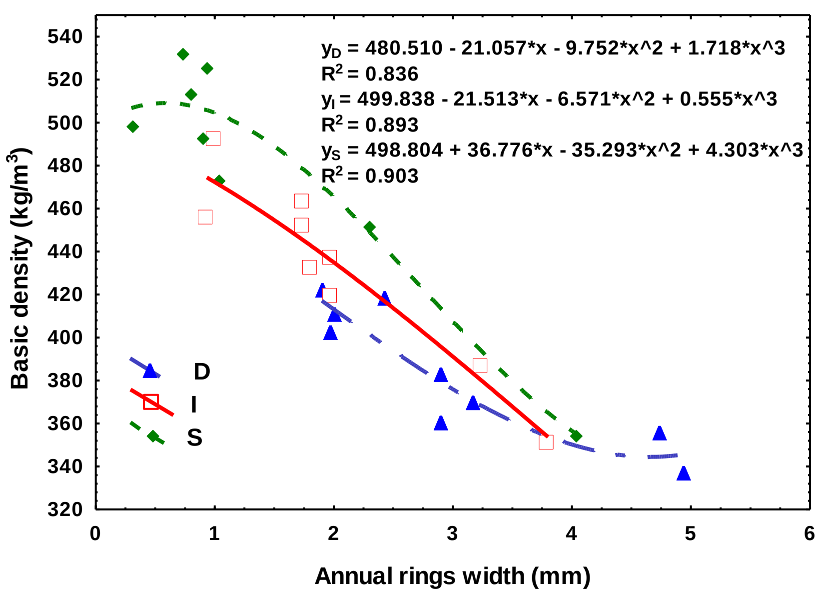

Fig. 6. The relationship between annual ring width and basic density of wood in dominant (D), intermediate (I), and suppressed (S) pine trees

For early wood (assuming percentage of late wood as 0%), the density did not depend on the social class of tree position and was approximately 300 kg/m^3.

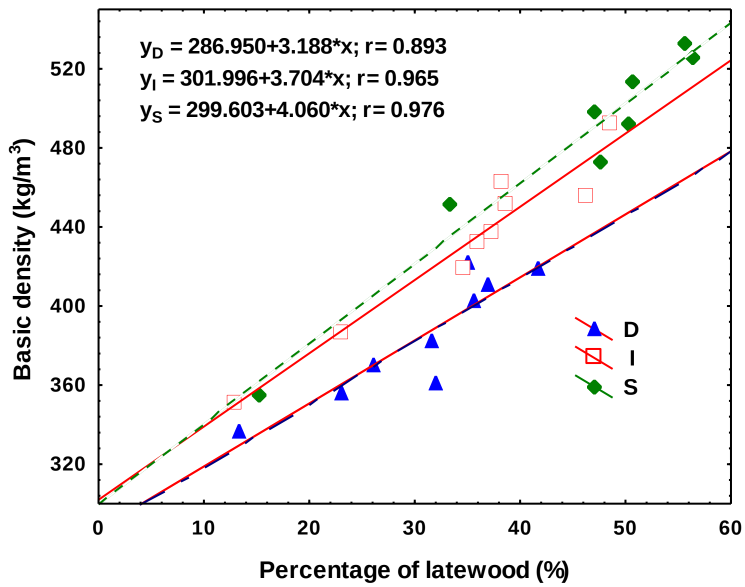

Fig. 7. The relationship between the percentage of late wood and basic density of wood in dominant (D), intermediate (I), and suppressed (S) pine trees

Thus, the variation in density of solid wood within the analysed social classes of tree position in the stand increased as the percentage of late wood increased. These results indicated that the structure of late wood, varied depending on the social class of tree position in the stand. The variation in this structure could be confirmed by the packing density of late tracheids, which is their number in a radial segment of 100 μm in length (Fabisiak and Helińska-Raczkowska 1992).

The tracheid packing density was 4.6 (4.1...5.6) in the outer annual rings (> 20) for dominant trees, 5.0 (4.5...5.4) for intermediate trees, and 5.3 (4.5...5.8) for suppressed trees. Further, the number of late tracheids per unit width of late wood in the annual ring increased with a deterioration of tree growth conditions. Thus, at the same percentage of late wood, the number of tracheids in the late section of annual rings of suppressed trees was higher than that in dominant trees, which resulted in a more compact packing of xylem per unit volume at the approximately identical thickness of their walls; thus, density increased (Fabisiak and Helińska-Raczkowska 1992).

Figure 8 presents the relationship between tracheid length and density of pine wood. Figure 8 shows that tracheid length increased as wood density increased. At an identical wood density range, the increment in tracheid length was greatest in wood of dominant trees (slope: b = 0.02), slightly lower in wood of intermediate trees (slope: b = 0.01), and it was the lowest in wood of suppressed trees (slope: b = 0.007). When wood density increased by 50 kg/m^3, tracheid length increased approximately 60%, 50%, and 20% for dominant, intermediate, and suppressed trees, respectively. The results were related because both tracheid length and wood density showed a largely constant value in further rings after a marked increase from the pith up to approximately the 30th annual ring.

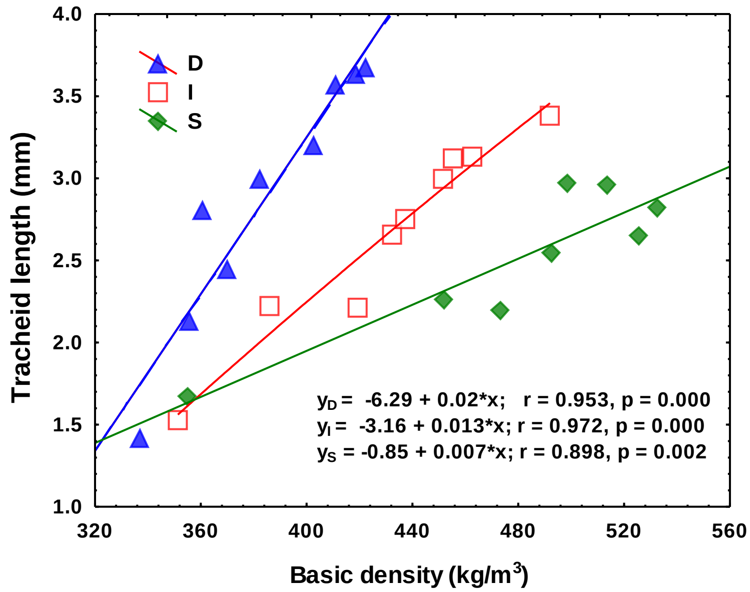

Fig. 8. The relationship between average tracheid lengths of a given annual ring and basic density of wood in dominant (D), intermediate (I), and suppressed (S) pine trees

CONCLUSIONS

1. Differences in the width of annual rings in trees from different biosocial classes in the even-aged stand of *Pinus sylvestris* L. were statistically significant. The widest annual rings occur in the wood of dominant trees and the narrowest in the wood of suppressed trees. A high negative correlation was found between the cambial age of annual rings and their width. This correlation increases with the improvement of the biosocial class of trees in the stand.
2. The highest percentage of late wood and wood density is characteristic for the wood of suppressed trees. High positive correlation coefficients were found for these wood features, and the value of this coefficient increases with the deterioration of the biosocial class of trees in the stand. Moreover, it has been shown that in the case of the same proportion of late wood, the density of wood is higher when the growth conditions of the tree are worse.
3. Irrespective of the biosocial class of trees, with the increase of the cambial age the length of the tracheids increases rapidly in the first dozen annual rings, then it reaches a more or less constant value, showing slight fluctuations. The wood of suppressed trees is characterized by the shortest tracheids in comparison to the wood of intermediate and dominant trees. Tracheid length increased as the biosocial class of trees in the stand improved. In each biosocial class of trees in the stand, tracheid length decreased as the width of annual rings increased and increased as wood density increased.

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