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The Influence of Habitat Conditions on the Properties of Pinewood

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Abstract: This article starts a series of articles on dependences between the conditions of the growth of trees in forests and the technical aspects and directions of using the raw material obtained from these trees. This is a key feature for wood purchasers because it determines the efficiency of production and directly affects the final financial result of their activity. Wood represents an environmentally sustainable and renewable material, which is a widely available raw material on the market and must meet specific quality and strength requirements. These parameters indicate the utility values of wood and the possibilities of its use. One of the factors influencing the properties of wood is the type of the forest habitat it comes from. In order to determine this influence, tests were carried out to show how tree growth conditions affected changes in the density and strength of raw wood. The assumption (hypothesis) about the correlation between the static bending strength of Scots pine (*Pinus sylvestris* L.) wood and the forest habitat was verified on four forest types, i.e., fresh coniferous forest (FCF), fresh mixed coniferous forest (FMCF), fresh mixed forest (FMF) and fresh forest (FF). The properties depend largely on the wood structure, its origin on the cross section and the length of the stems. The raw material selected for the study came from Scots pine trees growing in forests in central Poland. The study confirmed the influence of the habitat on changes in the density and strength of pinewood. There was a correlation between the habitat FMCF and the quality parameters of the raw material, which reflected the wood structure r = 0.775; $p < 0.05$.

Keywords: habitat; wood; scots pine; mechanical properties; strength; density; climate

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1. Introduction

Variability in the quality of raw wood is largely caused by the condition of trees. The technical parameters of wood vary depending on the species as well as the habitat, age of the trees and other factors. A set of climate-related and soil-related factors is an important parameter affecting both the health of trees and the quality of wood obtained from them. Factors determining soil fertility also affect the technical quality of trees, such as their knottiness and growth rate [1–5].

The analysis of the influence of the habitat on the wood structure enables prediction of its correlation with an expected performance quality. The type of forest habitat can influence changes in the wood structure. For Scots pine it is the ratio of mature wood to juvenile wood, or the share of the heartwood zone. The proportion of juvenile wood on a stem cross-section increases proportionally to the distance from its base and decreases with decreasing width of the of annual rings (the share of late wood increases) [6,7]. Therefore, the type of forest habitat may affect the mechanical properties of wood [8–11].

In order to accurately define the quality of wood products it is necessary to specify tree growth details, which affect the increase in tree density and the quality of raw wood. The type of forest habitat is a classification unit which comprises forest areas with similar climatic conditions, soil fertility, moisture, landform and geological structure. All these features significantly affect the habitat productivity and the breeding capacity of the type of forest habitat. The species composition of a tree complex, appropriate for a particular type of forest habitat, is related with the ecological selection and shaping of the tree complex. This selection is justified due to the potential economic value of the wood material with a specific volume increment and the shaped quality of the tree complex in a particular habitat [12,13].

The introduced division of forests is based on two basic parameters. The first parameter is soil fertility. They are graded from the lowest soils, i.e., coniferous forests, to fertile soils, i.e., fresh forests. The second factor is soil moisture, from dry to moist. The following types of pine-tree habitats are distinguished in Poland [1,2] and ordered as follows:

- coniferous forests (extremely poor soils): dry (DCF) water level (w.l.) less than 2.5 m below ground level (b.g.l.); fresh (FCF) w.l. 1.8–2.0 m b.g.l., wet (WCF) w.l. 0.4–0.8 m b.g.l. and marshy (MCF) w.l. 0.2–0.5 m b.g.l.;
- mixed coniferous forests (poor soils): fresh (FMCF) w.l. less than 1.8 m b.g.l.; wet (WMCF) w.l. 0.5–1.8 m b.g.l.; marshy (MMCF) w.l. 0.2–0.5 m b.g.l. and surface water occurrence 1–5 months;
- mixed forests (medium fertile soils): fresh (FMF) under moderate ground w.l. less than 1.8 m b.g.l.; wet (WMF) under moderate ground w.l. 0.5–1.8 m b.g.l.; marshy (MMF) under moderate ground w.l. 0.2–0.5 m b.g.l.;
- forests (fertile soils): fresh (FF) under the short-term influence of w.l. less than 1.8 m b.g.l.; wet (WF) under moderate ground w.l. 0.5–1.8 m b.g.l.; marshy (MF) shallow water (0.0–0.5 m b.g.l.), periodically flooding, i.e., alder carr.

The identification of the types of habitats translates into their influence on land and undergrowth plants, which are decisive factors in the classification of individual forest areas [14].

Habitat (a set of climate and soil factors, independent of plants and animals of a given environment) determines forest growth and the type of forest soil is strictly defined reflecting the fertility of the area in which trees grow. It determines the future species composition of the tree complex, its growth and qualitative development. Appropriate selection of tree species, which is based on the knowledge of their ecological conditions, ensures better use of land and provides natural soil protection [15,16]. The assessment of soil fertility, i.e., the content of soil nutrients and humus substances, mostly consists in the measurement of soil pH, its content of alkaline cations and the degree of soil saturation with these cations, the size of particles in the eluvium and the content of organic carbon and nitrogen compounds [17–19]. Scots pine trees grow best when the average pH of the entire soil profile ranges from 4.5 in H_2O to 4.5 in KCl. The following factors have the greatest influence on the productive capacity of pine trees: KCl pH, nitrogen and potassium content, the structure of fine particle fractions and the $CaCO_3$ content. Soil properties influence the qualitative aspects of the growth of trees and their productive capacity even by as much as 50% [20–23].

Due care, controlled selection of the best trees and reducing the number of weaker ones are important aspects affecting the quality of tree complexes and the stability of tree stands. As a result, the trees in a particular habitat receive optimal protection and stability. There is a greater volume of pine trees in coniferous tree habitats. The wetter a habitat is, the more work needs to be conducted to maintain the trees growing in it (reforestation, amendments and additions, introduction of undergrowth, early and late maintenance pruning, etc.) [24].

Scots pine (*Pinus sylvestris* L.) is the dominant species in forests in Poland. The more frequent presence of pine tree complexes in more fertile habitats than coniferous forests does not correspond to the ecological conditions of this tree species. However, pine trees are planted there to increase wood production. Contemporary management methods based on the environmentally friendly 'green order' trends favor the reconstruction of the species composition in tree complexes in accordance with the prevailing habitat conditions [25,26]. This action is taken to promote biodiversity in forests to create a higher stability of the stand and in order obtain higher wood quality by the natural elimination of malformed trees. As a result, the properties of habitats are used as much as possible to develop natural communities [27].

The tree characteristics influencing their quality, such as knottiness, wood density and the width of annual rings, mostly depend on the genotype and origin of individual trees [28–30]. Tree knottiness tends to increase along with the habitat fertility. On the other hand, curvature tends to decrease along with soil fertility. Wood defects are affected not only by the type of habitat but also by failure to cut some trees and by inadequate density of the tree complex [31,32].

The wood of Scots pine-trees is characterised by the following mechanical properties: average flexural strength 41—100—205 N/mm^2, tensile strength along the fibres 35—104—196 N/mm^2, and flexural modulus 6.9—12.0—20.1 kN/mm^2 [33]. The average density of completely dry mature wood is about 522 kg/m^3 (this value is lower for juvenile wood—about 370 kg/m^3). However, it is noteworthy that wood density and strength vary depending on the distance from the base of the trunk to the sample collection zone (strength and density decreases with distance from the butt) [34,35].

The variability of the habitat conditions directly translates into the internal macrostructure of wood and its quality. However, the correlation between these parameters is still not confirmed. As the share of mature wood has the greatest influence on loads, it is used in the sawn wood industry. Although the variability of the habitat significantly affects only the content of heartwood and sapwood in the trunk in older tree complexes of age class 5, separate habitat types, such as dry coniferous forest, fresh coniferous forest and mixed fresh coniferous forest are essential in all age classes for the quality of mature and juvenile pinewood [36–39], because there are significant differences in pines aged over 60 years [4]. There is also greater variability in the wood of trees of different ages growing in a dry coniferous forest habitat, which has a low content of minerals and water [40]. The density of wood from a fresh mixed coniferous forest is on average about 20 kg/m^3 [41] greater than the density of wood from a fresh coniferous forest. Trees growing on post-agricultural lands tend to create denser structures in both of the abovementioned habitats, on average by about 30–40 kg/m^3. At the same time, the radial variability of trees on post-agricultural lands is similar to that of trees on forest lands [42,43]. Such a considerable variability of habitats was the basis for undertaking a study to investigate the correlation of Scots pine (*Pinus sylvestris*) wood quality determined by bending strength with respect to forest site types in selected areas of northern Poland. In order to minimise the factors shaping the quality characteristics of pine raw material (density, strength), an area with a similar form of forest management and a similar level of groundwater for variable soil fertility was assumed.

2. Materials and Methods

The influence of the habitat on the quality of trees growing in forests was studied in the Miradz Forest District, Regional Directorate of State Forests in Toruń, Poland. In terms of climate, the local forests belong to the Kujawy Region. The region is characterised by the lowest precipitation in Poland (the average precipitation is 500 mm). The average annual temperature is +8 °C, the average temperature in January is −0.7 °C and the average temperature in July is +18 °C. The forest area is 8204.13 ha, including 7986.13 ha of afforested land, 42.46 ha of non-afforested land and 175.54 ha of forest management land. The remaining non-forest land amounts to 615.42 ha as of 1 January 2018 [30]. The geomorphological area selected for the study is mostly of glacial and hydro-glacial origin. There are numerous ribbon lakes, which form the boundaries of lower-order units lying near uplands. The altitude of the area ranges from 70 to 110 m AMSL.

The forest district area includes various forms of nature conservation, including Natura 2000 protected areas. There are 14 types and 28 subtypes of soil in the forest district. The predominant type is rusty soils (55%), which are mostly found in the habitats of FMF, FMCF and poorer FCF. Luvisoils are found in 20% of the forest area and, together with brown soils, whose share is 12%, they can be found in the habitats of FF and FMF. There are few other soil types, with the highest share of mucky soils (4.5%). Figure 1 shows the percentage share of forest habitat types.

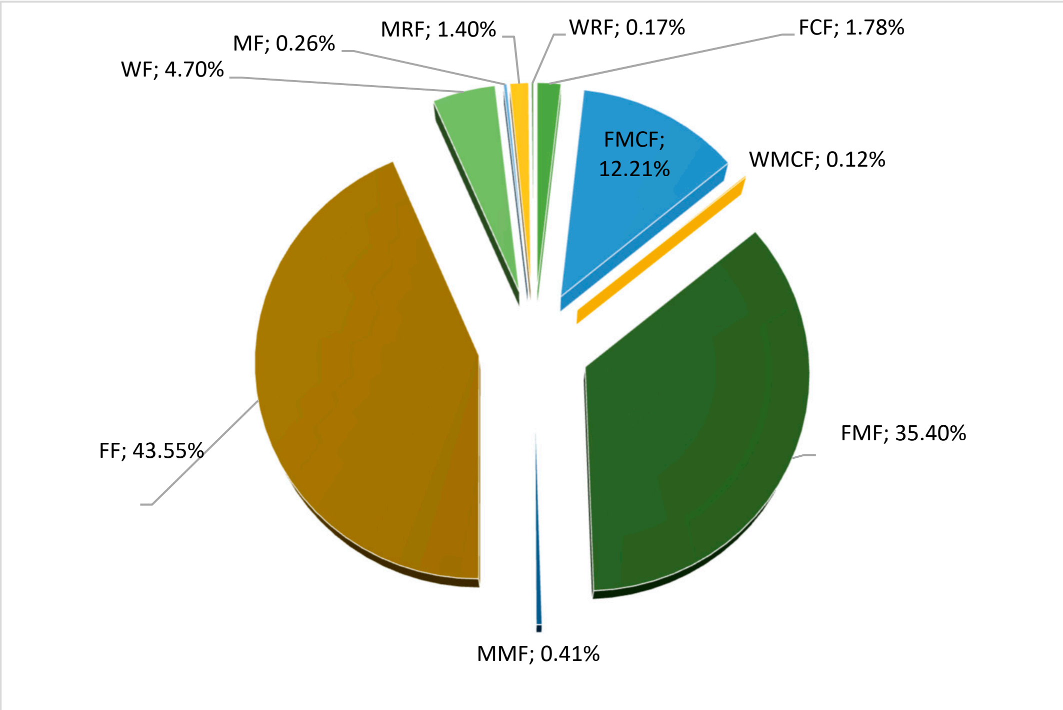

Figure 1. The percentage share of forest habitat types in the research area. Coniferous forests: fresh (FCF); mixed coniferous forests: fresh (FMCF), wet (WMCF); mixed forests: fresh (FMF), marshy (MMF); forests: fresh (FF), wet (WF), marshy (MF), i.e., alder carr. riparian forests: wet (WRF), marshy (MRF), or ash alder (Source: Author's original compilation).

Scots pine is the dominant species in the research area, where its share amounts to 72% of all resources. Other tree species in the complex are: pedunculate oak (Quercus robur) (20%), black alder (*Alnus glutinosa* L.) (2.2%), Norway spruce (*Picea abies* L.) (1.4%), silver birch (*Betula pendula*) (1.2%), European larch (*Larix decidua)* (1.0%) and European beech (*Fagus sylvatica* L.) (0.5%). The area share is proportional to the volume share and amounts to 64.6% of the area occupied by Scots pine (*Pinus sylvestris)*, 21.4% by pedunculate oak (*Quercus robur*), 4.4% by European beech (*Fagus sylvatica* L.), 3.2% by black alder (*Alnus glutinosa* L.), 1.8% by Norway spruce (*Picea abies* L.), 1.5 % by silver birch (*Betula pendula*), 1.2% by European ash (*Fraxinus excelsior* L.) and 1.0%by European larch (*Larix decidua)*. Other species occupy a total of 1.0% of the total forest area in the district [44].

The wood strength (static bending strength) was tested on laboratory samples (forty specimens with dimensions 20 × 20 × 300 mm^3) obtained from 1.2 m long pieces taken from the butt part of logs of selected test trees (five trees per area) in the research area (52.50, 18.10–52.60, 18.20). Five trees were separated from each plot according to Kraft's classification: one Class II-dominant forming the main ceiling of the stand, with a well-developed crown; three pieces of class III-co-dominant with normally developed crowns, but with marked degradation; one piece of class IV-controlled with more or less deformed crowns, with double or multilateral thinning or with one-sided development. The logs came from four basic types of forest habitats: fresh coniferous forest (FCF), fresh mixed coniferous forest (FMCF), fresh mixed forest (FMF) and fresh forest (FF). The divisions chosen for the tests met the habitat selection criteria—Scots pine was the dominant species and the type of cuttings corresponded to final cuttings. The following divisions were selected for the research:

- FCF—267 f located in the forest district of Wycinki, forest stand aged 123 years;

- FMCF—176 b located in the forest district of Przyjezierze, forest stand aged 111 years;
- FMF—206 d located in the forest district of Wysoki Most, forest stand aged 86 years;
- FF—35 f located in the forest district of Kurzebiela, forest stand aged 122 years.

The raw wood selected for tests had no shape defects, cracks, discoloration, rot, mechanical damage or foreign bodies. The knots were mostly overgrown. Only the log from the FMF habitat had an open broken knot. Next, each piece of wood was sawn so that the material contained a 50 mm thick core part in order to create a uniformity in the samples from each tree. In this way, samples for mechanical tests were prepared.

The tests of selected physical properties, such as wood density and moisture content, were conducted in accordance with the density standard specified in PN-D-04101:1977 and PN-EN 408+A1:2012 [45,46].

The mechanical properties of pinewood were tested with a Tinius Olsen H10KT device, with a maximum load up to 10 kN. The flexural strength was tested in accordance with the PN-D-04103:1977 [47] standard. The test results were used to assess and analyse the parameters and to make conclusions about the material strength at a humidity of 12% (wood was conditioned to this humidity the wood has been adapted to this moisture content under conditions of air 20 °C and 65% moisture content). The specimens were prepared as pieces without defects with dimensions of 20 × 20 × 300 mm^3 bent at a support spacing of 240 mm. The Tujey HSD test software was used for the analyses (significance level of α = 0.05).

3. Results

The average density of all dry pinewood samples collected from different habitats was 455 kg/m^3. The wood from the fresh mixed coniferous forest (FMCF) was characterised by the highest average density, whereas the wood from the fresh mixed forest (FMF) had the lowest density. The wood from the FMCF habitat was characterised by a large spread between the lowest density sample (313 kg/m^3) and the highest density one (715 kg/m^3). The wood from the FMCF habitat was characterised by higher average density of all the habitats. The average density of the wood collected from different forest habitats is shown in Figure 2.

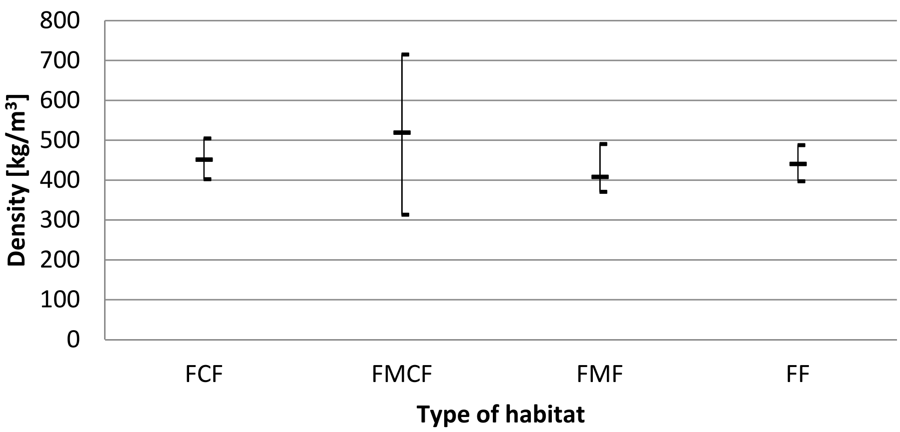

Figure 2. The average density of wood collected from different types of forest habitat (Source: Author's original compilation).

In order to verify the thesis that the type of forest habitat significantly affects wood density, the test results were analysed statistically. One-way analysis of variance showed that the variability of the type of forest habitat significantly affected wood density. The Tukey HSD test showed that the FMCF habitat was the decisive variable belonging to the second homogeneous group, as opposed to the other habitat types. This means that the FMCF habitat significantly influenced variation in wood density. The statistics of the average wood density in relation to the type of forest habitat was made at a 95% confidence interval. Table 1 shows the homogeneous groups of habitat types in the Tukey HSD test.

Table 1. Statistically homogeneous groups based on the Tukey HSD test for the wood density in the forest habitats at a 95% confidence interval.

Type of Forest Habitat	Wood Density		Homogenous Group	
	Mean	SD	1	2
	(kg/m^3)			
FCF	451.22	24.95	***	
FMCF	518.96	105.43		***
FMF	407.82	31.15	***	
FF	440.33	25.22	***	

*** belonging to one or two homogeneous groups; source: Author's original compilation.

Another parameter under analysis was the flexural strength of wood. The average strength of all pinewood samples from various habitats with a 12% moisture content was 67.12 N/mm^2. The most durable wood came from the FMCF habitat—it withstood a load of 73.32 N/mm^2. The wood from the FMF habitat was characterised by the lowest flexural strength, i.e., 60.05 N/mm^2. A detailed comparison of individual samples from different habitats revealed a similarity between the wood density and flexural strength values. There were relatively similar averaged results of the strength and density of the samples as well as similarities between the maximum and minimum values of individual samples. For example, some wood samples from the FMCF habitat were characterised by the highest strength (89.55 N/mm^2), whereas others had the lowest strength (34.33 N/mm^2). The wood samples collected from the FCF and FMF habitats were more durable. The average flexural strength of wood for the moisture content of 12% in relation to the types of forest habitat and the cardinal directions is shown in Figure 3.

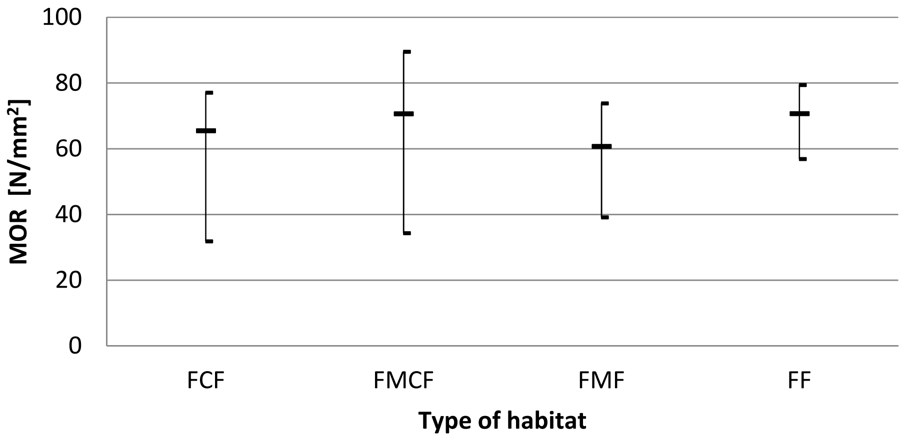

Figure 3. The average flexural strength of wood from different forest habitats (Source: Author's original compilation).

In order to verify the thesis that the type of forest habitat significantly affects wood strength, the results of the wood strength tests were calculated for a moisture content of 12%. The one-way analysis of variance confirmed the fact that variability of the type of forest habitat had a highly significant effect on the wood strength, regardless of the cardinal direction. The Tukey HSD test confirmed the fact that the wood from the FMF habitat had the lowest resistance, because it belonged to the second homogeneous group, whereas the FCF habitat belonged to the first and second groups. The research determined the average wood strength in relation to the type of forest habitat at a 95% confidence interval. Table 2 shows the homogeneous groups of habitat types in the Tukey HSD test.

Table 2. Statistically homogeneous groups based on the Tukey HSD test for the wood strength in the forest habitats at a 95% confidence interval.

Type of Forest Habitat	Wood Flexural Strength (MOR)		Homogenous Group	
	Mean	SD		
	[N/mm²]		1	2
FCF	66.84	8.88	****	****
FMCF	70.63	14.53	****	
FMF	60.71	7.86		****
FF	70.67	7.38	****	

**** belonging to one or two homogeneous groups.

Figure 4 shows the characteristics of Scots pinewood flexural strength in relation to wood density. Despite the small range of average density, the research material from this group was characterised by a considerable spread of mechanical properties.

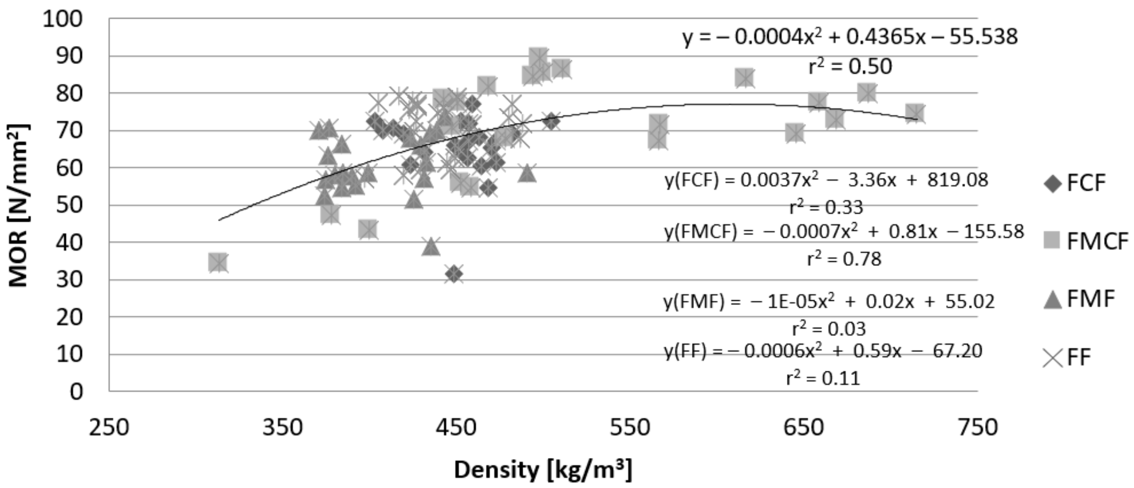

Figure 4. The average flexural strength of wood from various types of forest habitat (Source: Author's original compilation).

The dependencies between the pinewood flexural strength and density was graphically analysed for individual research sites in the FMF, FF, FMCF and FCF habitats. The samples from the FMCF habitats were characterised by a relatively strong correlation between the wood strength and density (r^2 = 0.78), whereas those from the FCF habitat were characterised by a weak correlation (r = 0.33). The samples from the FMF and FF habitats did not exhibit any correlation between the wood strength and density.

4. Discussion

Earlier studies on the variability of the physical properties of wood [48] showed that its density increased with age. The results of our study are consistent with earlier findings, despite the slight difference in the age of the wood samples. According to Tomczak et al. [49], the specific density of wood has a direct influence on its mechanical properties and it affects the assessment of the quality of raw wood. The same study showed high variability of wood density within tree species as well as individual trees. Apart from that, the variability of wood density also depends on external factors, but it is difficult to verify their influence, because there are too many parameters, i.e., the type of forest habitat, wind and other forces to which trees are exposed. Our study showed a strong correlation between the density and strength of wood only in the FMCF habitat. Therefore, it is necessary to conduct more tests to analyse this problem.

The diversity of habitats where trees grow determines the structure of wood, including its density, which translates into its strength. Tomusiak et al. [50] observed that Scots pine trees growing in extreme habitats were more likely to generate wood of lesser strength, but this had minimal influence on the technical quality and mechano-physical properties. Our study showed that the change of the habitat affected the wood strength. The statistical analysis showed that the FMF habitat generated the least weak wood, which belonged to the second homogeneous group (Table 2). The results obtained in this study confirmed the significance of the wood quality to habitat correlation test conducted.

The type of the forest habitat significantly affects the technical quality of forest stands. This quality directly translates into the possibilities of rational use of raw wood in the technological process. Strength characteristics are decisive when wood is used for the production of constructional elements. Scots pine is one of the main species used, among other things, for the production of cross laminated timber (CLT) [51–53]. In structural timber testing, the lower 5% quantile of strength plays an important role. The results of the minimum strength in comparison with the strength classes according to EN 338 [54] show that the raw material from the better habitat (FF) has the best properties. But the results do not take into account the accumulation of defects that occurs in full-size structural elements (samples without defects were tested). A higher strength of wood provides more possibilities of its use, which meets customers' higher and more individualised expectations. The technical characteristics of wood directly influence its value and, consequently, the economic effect expected by both producers and purchasers [55]. Raw wood can be assigned to higher quality and utility classes if its strength parameters are sufficiently high [56]. In the light of the research, planned wood management should make use of habitat conditions to shape the quality of wood assortments in response to the market demand. This is an important element of the economic analysis, which mostly consists of the costs of raw material and its transport. The higher the price of raw material is, the lower the relative cost of its transport is. Therefore, taking the economic aspect into account, the raw material from the FMCF habitat, which had higher strength parameters, could be transported to more distant places. As raw wood from the FMF habitat has lower strength parameters, it will mostly be profitable for local recipients to acquire it [57]. It is noteworthy that the efficiency of wood processing is of fundamental importance for companies purchasing wood. This indicator, which is defined as the total commodity value of products (timber and other sawmill products) in relation to the cost of purchasing the raw material for their production, affects the profitability of the manufacturing process [58,59]. Therefore, further research should be conducted in this area.

The analysis of the results of the study enabled assessment of the influence of the forest habitats fresh coniferous forest (FCF), fresh mixed coniferous forest (FMCF), fresh mixed forest (FMF) and fresh forest (FF)) on the average strength of raw wood. The wood from the habitats differed from each other not only in density, but also and more importantly, in strength. The comparison showed habitat-dependent differences in the results, which were confirmed by heterogeneous diagrams of one-way analysis of variance. Heterogeneity of variance in the strength of the habitats studied means that the population variances of the habitat groups compared are not homogeneous or equal. Homogeneity was defined only in the first group at the level of habitats FCF, FMCF and FF. The conducted research confirms the experience of other researchers for Scots pine in northern and central Europe, where an increase in the proportion of higher-density wood, responsible to a considerable extent for wood strength on poor soils, was confirmed. Habitats that are too rich (former farmland) increase the width of annual increment and decrease the strength of Scots pinewood [7,8,41,42,48,49].

It is noteworthy that wood, as an anisotropic material, is shaped by various factors, which may cause differences in the quality characteristic under analysis. These differences may be caused not only by the habitat, but also by the age of the tree. Differences in the age of the trees from which the samples were collected were not taken into account in our study. However, dependence between the share of mature wood in the material structure and its average strength was observed. The test results also depend on the height at which wood samples are collected. Apart from the species and habitat factors, these are additional elements which affect variability in the physical and mechanical properties of wood.

5. Conclusions

- The type of forest habitat influenced the average strength of pinewood. The highest variability of the average flexural strength was observed for the FMF habitat (SD 14.5 N/mm^2). The wood from this weak habitat was characterised by the lowest strength (60.7 N/mm^2) and belonged to the second homogeneous group according to the Tukey HSD test;
- The wood from the FMCF, FCF and FF habitats was in the same homogeneous group. At the same time, the wood from the FCF weakest habitat belonged to the first and second homogeneous groups and was characterised by the second lowest average strength;
- The type of forest habitat influenced the average density of wood. The wood from the FMCF habitat was characterised by noticeably different density. It belonged to the second homogeneous group and had the highest average density (519 kg/m^3);
- Height in habitat quality have resulted in a decrease in average pinewood density;
- Increasing habitat quality promotes a decrease in the standard deviation for the distribution of static bending strength scores of pinewood;
- In the strength classification, the highest lower strength value was confirmed for the best fresh forest (FF) habitat.

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