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A comparison of the selected properties of macrostructure and density of wood of scots pines (*Pinus sylvestris* L.) growing on various mine soil substrates

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Abstract

The research was conducted on the external spoil heap of the 'Piaseczno' Sulphur Mine (southern Poland). This paper is aimed to compare the selected properties of macrostructure and density of wood of Scots pine trees planted onto the external spoil heap of the mine, in the scope of forest reclamation, depending on the soil substrate and employed reclamation treatments. The annual rings of pine trees on the Quaternary sands and Tertiary Krakowieckie clays (S&C) were significantly wider than those of the individuals on the Quaternary loose sands (S) and Quaternary sands and Tertiary clays after an intense initial fertilization (F). However, the share of latewood zone and density of wood of the pine trees growing on the substrate F were significantly greater in comparison to those of substrates S and S&C.

Key words

annual rings, latewood, density, increment core, soil

Introduction

Scots pine (*Pinus sylvestris* L.) is the most widespread woody plant species in the territory of Poland. Pines grow in almost 60% of all Polish forests (Lasy Państwowe 2017). A relatively high flexibility of pine in terms of their adaptation to changeable environmental conditions is the reason for using this species commonly for afforestation of post-industrial areas (Pietrzykowski et al. 2015). Trees growing in such areas develop under difficult habitat conditions, facing strong competition for nutrients and water with other species (Pietrzykowski 2008). These conditions are so distinct from those encountered in natural habitats that they can ultimately result in developing stands of different structures and changing the macrostructure of wood of Scots pine (Ochał et al. 2010). A major objective of reclamation of post-industrial sites is to restore their utility value. Thus, reclamation to forest aims to introduce new trees onto areas previously defor-

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ested and recreate multifunctional forest ecosystems (Krzaklewski 2001). However, if an investor decides to bear certain costs of afforestation, he surely hopes to gain some profits from selling the trees planted on waste dumps. His income will depend on the dimensions of timber harvested, which are mostly affected by the widths of annual rings forming the tree trunk, and the wood quality being a derivative of technical quality of the stem and wood density (Barszcz et al. 2014; Michalec et al. 2016).

Scots pine wood is one of the major resources used in wood-based industry; therefore, an accurate recognition of its properties is of great interest. Both in Poland and Europe, the study of Scots pine wood properties was carried out mainly on the material taken from the trees growing in a forest environment (Paschalis 1980; Pazdrowski and Spława-Neyman 1993; Niedzielska et al. 2001; Witkowska and Lachowicz 2012, 2013; Kask et al. 2008; Fernandes et al. 2017) as well as on post-agricultural land (Jelonek et al. 2008, 2009, 2010). Whereas, the properties of wood macrostructure of pines used in the afforestation of reclaimed post-industrial waste sites were neglected.

The aim of this study was to verify the hypothesis that between Scots pines growing on different substrates, there are significant differences of following features: the share of sapwood on the stem cross-section, the annual ring width, the share of latewood and wood density.

This is the third paper regarding the Scots pine trees, growing on a waste dump of the Piaseczno sulphur mine. The previous two concerned the variability of the morphological features of the trees' structure (Pająk et al. 2016b) and the assessment of their stems' quality (Pająk et al. 2016a).

Material and methods

Study sites

The studies were carried out on the external waste dump of the Piaseczno Sulphur Mine, the construction of which started in 1959. The site under scrutiny is located on the left-bank flood plain of the Vistula River, near Tarnobrzeg in the Sandomierz Basin, within the mesoregion of the Vistula Lowland (Zielony and Kliczkowska 2012). The waste dump was built of overburden of the sulphur mine accumulated in an unselective manner, consisting of the Quaternary and Neogene sands, as well as the Neogene Krakowiec clays (Pawłowski et al. 1985). The waste dump was shaped in the form of a frustum of a cone and took up an area of 120 ha. Woody plants were introduced on the dump in the years 1967–1969. The plantations established on the external waste dump were characterised by a diversified species composition and varied forms of mixing, the aim of which was to grow mixed forest stands. The structure of regeneration was dominated by alder (introduced as a transitional species) and Scots pine. Apart from these, there were also other tree species, planted as a group mixture, such as: a European larch (*Larix decidua* Mill.), red oak (*Quercus rubra* L.) and a sessile oak (*Quercus petraea* (Matt.) Liebl) (Ziemnicki et al. 1980; Węgorek 2003). The field research was conducted in spring of 2014, in the north-western part of the waste dump. The investigations covered, circular trial plots with an area of 1 ar, located in Scots pine stands. The selection of certain locations for establishing trial plots was preceded by the soil survey.

Table 1. Mean values of selected physical and chemical properties of mine soil substrates

Substrate	Level (cm)	Silt (%)	Clay (%)	pH		C (%)	N (%)
				H_20	KCl		
S	0–5	5	1	5.3	4.4	0.76	0.03
	5–30	4	1	6.3	5.6	0.10	0.01
	30–110	3	1	7.0	6.2	0.04	0.01
S&C and F*	0–5	23	3	5.7	5.0	1.84	0.10
	5–30	24	4	6.4	5.6	0.31	0.02
	30–110	22	3	6.6	5.8	0.14	0.01

F* – in the course of the reclamation treatment, the substrate was additionally subjected to an intensive fertilisation (200 kg of urea, 200 kg of 40% potassium chloride and 320 kg of superphosphate per one hectare [Ziemnicki 1980; Węgorek 2003].

In total, 17 sample plots were set up, located on various mine soil substrates, such as:
– 5 trial plots on the Quaternary loose sands (substrate S)
– 5 trial plots on the mixture of the Quaternary sands and the Neogene Krakowiec clays (substrate S&C)
– 7 trial plots on the mixture of the Quaternary sands and the Neogene clays after an intensive fertilisation (substrate F).

Basic information referring to the physical and chemical properties of mine soil substrates encountered on particular trial plots are presented in Table 1.

Field sampling

Analyses of wood properties covered a total of 68 trees, including 20 individuals growing on the substrates S and S&C each, and 28 trees on the substrate F.

Four pine trees were chosen, in every trial plot, from which a single increment core was taken. The core was sampled from the northern side of a tree trunk at breast height (1.3 m above the ground level). All the investigated trees belonged to the second class (co-dominant trees) according to the Kraft's classification system.

Sample preparation and measurements

The increment core samples were placed in a special holder, and then, a very thin layer of wood was trimmed perpendicular to the grains using a segment knife. Provided that no traces of coloured heartwood had been detected, a cross-section of the core obtained in the above-mentioned manner was subject to measurements covering the width of sapwood zone using a ruler with an accuracy of 1 mm. Afterwards, cross-sections of the increment cores were scanned with a resolution of 1200 dpi, which allowed to obtain their digital images in the form of bitmaps. These images served for measuring the widths of the annual rings, as well as the widths and shares of latewood zones performed with the use of a specialised software 'Przyrost WP' (Biotronik 2001). The measurements were taken successively, starting from the bark towards the stem pith. Then, based on the results of measurements, the increment cores were divided into sections. In each section, five annual rings were enclosed, starting from the bark of the trunk. The last section, located directly by the stem pith, usually contained less than five annual rings. For every section, a relative (stipulated) wood density was determined, calculated as a quotient of weight of absolutely dry wood and its volume in the maximally swollen state. The volume was measured using the hydrostatic method (Olesen 1971). According to the methodology assumed by Ericson (1959), wood density obtained for particular sections of the increment core was converted into wood density of the trunk cross-section at breast height, through computing a mean value weighted by shares of every section within the entire area of the trunk cross-section.

Statistical analysis

The results were compared, and the mean values and coefficients of variation were calculated for particular trees and types of substrates on which they grew. Statistical analyses were performed employing standard procedures, for which the significance level $p = 0.05$ was assumed (StatSoft Inc. 2011).

A consistency of empirical distributions with the normal distribution was assayed using the Shapiro-Wilk test. A homogeneity of variances within the groups compared was evaluated with the use of Levene's test. A significance of differences between mean values for multiple samples was verified by means of the variance analysis, while the Scheffe's test was used for indicating the community responsible for rejecting the null hypothesis of equality of means. If the assumptions of parametric test were not meet, the Kruskal-Wallis (KW) and the multiple comparison tests (MC) were performed as required. The significance level $p \leq 0.05$ was assumed.

Results

Technical mean values of height and dbh of the pines under analysis for particular mine soil substrates amounted to, respectively: 15.9 m and 18.9 cm for the substrate S, 16.0 m and 23.1 cm for the substrate S&C, and 18.3 m and 22.5 cm for the substrate F (Pająk et al. 2016). Based on the data given in Table 2, the mean numbers of annual rings within the increment cores sampled from pine trees growing on the substrates S and S&C amounted to 29.3 and 29.2 (Fig. 1), with relatively low coefficients of variation accounting for 6.7% and 8.1%, respectively. A higher mean number of annual rings and greater variability in this value were recorded for the increment cores taken from individuals on the substrate F. These values amounted to 35.6 and 16.7%, respectively. Statistically significant differences in the number of annual rings within the increment cores sampled from trees growing on various substrates were revealed (KW test: $p = 0.0000$), whereas the MC test proved a significantly greater number of annual rings within the cores taken from pines on the substrate F when compared with those growing on two other substrates (substrates F and S – MC test: $p = 0.0001$, substrates F and S&C – MC test: $p = 0.0002$).

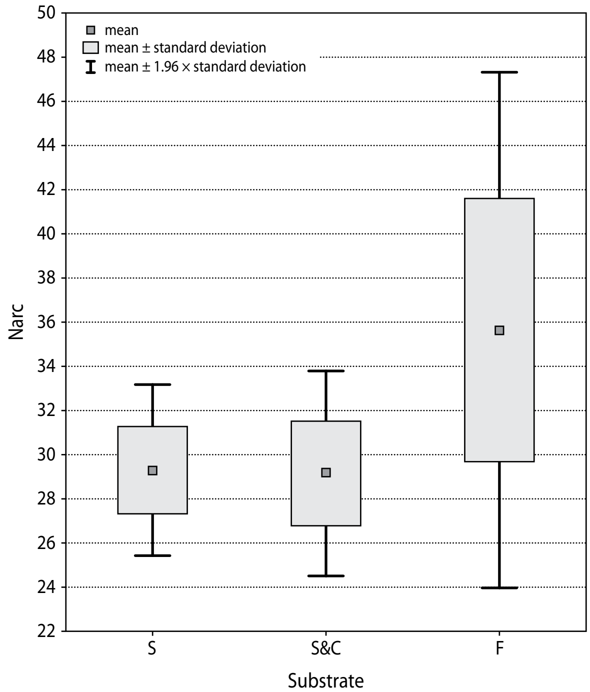

Figure 1. Numbers of annual rings within the increment cores

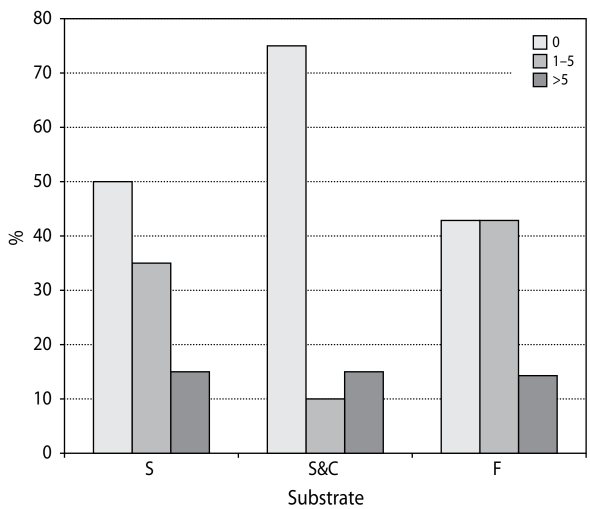

Figure 2. Share of trees depending on the number of increments within the heartwood

Number of annual rings in cores

Figure 2 displays the frequency of trees per particular substrates depending on the number of annual rings enclosed in the heartwood. Based on the data given in this figure, coloured heartwood was not detected within the wood of half of all trees growing on the substrate S, 75% of individuals on the substrate S&C (15 trees), and 43% of pines on the substrate F. The maximum number of annual rings within the heartwood zone encountered in the trunks of particular tress amounted to eight rings for the substrates S and F, and ten rings for the substrate S&C. Due to a small number of annual rings within the heartwood zone of pine trees under analysis, we did not continue further and more thorough examinations referring to the percentage of this value on the radius and within the area of the trunk cross-section.

Annual rings' width

A mean width of annual rings amounted to 2.66 mm for the substrate S, 3.47 mm for the substrate S&C, and 2.52 mm for the substrate F (Tab. 2, Fig. 3). While the coefficients of variation describing this property accounted for 17.1%, 24.0% and 22.1%, respectively. The KW test revealed statistically significant differences in the width of annual rings between pines growing on various mine soil substrates ($p = 0.0001$), while the MC test proved that the annual rings of trees on the substrate S&C were significantly wider than those of individuals on the substrates S and F ($p = 0.0139$ and $p = 0.0001$, respectively).

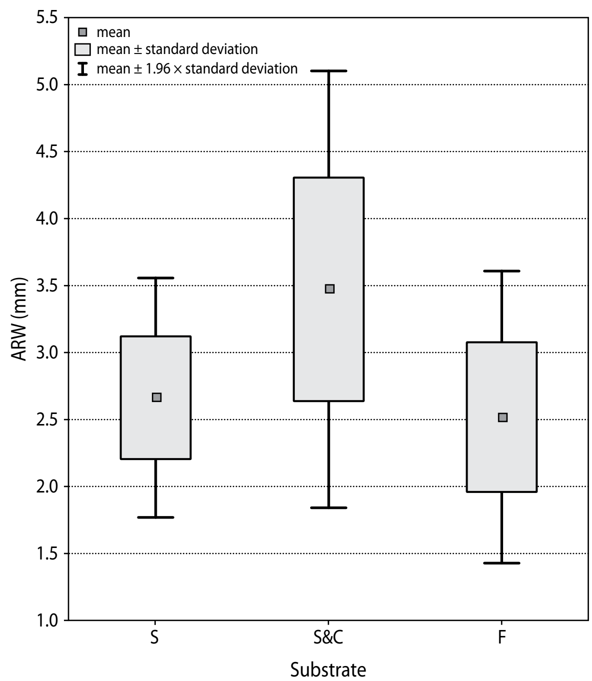

Figure 3. Annual rings' width

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Table 2. Values of the studied properties of wood of pine trees on the 3 substrates

Number of tree	NARC	ARW (mm)	SL (%)	γ_w (g · cm^{-3})
1	2	3	4	5
SUBSTRATE S				
19	32	2.93	32.3	0.498
20	33	2.56	29.8	0.444
21	32	1.69	29.5	0.446
22	27	3.38	35.3	0.456
49	29	3.12	30.9	0.437
50	31	2.62	29.7	0.472
51	30	2.66	34.3	0.448
52	25	3.01	30.0	0.454
60	28	3.29	36.1	0.519
61	28	2.96	24.6	0.488
62	28	2.68	35.0	0.454
63	28	2.33	30.5	0.429
67	29	2.95	34.5	0.447
68	29	1.94	37.8	0.474
69	29	2.06	30.2	0.484
70	27	2.18	25.2	0.436
77	31	3.17	35.7	0.433
78	30	2.50	31.6	0.467
79	29	2.56	34.2	0.446
80	31	2.63	27.6	0.432
Mean	29,3	2.66	31.7	0.458
CV [%]	6,7	17.1	11.4	5.3
SUBSTRATE S&C				
1	30	3.12	31.8	0.437
2	30	2.75	39.8	0.492
3	30	4.24	35.2	0.483
4	30	3.71	31.6	0.465
11	31	2.31	33.4	0.447
12	25	2.88	39.2	0.426
13	32	2.64	36.9	0.449
14	28	2.00	39.1	0.517
31	30	4.10	33.4	0.425
32	30	3.38	33.5	0.435
33	30	4.79	26.3	0.404
34	32	3.99	37.6	0.381
37	22	4.06	24.5	0.422
38	27	2.63	42.9	0.440
1	2	3	4	5
39	29	2.87	35.9	0.449
40	31	3.17	41.4	0.488
43	30	5.00	29.4	0.440
44	28	4.41	31.8	0.408
45	28	3.87	30.3	0.397
46	30	3.51	25.7	0.406
Mean	29,2	3.47	34.0	0.441
CV [%]	8,1	24.0	15.4	8.0
SUBSTRATE F				
86	32	2.07	44.7	0.543
87	37	1.60	37.5	0.487
88	38	2.36	37.9	0.530
89	35	2.58	48.0	0.522
98	37	2.67	34.9	0.495
99	40	2.04	40.9	0.484
100	39	2.11	38.3	0.506
101	39	2.36	36.4	0.478
106	34	1.94	33.4	0.461
107	37	3.12	44.6	0.464
108	31	2.74	38.8	0.524
109	39	2.34	42.4	0.506
111	35	3.00	50.1	0.485
112	40	2.72	45.7	0.558
113	40	2.66	42.1	0.464
114	41	2.56	42.9	0.540
116	42	2.64	37.8	0.477
117	39	1.91	37.1	0.478
118	38	2.16	45.4	0.496
119	37	2.13	37.5	0.430
121	38	2.21	39.1	0.476
122	39	2.16	37.9	0.474
123	41	1.92	37.2	0.469
124	39	2.55	44.8	0.506
130	22	2.85	44.6	0.440
131	23	4.01	42.0	0.442
132	25	3.75	31.7	0.433
133	21	3.34	34.7	0.444
Mean	35,6	2.52	40.3	0.486
CV [%]	16,7	22.1	11.3	7.0

NARC – number of annual rings per one increment core; ARW – annual ring width; SL – share of latewood; γ_w – relative wood density; CV – coefficient of variation

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Share of latewood

Mean share of latewood in pine trees on the substrate S amounted to 31.7%, with the coefficient of variation of 11.4% (Tab. 2, Fig. 4). In respect to the individuals growing on the substrate S&C, these values were 34.0% and 15.4%, respectively, while on the substrate F, they accounted for 40.3% and 11.3%, respectively (Tab. 2). The variance analysis revealed statistically significant differences in the share of latewood between pines growing on various mine soil substrates (p = 0.0000), while Scheffe's test proved that the share of latewood within the wood of trees on the substrate F was significantly higher when compared with those growing on the other two substrates (substrates F and S: p = 0.0000, substrates F and S&C: p = 0.0001).

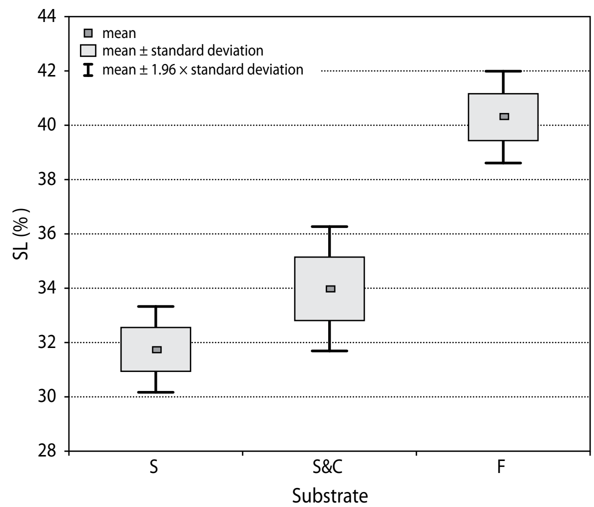

Figure 4. Share of latewood

Wood density

Mean relative wood density of pine trees on the substrate S amounted to 0.458 g•cm^{-3}, for the substrate S&C it was 0.441 g•cm^{-3}, while for the substrate F, the mean relative wood density reached the value of 0.486 g·cm^{-3} (Tab. 2, Fig. 5). A variability of this characteristic amongst individuals growing on different substrates was relatively low, and the coefficients of variation accounted for 5.3%, 8.0% and 7.0%, respectively. The variance analysis revealed significant differences in wood density between pines growing on the three mine soil substrates under scrutiny (p = 0.0000), while Scheffe's test proved that a significantly higher value of the characteristic in question was that of pines on the substrate F when compared with individuals growing of the substrates S and S&C (respectively: p = 0.0149 and p = 0.0000).

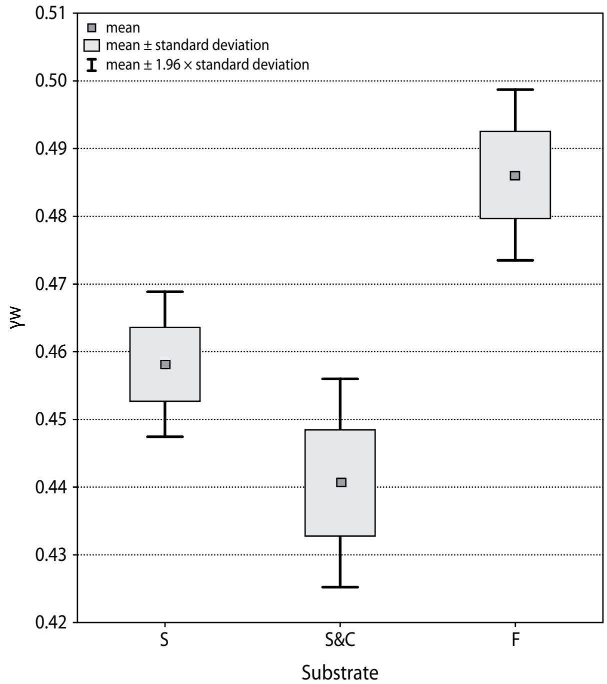

Figure 5. Relative wood density

Variability in wood features on the radius of the cross section of trunks

Based on the data given in Figure 6, a variability in annual ring widths observed on the radius of the trunk cross-section of pine trees growing on the substrates S and S&C was similar and characterised by a considerable decrease in this value. The variability in annual ring widths revealed a decreasing tendency in this value, dropping down from the sections located close to the stem pith (V, VI and VII), towards the trunk girth. In the recent 5-year period of tree development (section I), a clearly readable increase in the annual ring widths was recorded with regard to both of the above-mentioned research samples. In respect to the individuals growing on the substrate F, after a rapid decrease in annual ring widths between the sections VIII and VII, that is, at the beginning of lifespan of those trees, a small, gradual increase in this value was observed. This increase started from the section IV and was followed by another gradu-

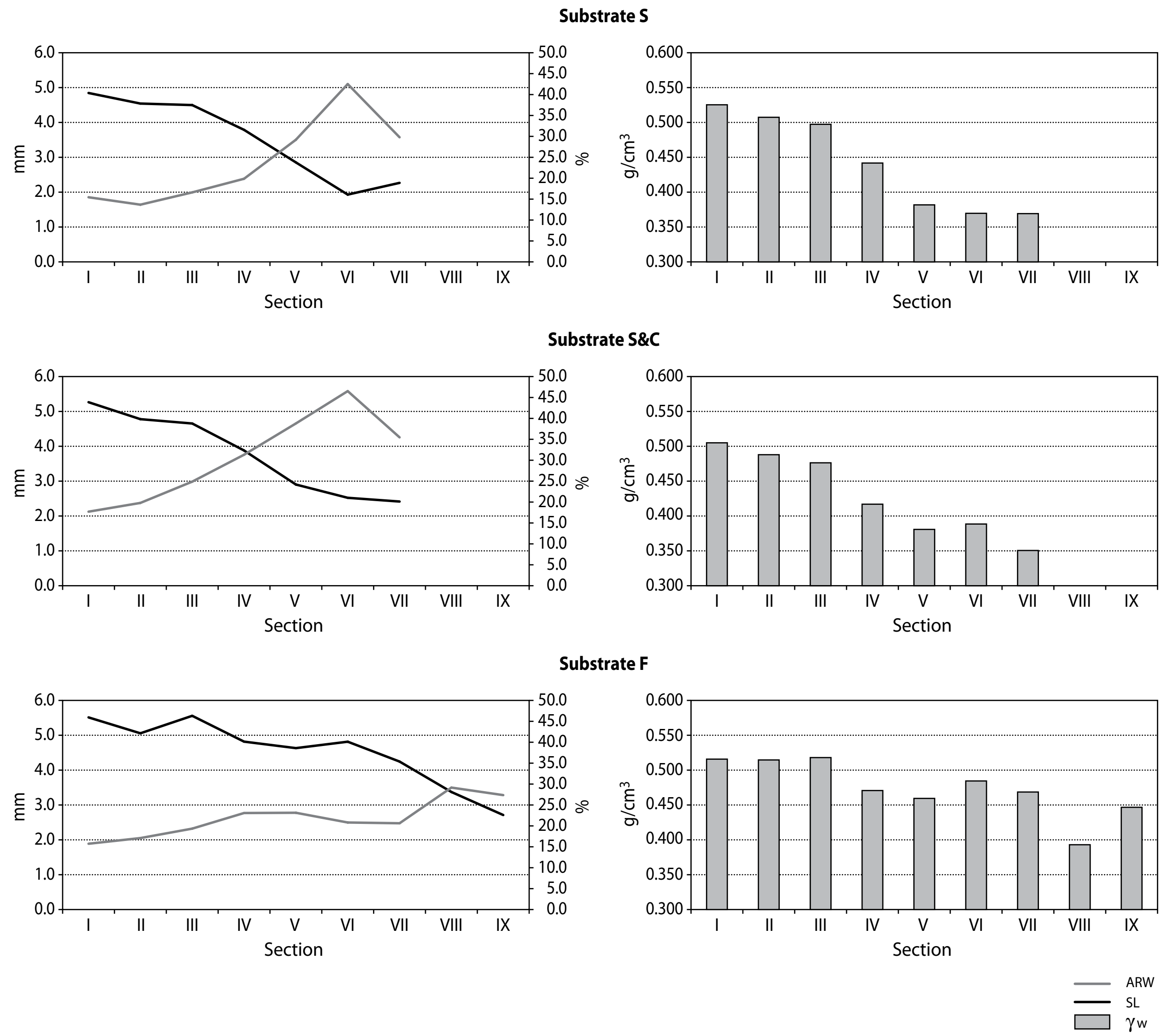

Figure 6. Variability in the annual increment width, the share of late wood and wood density on the radius of the cross section of trunks of pine trees growing on various substrates

Explanation of symbols – see Table 2.

al decrease towards the trunk girth. Noteworthy are the higher mean widths of annual rings located close to the stem pith recorded in pine trees on the substrates S and S&C, and reaching the values of ca. 5 mm. Whereas, the annual ring widths of trees growing on the substrate F did not exceed 4 mm.

Discussion

The area of the land on which forest-reclamation is planned in the coming years is estimated to be over 800 ha all across Poland (Referowska-Chodak 2017). In this context, the results presented in this paper are important both from a scientific and a practical point of view. The study covered examinations of wood of pine trees planted on the waste dump in two episodes, that is, in the period between 1967 and 1971, and in the years 1974–1976 (Ziemnicki et al. 1980; Węgorek 2003). Thus, when the study was conducted, they would have been nearly 50 years old. An occurrence of a considerably smaller number of annual rings within the increment cores sampled at breast height from the trunks of trees growing on the substrates S and S&C may be due to the fact that these individuals were planted in the younger planting episode. On the other hand, a greater number of annual rings in the cores taken from pines on the substrate F seems to indicate that they were planted within the earlier episode.

Coloured heartwood was not detected in the wood of half of the increment cores sampled from the trunks of pine trees growing on the substrate S, and 75% of samples taken from the individuals growing on the substrate S&C. Whereas, in respect to the substrate F, heartwood occurred within 57% of increment cores; however, in 43% of the samples, heartwood enclosed no more than five annual rings. This was due to the fact that the trunks of pine trees under analysis had just started the process of heartwood formation, taking into account a relatively great variability in the mean number of annual rings within the sapwood. These findings are supported by studies carried out by Skrzyszewski et al., who investigated pine trees from the Carpathian and Sudeten Mountains, ranged from 35 to 71 (Skrzyszewski et al. 2001). It should be interesting to examine the wood of the pine trees under scrutiny once again, after a dozen or so years would pass.

The mean widths of annual rings obtained in these studies amounted to 2.66 mm, 3.47 mm and 2.52 mm, respectively for the substrates S, S&C and F. Therefore, the wood of pines growing on the substrates S and F can be considered to be fine-ringed wood (with an annual ring width below 3 mm), while that of individuals from the substrate S&C can be classified as wide-ringed wood (with an annual ring width above 3 mm) (Krzysik 1974). The mean values given in this paper were in significantly higher than those quoted by Paschalis (1980) and Skrzyszewski et al. (2001), which could have been a result of the younger age of pines growing on the waste dump in Piaseczno. Statistical analyses revealed that the wood of individuals on the substrate S&C (mixture of sands and clays) had significantly wider annual rings when compared with those of trees growing on two other substrates. Taking into account that the dbh values of pines growing on the substrates S&C and F did not differ significantly (Pająk et al. 2016b), we concluded that the growth in diameter of the trees on the substrate S&C was faster than that of the individuals on the substrate F. This seems to be due to a higher share of juvenile wood within the dbh cross-section of the trunk in pines growing on the substrate S&C. Admittedly, we did not conduct an analyses of the juvenile zone area; however, an observation of the figures displaying the variability in the investigated properties of wood of radius trunk cross-section allowed us to conclude that nearly half of the cross-section radius (sections IV–VI) of trees on the substrate S&C enclosed the juvenile wood. This was indicated by both, high mean values of annual ring widths within the above-mentioned sections, exceeding 3 mm, as well as low shares of latewood and wood density. In respect to the trees growing on the substrate F, the properties of wood tissue typical of juvenile wood were recorded only within two sections, those most closely located to the stem pith (sections VIII and IX). While, the respective values of these properties analysed for the other seven sections indicated an occurrence of mature wood. Based on the obtained results, we concluded that the trunks of pines on the substrate F revealed a higher share of mature wood at breast height, in comparison to the individuals on the other two investigated substrates. Most likely, this was due to their older age. Juvenile wood is characterised by smaller density and lower strength parameters; therefore, its technical quality is worse than that of mature wood (Tomczak et al. 2010; Tomczak and Jelonek 2012). Thus, the above-mentioned quality of wood obtained from the trunks of pines presently growing on the substrate F is expected to be a little higher than that of trees from the other two substrates. Nevertheless, it seems that these differences will blur over time, since the share of mature wood within the trunks of pines on the substrates S and S&C will increase, resulting in an increase in wood density as well. After analysing the data given in Figure 2, we concluded that even now pine trees growing on the above-mentioned substrates have started to form mature wood. This conclusion is based on the fact that the density of wood in their outermost sections exceeded the value of 0.500 g•cm^{-3} and is comparable with that of the outermost sections of individuals on the substrate F. Thus, taking into account both cognitive and utilitarian perspectives, it seems very important to replicate similar studies cyclically to determine the impact of fertilisation of mine soil substrates on properties of pine wood.

Results of studies conducted by Pająk et al. (2016a) revealed that the technical quality of trunks expressed by a certain class of large-sized timber (Warunki techniczne 2002) was higher with regard to the trees growing on the substrates S&C and F in comparison to the individuals on the substrate S. Cyclical replication of studies to verify the results obtained would also be recommended.

Mean share of latewood computed for pine trees from the substrates S, S&C and F amounted to 31.7%, 34.0% and 40.3%, respectively. The mean shares obtained for the substrates S and S&C were close to the data given by Paschalis (1980) referring to pines from eastern Poland, and Skrzyszewski et al. (2001) with regard to most of the individuals they examined in the Carpathian and Sudeten Mountains. The mean value calculated for the trees from the substrate F was significantly higher when compared with those determined for the other two substrates. This was due to an occurrence of mature wood within the prevailing part of the radius of the trunk cross-section, as mentioned above. As a consequence of the higher share of latewood zone within the annual rings of tree trunks growing on the substrate F, the density of their wood was significantly greater, with a mean value reaching up to 0.486 $g \bullet cm^{-3}$. The other two mean values of wood density amounted to 0.458 $g \bullet cm^{-3}$ for the substrate S and 0.441 $g \bullet cm^{-3}$ for the substrate S&C. The total volumetric shrinkage of pine wood is assumed to maintain at the level of 13.6% (Meier 2015). Therefore, the mean values of absolute wood density, that is, absolutely dry wood, computed for the substrates S, S&C and F would account for 0.530 $g \bullet cm^{-3}$, 0.510 $g \bullet cm^{-3}$ and 0.563 $g \bullet cm^{-3}$, respectively. This would place the pine trees under analysis in the group of species forming light wood, that is, with a density ranging from 0.510 to 0.600 $g \bullet cm^{-3}$ (Krzysik 1974). The values of relative (stipulated) wood density obtained in these studies are comparable with those quoted by Niedzielska et al. (2001), while the calculated values of absolute wood density correspond to the density ranges reported by Paschalis (1980). Amongst the properties subjected to examination as discussed in this paper, wood density proved to be the least varying property.

As it was mentioned in the introduction, as per the authors' knowledge, the results presented in the paper are the first ones regarding the wood properties of pines growing on the industrial waste dump. However, taking into consideration the differences in the age of pines growing on different substrates, it would be necessary to repeat the same research in a few years to verify the research hypothesis included in the aim of study. It would also be interesting to broaden the scope of the analysis with a variability in the wood anatomical structure and some mechanical properties.

Conclusions

1. With regard to most of the pine trees under analysis, an occurrence of coloured heartwood within their wood was not detected. Whereas, in respect to those that actually contained heartwood, these did not contain more than the oldest few annual rings. Consequently, at the moment of conducting these studies, the pines under scrutiny had just entered the stage of heartwood formation.
2. The pine trees growing on the substrate S&C (sands and clays) had considerably wider annual rings when compared with those of the individuals on the substrate S (sands) and F (fertilised sands and clays).
3. The share of latewood zone and density of wood of the pine trees growing on the substrate F were significantly greater than those of the individuals on the other two substrates. Such a result should be associated with a higher age of pines from the substrate F compared to the pines from the substrates S and S&C. These differences are expected to blur over time.
4. Taking into consideration that the age differences between the groups of pines growing on different substrates could have influenced on the obtained results, it would be necessary to repeat the same tests in a few years to verify the hypothesis about the substrate's impact on the wood properties of the pines growing on it.

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