Mechanical Performance of Scots Pine Wood from Northwestern Poland – A Case Study

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Scots pine is one of the most commercially important wood species in Europe. This study assessed the potential usefulness of pinewood from the Noteć Forest for construction purposes by evaluating its mechanical properties and investigating the influence of the site conditions on the pinewood performance. Additionally, the variability of the mechanical properties from the bark to the pith was analyzed. The results showed that the properties of pinewood varied significantly within the Noteć Forest despite similar growing conditions, which may be a result of genetic variation. Wood from Sowia Góra had the greatest density (566 kg/m^3) and excellent mechanical performance (compressive strength of 64 MPa), while wood from Zamyślin exhibited the lowest density (526 kg/m^3) and a lower compressive strength (54 MPa). Comparison of the properties of the pinewoods from various locations indicated that the general conditions in the forest stand, however crucial for tree growth, were not the only determinants of wood performance. The results also showed high variability in density and mechanical properties between juvenile and mature wood in all the examined trees. Overall, pinewood from the poor habitats of the Noteć Forest could be a useful raw material for various industrial purposes.

Keywords: Scots pine; Pinus sylvestris; Mechanical properties; Material characteristics; Compressive strength; Modulus of elasticity; Bending strength; Pinewood

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INTRODUCTION

Scots pine (*Pinus sylvestris* L.), also known as red fir or common pine, is a species native to Eurasia, ranging from Western Europe to eastern Siberia and from northern Scandinavia to the mountains of Southern Europe. Common in boreal, hemiboreal, and nemoral forests, it covers approximately half of the forested area. Often found on poor sandy and stony soils or peat bogs, it is usually out-competed by other species on more fertile soils. This conifer can reach 35 m in height (in good locations, even 40 m) and approximately 50 cm to 130 cm in diameter. It has relatively short blue-green leaves (needles) set in pairs, cones 5 cm to 8 cm in size, and bark with a grey-brown color on the lower stem and a characteristic reddish-brown color on the upper stem. Its lifespan is approximately 250 years but is sometimes even 400 years or 800 years (Mason and Alía 2000; Xenakis *et al*. 2012; Gardner 2013; Barbati *et al*. 2014; Earle 2020).

Scots pine is one of the most commercially important tree species in Europe. It is applied for the production of rosin and turpentine and served for making tar in the past. It is frequently used in dendrochronology, and a textile known as “vegetable flannel” is produced from its fibers. As a pioneer species able to grow on poor soils, it is planted for anti-erosion measures, land reclamation, and as a windbreak. It is also utilized for bioenergy production. Most importantly, however, Scots pine has been commonly used for pulp and sawn timber products. Its easily workable, pale brown to red-brown wood, with a dry density of approximately 450 kg/m^3 (varying with growth conditions), is one of the strongest amongst softwoods and is commonly utilized in the furniture and construction industries, *e.g.*, for construction timber, fencing, crates, boxes, pallets, fiberboard, particleboard, laminated wood, and other wood-based materials (Trendelenburg and Mayer-Wegelin 1955; Routa *et al*. 2011; Gardner 2013; Auty *et al*. 2014; Cao *et al*. 2015).

Pinus sylvestris has been extensively planted throughout Europe over the past 200 years. New seedling stands can be created by natural regeneration, sowing, or planting. Rotation in the commercial plantations ranges from 50 years to 120 years; however, due to the different climate, it is usually longer in the Northeast. Notably, however, not all wood is suitable for every application. Wood properties depend on genetic factors, tree age, and the growing conditions of the trees (*e.g.*, type of soil, water and nutrient availability, temperature, insolation, spacing between trees, and presence of other tree species) (Mederski *et al*. 2015; Rocha *et al*. 2019). Therefore, recognizing use-values of wood from different types of forest stands is of particular practical importance, because sustainable management of forests and wood is a key factor of an effective economy and mitigation of climate change (Eriksson *et al*. 2012; Canadell and Schulze 2014).

The Noteć Forest (Puszcza Notecka), covering more than 1350 km^2 in the Gorzów Basin (Kotlina Gorzowska) between the rivers Warta and Noteć in northwestern Poland, is the second-largest compact forest complex in the country. It grows mainly on inland dunes. Due to water stress on nearly 50% of the area and an appreciable share of podzolic soils, the Noteć Forest is dominated by fresh coniferous and mixed fresh coniferous forests, with Scots pine as the main tree species (approximately 92%). The afforestation of the region by artificial planting started in the second half of the nineteenth century. However, due to the invasion of the pine beauty moth (*Panolis flammea* Denis & Schiff.) in the 1920s and devastation of the forest, further reforestation was necessary (Sukovata and Kolk 2000). As a result, today's Noteć Forest is composed mainly of over-70-year-old pine trees and is classified as a low-capacity forest that is currently heavily used (Roszyk *et al*. 2016).

Exact characteristics of the timber are crucial for its sustainable usage in the industry. The goal of this research was to assess the potential usefulness of Scots pine wood from the Noteć Forest with a relatively small trunk diameter for construction purposes. To achieve this, the mechanical properties of the pinewood were investigated. Wood density, modulus of elasticity, compressive strength, and bending strength were determined. The variability of these properties, depending on the distance from the pith, was analyzed. Additionally, the influence of the site conditions on the useful properties of the pinewood was evaluated by comparing Scots pine wood from poor habitats of inland dunes of the Noteć Forest with pinewood from the neighboring post-agricultural land in Muchocin and forest land in Goraj.

EXPERIMENTAL

Materials

Sampling sites

Research material was collected from fresh coniferous forests mainly composed of Scots pines, located in the Międzychód Forest District (Nadleśnictwo Międzychód), Greater Poland (Wielkopolska). Two main research areas were selected from within the Noteć Forest: Sowia Góra (52.705111° N, 15.845352° E) and Zamyślin (52.3780863° N, 18.3795859° E). They were characterized by poor podzolic soils (Bw soil type in Poland) covered with moss and scant underbrush. In Sowia Góra, in some places, spruce was found. For comparison, two more locations with different growth conditions were selected: post-agricultural land in Muchocin (52.603014° N, 15.845263° E) and forest land in Goraj (52.3802427° N, 18.6752343° E), with post-agricultural sodded brown colluvial rendzinas (RDB type) and brown colluvial rendzinas covered with moss, respectively. Both locations included places where except for Scots pine, also birch and common oak were present (Kusiak 2013; Roszyk *et al.* 2016).

Material characteristics and sampling strategy

Two representative pine trees from within each of the selected plots were sampled for the study. They were of average height and diameter for the particular forest stand, free from structural defects, and classified as Kraft's social class II (dominant trees, creating the main canopy of the stand, having well developed crowns) (Kraft 1884). The following data were obtained from all the trees: tree height, diameter at breast height (calculated from the girth measured at 1.3 m), and crown depth (expressed as a percentage of total tree height) (Table 1). The trees' ages were estimated based on the number of annual rings, as determined from wooden discs cut out near the base of a trunk.

For pine trees from the Noteć Forest, the average values of the growth parameters (tree height and diameter at breast height) were lower than those for trees from the comparative areas. For trees from the post-agricultural land in Muchocin, the parameters were notably greater, despite the lower age of the trees.

Table 1. Average Values of the Parameters Measured for Selected Pine Trees (Roszyk *et al.* 2016)

Sampling Area	Type of Area	Tree Height (m)	Crown Depth (%)	Diameter at Breast Height (cm)	Tree Age (years)
Sowia Góra	Noteć Forest	21.1	0.29	22.7	80
Zamyślin	Noteć Forest	20.5	0.29	22.0	83
Muchocin	Post-agricultural land	22.6	0.29	25.0	74
Goraj	Forest land	21.2	0.36	23.0	81

Wooden pieces, north-south (N-S) oriented along their diameter and measuring 70 mm in the tangential direction, were cut out from each tree at a height greater than 1.3 m (Fig. 1). Then, they were sawn off into smaller parts at whorl sites and seasoned under semi-open conditions (in a roofed shed) for six months.

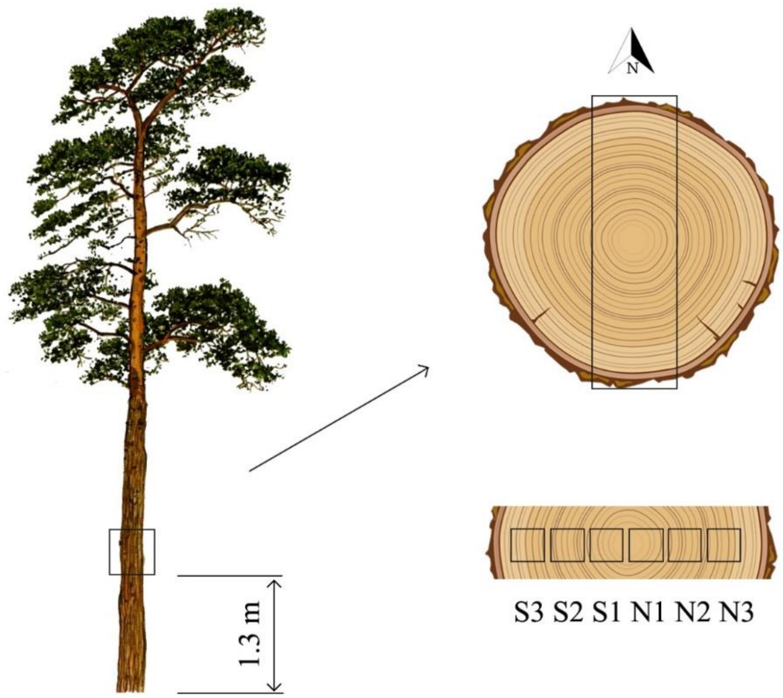

Fig. 1. Sampling strategy diagram

Sample preparation

Seasoned timber was cut into slats with a cross-section of 20 mm × 20 mm, diverse in terms of their distance from the pith and orientation to the north direction: N3, N2, N1, S1, S2, and S3 (Fig. 1). The fibers were parallel to the longitudinal axis of a slat, and the annual rings on a cross-section were tangential to one of the longitudinal planes.

Small samples were cut out from particular slats: 30 mm long for compression tests and 300 mm long for bending tests. Because wood structure varies based on the pith's distance, dividing the specimens into six groups, as presented in Fig. 1, allowed for studying their mechanical parameters in relation to their position relative to the pith. Samples were then seasoned at room temperature (21 °C ± 1 °C) and an air relative humidity (RH) of 40% ± 5% until equilibrium moisture content (constant mass) was achieved.

In accordance with ISO 13061-2 (2014), the density of the conditioned samples was determined by a stereometric method, using an analytical balance accurate to 0.001 g (Sartorius GmbH, Göttingen, Germany) to measure the mass of samples and a digital caliper with an accuracy of up to 0.01 mm to determine their dimensions. The density was calculated as the ratio of the mass to the volume. Wood moisture content (MC) was determined by a gravimetric method, according to ISO 13061-1 (2014).

Methods

Compression tests

Compression tests in the longitudinal direction were performed in accordance with ISO 13061-5 (2020) using a numerically controlled test machine Zwick Z050TH (ZwickRoell, Ulm, Germany). Ten samples of each variant (the position relative to the pith: N3, N2, N1, S1, S2, and S3) from each tree were examined. For each sample, two mechanical parameters were determined: the modulus of elasticity (MOE_L) and the stress to failure (or, compressive strength, R_c^L).

Bending tests

Static three-point bending tests were conducted according to PN-77/D-04103 (1977) utilizing the equipment mentioned above. The distance between supports during the experiment was 240 mm. The load was applied at the midpoint of the sample on the radial surface. The rate of loading was adjusted to complete the test in 90 s ± 30 s. Free from structural defects, 5 to 6 samples from each variant of each tree were examined. The modulus of rupture (MOR), *i.e.*, bending strength, was determined for each sample.

Statistical analysis

The data obtained were statistically analyzed using Statistica 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA).

RESULTS AND DISCUSSION

Comparing the measured mechanical parameters of the pinewoods from the selected forest stands (Table 2), it is clear that the mean values of the modulus of elasticity and the modulus of rupture were similar for all the samples (differences not statistically significant), despite the differences in wood density. However, for compressive strength, there were significant differences among the samples from different locations. Interestingly, the greatest (approximately 64 MPa) and the lowest (54 MPa) R_c^L values were obtained for two stands within the Noteć Forest, Sowia Góra and Zamyślin, respectively.

Unsurprisingly, the mechanical performance of the pinewood from Zamyślin was the worst among all the tested locations, but the excellent properties of wood from Sowia Góra were surprising. Both areas are within the Noteć Forest and have similar growing conditions (*e.g.*, sparsely hydrated poor podzolic soils), worse than the more fertile comparative areas of Muchocin and Goraj, which should generally result in lower quality wood. Nevertheless, this was not true for the wood from Sowia Góra. All the trees from the Noteć Forest were thinner than those from comparative areas, and their properties differed significantly depending on the particular location within the forest. It is well known that the mechanical properties result directly from the wood structure, chemical composition, and physical parameters. The most resistant wood from Sowia Góra, despite relatively narrow annual rings with a low share of latewood (Roszyk *et al*. 2016), had the greatest density (approximately 566 kg/m^3) among all the tested samples. This result may be due to the specific wood microstructure (greater thickness of the cell walls). Moreover, according to the present authors' previous studies, it also had the greatest percentage share of heartwood (43.5%), the greatest concentrations of holocellulose (77.5%) and lignin (27.7%), and the greatest crystallinity index and order of cellulose structure (Roszyk *et al*. 2016, Zborowska *et al*. 2018). All these parameters positively affect the compressive strength of wood (Kollmann and Côté 1968). Consequently, the less resistant wood from Zamyślin had the lowest (526 kg/m^3) density, as well as the lowest holocellulose (74.2%) and lignin (26.9%) contents (other parameters were comparable with those of the wood from Muchocin and Goraj) (Roszyk *et al*. 2016; Zborowska *et al*. 2018). The significant differences between the properties of the woods from the two locations within the Noteć

Forest were quite surprising, considering their similar age and growing conditions, but they may result from genetic differences.

The mean values of the parameters measured for wood from both locations of Noteć Forest were similar to the values obtained for wood from post-agricultural land in Muchocin and forest land in Goraj (Table 2). This observation was unexpected. Because the growing conditions in Muchocin and Goraj are better than those in the Noteć Forest, and the growth parameters of the trees from these locations were greater (especially in the case of Muchocin, despite the lower age of the trees) (Table 1), the wood should show much better mechanical performance, but it did not.

Mederski *et al*. (2015) characterized Scots pines growing in a seedling seed orchard. Trees grew there in wider spacing than in a typical forest, which resulted in better access to sunlight and less competition between trees, so the growing conditions were better in the orchard. However, this behavior was reflected in larger annual rings and a consequently lower wood density (approximately 327 kg/m^3), resulting in worse mechanical behavior (R_c^L in the range of 25 MPa to 37 MPa and MOR between 48 MPa and 62 MPa for 15% MC). The decreased density and mechanical parameters (on average, by approximately 30% compared with wood from regular stands) made the wood from the orchard useless for construction purposes and rather more useful for the paper industry.

Summarizing the results mentioned above, the general conditions in the forest stand, however important for tree growth, were not the only determinants of wood performance.

Table 2. Mean Values and Standard Deviations of Properties of Pinewood from the Selected Areas

Sampling Area	MC (%)	Density (kg/m^3)	R_c^L (MPa)	MOE$_L$ (MPa)	MOR (MPa)
Sowia Góra	8.1	566 ± 65.2^b	63.6 ± 13.3^c	7849 ± 3730^a	109.1 ± 24.1^a
Zamyślin	8.1	526 ± 68.9^a	54.0 ± 14.4^a	7012 ± 3442^a	100.3 ± 22.7^a
Muchocin	8.1	541 ± 69.7^a	58.4 ± 13.8^b	7901 ± 3442^a	97.6 ± 24.7^a
Goraj	8.1	542 ± 35.9^a	58.0 ± 8.5^{a,b}	6983 ± 2242^a	101.5 ± 18.2^a

Different superscripts denote statistically significant ($p < 0.05$) differences among mean values according to Tukey's honestly significant difference (HSD) test. MC – moisture content; R_c^L – compressive strength; MOE$_L$ – Modulus of elasticity; MOR – modulus of rupture

Comparing the mechanical parameters obtained for the studied pinewood with generally accepted scientific data for this wood species (Table 3) reveals that the parameters taken into account were quite similar. However, the wood from Sowia Góra exhibited above-average mechanical performance, which was directly related to its above-average density (583 kg/m^3 *vs*. 540 kg/m^3 for 12% MC) (Kollmann and Côté 1968). Overall, the mechanical properties of the pinewoods from all the studied areas, and particularly those from the Sowia Góra region, indicate their potential suitability for all industrial construction purposes typical of this wood species.

Another aim of this study was to analyze the variability of the mechanical properties of pinewood from the pith to the bark, as it is well known that the structure and properties of juvenile wood differ noticeably from those of adult wood (Pazdrowski 2004; Pikk and Kask 2004; Gryc *et al*. 2011). The results obtained for juvenile, maturing, and adult pinewood from selected locations are presented in Table 4.

Table 3. Mean Values and Standard Deviations of Properties of Pinewood from the Selected Areas, Recalculated for 12% and 15% MC Using the Bauschinger Formula (Krzysik 1978)

Sampling Area	MC (%)	R_c^L (MPa)	MOR (MPa)
Sowia Góra	12% 15%	51.2 ± 12.6 41.6 ± 12.2	92.1 ± 20.4 79.0 ± 20.0
Zamyślin	12% 15%	43.5 ± 11.8 35.4 ± 11.4	84.6 ± 20.9 72.6 ± 20.2
Muchocin	12% 15%	47.0 ± 12.2 38.3 ± 11.9	82.4 ± 20.1 70.7 ± 19.5
Goraj	12% 15%	46.7 ± 8.2 38.0 ± 8.0	85.7 ± 16.7 73.5 ± 16.1
Literature data*	12%	47	87

*Kollmann and Côté (1968); MC – moisture content; R_c^L – compressive strength; MOR – modulus of rupture

Table 4. Mean Values and Standard Deviations of Properties of Selected Pinewood Samples, Depending on the Distance from the Pith

Sampling Area	Zone*	Density (kg/m³)	R_c^L (MPa)	MOE_L (MPa)	MOR (MPa)
Sowia Góra	3	617 ± 14.5^c	72.8 ± 5.4^a	10231 ± 3915^c	122.3 ± 11.3^a
	2	604 ± 18.6^b	71.4 ± 7.0^a	8673 ± 2929^b	123.3 ± 11.1^a
	1	477 ± 7.8^a	46.7 ± 3.9^b	4643 ± 1222^a	74.7 ± 6.6^b
Zamyślin	3	573 ± 55.4^a	65.0 ± 10.4^c	8722 ± 3796^a	113.1 ± 13.8^a
	2	552 ± 48.5^a	60.4 ± 8.5^b	8463 ± 2695^a	106.5 ± 16.3^a
	1	458 ± 38.4^b	37.7 ± 3.4^a	4021 ± 839^b	69.5 ± 14.3^b
Muchocin	3	579 ± 32.0^a	65.9 ± 8.9^a	8936 ± 3395^a	115.7 ± 12.8^c
	2	579 ± 49.7^a	64.8 ± 11.3^a	9139 ± 3462^a	95.5 ± 22.8^b
	1	466 ± 5.2^b	44.3 ± 8.3^b	5628 ± 2163^b	72.1 ± 16.7^a
Goraj	3	565 ± 22.1^a	65.8 ± 4.4^c	8149 ± 2451^a	111.9 ±14.8^a
	2	552 ± 33.5^a	59.9 ± 4.8^b	7244 ± 2124^a	105.0 ± 8.2^a
	1	509 ± 24.8^b	48.4 ± 4.2^a	5559 ± 1132^b	77.6 ± 8.9^b

* 1 – close to the pith (juvenile wood); 2 – middle zone (maturing wood); 3 – close to the circuit (adult wood); Different superscripts denote statistically significant ($p < 0.05$) differences among mean values according to Tukey's HSD test. R_c^L – compressive strength; MOE_L – modulus of elasticity; MOR – modulus of rupture

A typical significant difference in density between juvenile and mature wood was observed for all the examined trees (Fig. 2), showing a clear increase from the pith to the bark (Ivković *et al*. 2013; Schönfelder *et al*. 2017). Notably, the greatest variability in density was seen in wood from Sowia Góra, where the mean density of juvenile wood was only 77% of the mean density of the adult wood, while for Zamyślin and Muchocin this figure was approximately 80%, and for Goraj it was as much as 90%. Nevertheless, all the obtained values were within the ranges reported by other researchers: Gryc *et al*. (2011) studied approximately 100-year-old pinewood from the Czech Republic and observed that the juvenile wood density ranged from 66% to 80% of the adult wood density (with an average value of 71%). Pikk and Kask (2004) reported a corresponding value of 85% for 60-year-old pinewood from Estonia, while Tomczak and Jelonek (2012) studied 90-year-old pines from fresh coniferous and mixed fresh coniferous forests in Poland (conditions similar to those in this study) and reported a value of 90%.

Interestingly, for pinewood from Sowia Góra, there was also a statistically significant difference in density between maturing and adult wood, which was not observed for wood from other locations. In contrast, pinewood from Goraj (regular forest stand) was the most homogeneous in density.

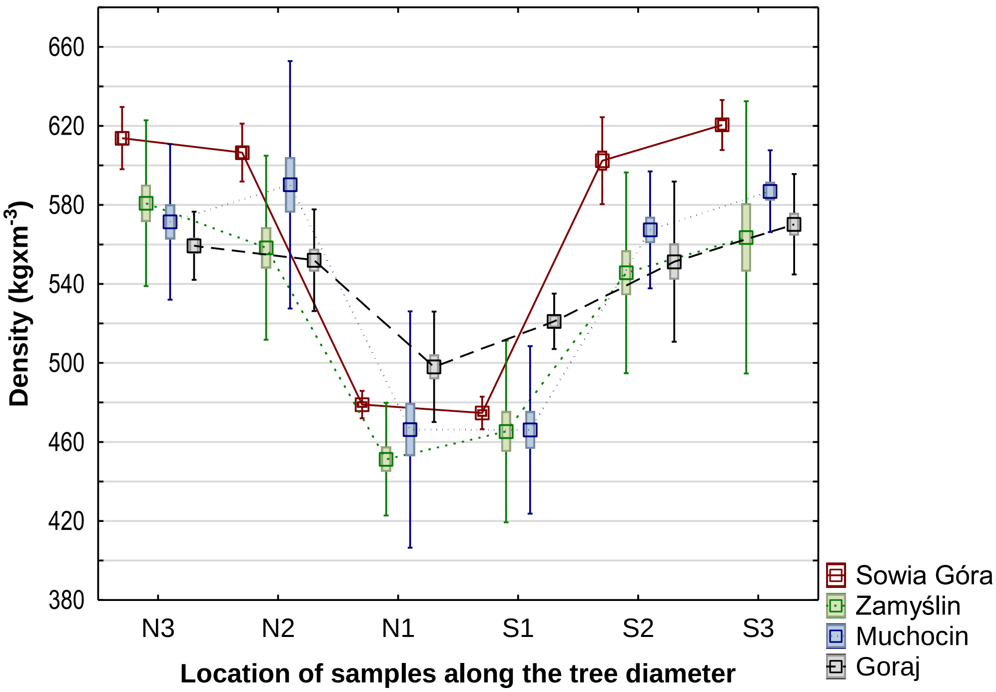

Fig. 2. Variability of wood density along the N-S axis

Changes in density between juvenile and mature wood translated directly into variations in all the measured mechanical properties of the pinewood (Table 4 and Figs. 3 to 5). The greatest difference was seen for the MOE_L, while for R_c^L and MOR, the differences were smaller but statistically significant.

The R_c^L of the juvenile wood was 61% of the R_c^L of mature wood for Zamyślin, 65% for Sowia Góra, 67% for Muchocin, and 76% for Goraj. For comparison, Pikk and Kask (2004) reported a corresponding value of approximately 67% for pinewood from Estonia. As shown in Fig. 3, the R_c^L of wood from Goraj was much less diversified along the tree diameter than that of wood from other locations. Interestingly, despite similar densities, there were also significant variations in R_c^L between maturing and adult wood for pinewood from Zamyślin and Goraj (Table 4).

A typical significant difference in the MOE_L between juvenile and mature wood, strictly related to the changes in wood density, was also seen for all the examined trees (Table 4 and Fig. 4). The MOE_L of juvenile wood was 47% of the value measured for mature wood for Zamyślin, 49% for Sowia Góra, 62% for Muchocin, and 72% for Goraj. Overall, the tendency was similar to that of R_c^L, including the minimal variation of MOE_L along the tree diameter for wood from Goraj. However, for pinewood from Sowia Góra, there was also a statistically significant difference in MOE_L between maturing and adult wood, reflecting the changes in wood density. This result was not observed for the wood from the other studied locations.

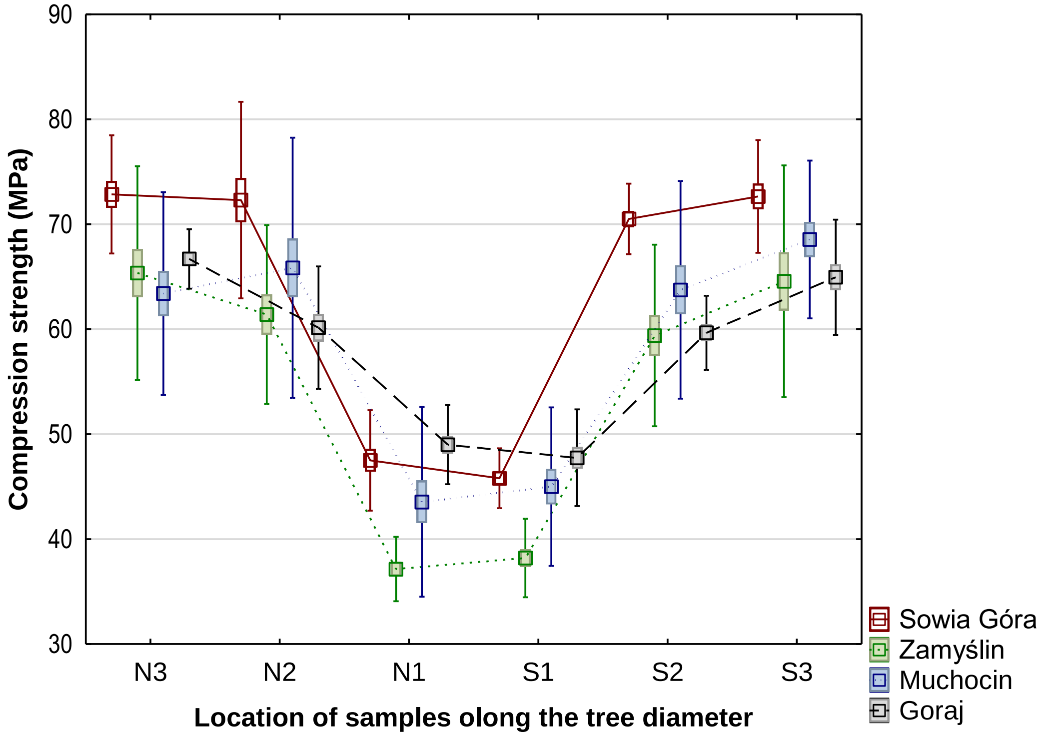

Fig. 3. Distribution of R_c^L along the N-S axis

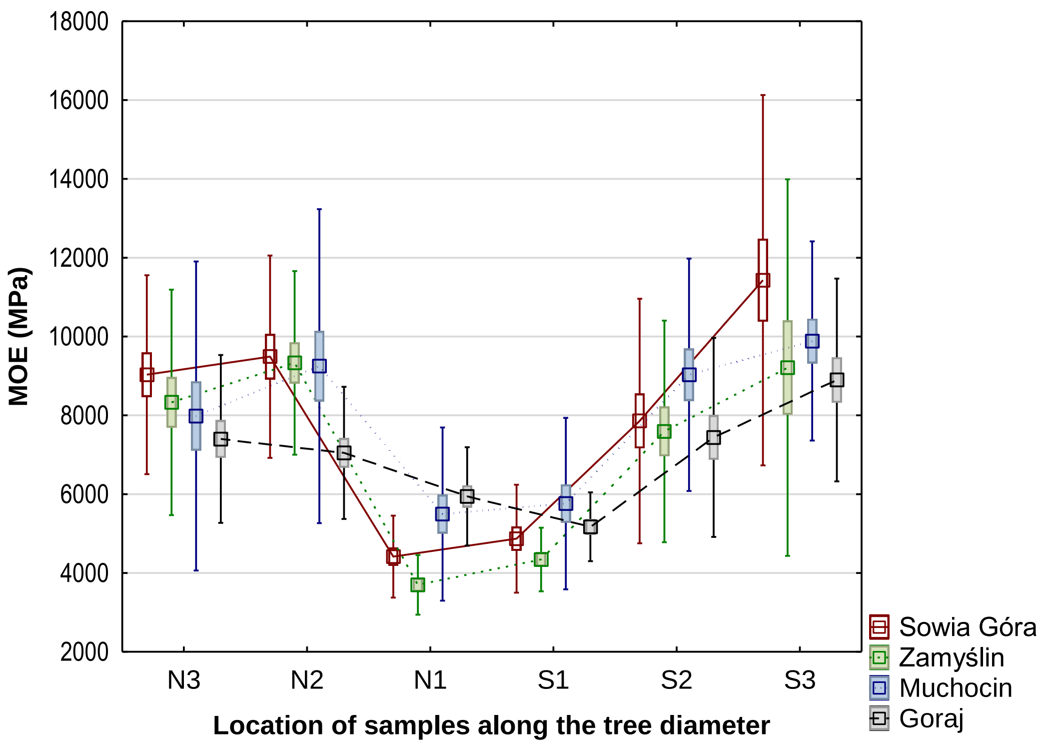

Fig. 4. Distribution of MOE_L along N-S axis

The MOR values for juvenile wood in comparison with mature wood were similar to those observed for R_c^L: 61% for wood from Sowia Góra, 64% for Zamyślin, 68% for

Muchocin, and 72% for Goraj (Table 4). For comparison, Pikk and Kask (2004) reported a corresponding value of 71% for pinewood from Estonia. Thus, pinewood from Zamyślin had the greatest homogeneity along the diameter for this parameter (Fig. 5). In contrast, despite similar density, there were also significant variations in MOR between maturing and adult wood for wood from Muchocin.

It is worth mentioning that the relationships between wood strength and density were not identical for all the examined locations, which clearly shows that density is not the only determinant of its mechanical properties. As many researchers have confirmed, another factor that significantly affects wood strength in the longitudinal direction is microfibril angle in S2 layer of the secondary cell wall (Barnett and Bonham 2004; Wessels *et al.* 2015; Xu *et al.* 2005). Therefore, the reason for the observed phenomenon is presumably the variation in microfibril angle between juvenile and mature wood that was different for wood from different locations.

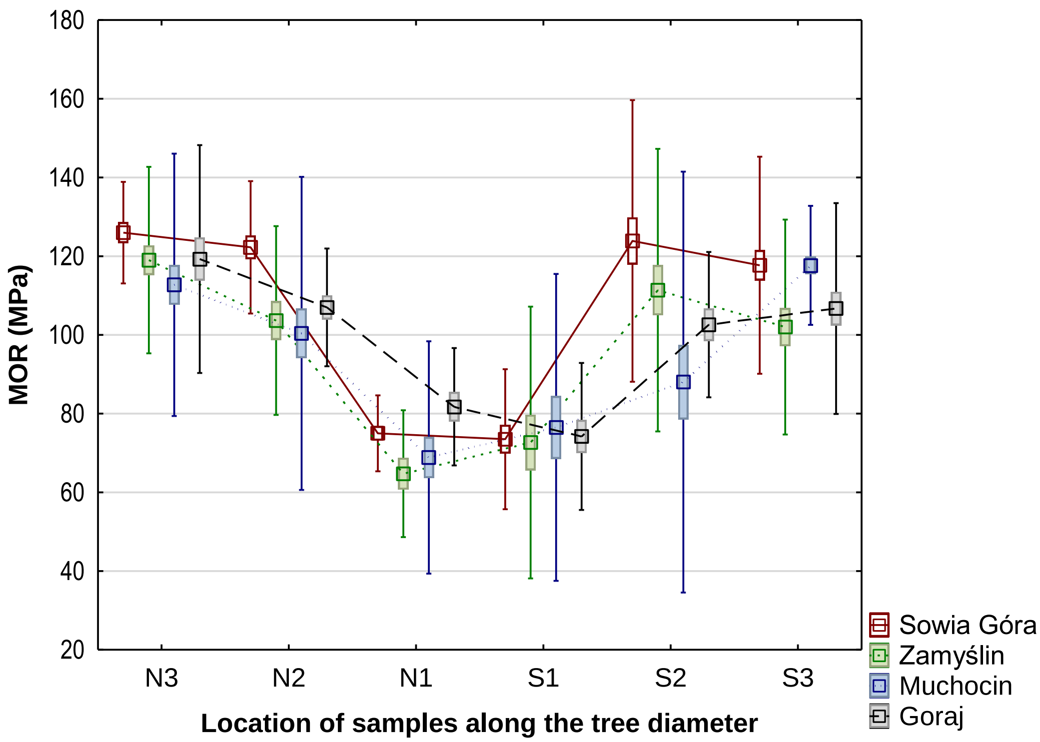

Fig. 5. Distribution of MOR along N-S axis

To summarize, clear differences in wood density and mechanical properties from the pith to the bark were seen for wood from all the studied locations. The greatest variations occurred in wood from the Noteć Forest, while the smallest variations were in wood from typical forest land in Goraj. The observed variability between juvenile and adult zones affects the functionality of wood and should be considered when choosing wooden material for particular applications.

The industrial applicability of pinewood from the inland dunes of the Noteć Forest was one of the targets of this study. Wood from Sowia Góra seemed potentially suitable for construction purposes due to its excellent mechanical performance and high density. However, because of the high heterogeneity from the bark to the pith and the poor properties of juvenile wood, only mature wood should be considered for such applications. It has been shown that wood from this location has the greatest amount of carbohydrates of high molecular weight, which also makes it an appropriate raw material for the paper industry (Zborowska *et al*. 2018). Pinewood from Zamyślin, in contrast, had the lowest density and the weakest resistance and was therefore not particularly suitable for construction applications. Conversely, it also has the lowest lignin and extractive contents, which makes it a better resource for biofuel production using biotechnological methods (Zborowska *et al*. 2018). Overall, Scots pine wood from the Noteć Forest can be a proper raw material for various industrial purposes. The basic characterization of its wood properties will allow for finding the most favorable application for it under the rules of sustainable management of forests and forest products.

CONCLUSIONS

1. The properties of Scots pine wood from the poor habitats of the Noteć Forest, despite a relatively small trunk diameter, were sufficient for its potential use for construction purposes. Wood from Sowia Góra, due to its excellent mechanical performance and high density, was especially suitable for the construction industry.
2. The properties of pinewood from the Noteć Forest varied significantly depending on the particular location within the forest. The observed differences seemed to be due to genetic variation because the examined trees were of similar ages and habitats and grew in nearly the same conditions.
3. Comparison of the properties of pinewoods from various locations indicated that the general conditions in the forest stand, however important for tree growth, were not the only determinants of wood performance.
4. Due to the high differentiation of wood density and mechanical properties from the pith to the bark observed for wood from all studied locations, it is essential to consider which part of the tree is chosen for further industrial processing.
5. Exact characterization of wood allows for its most appropriate and sustainable application in the relevant branch of industry.

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