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THE VARIABILITY OF CERTAIN MACROSTRUCTURAL FEATURES AND THE DENSITY OF GRAND FIR (*ABIES GRANDIS* LINDL.)WOOD FROM SELECTED STANDS IN SOUTHERN POLAND

The paper presents the results of investigations into the variability of certain features of the wood macrostructure, such as the width of the annual ring, the share of late wood, and the relative density of the wood of grand fir, growing in four stands in southern Poland. The trees under investigation were 30-35 years old. The research material consisted of incremental cores sampled from trial trees with the use of a Pressler borer. The examined wood features were analysed in sections, each one comprising five annual rings. The rings were given numbers, sorted in an ascending order from the trunk circumference. The mean values of the analysed features were as follows: the annual ring width – 4.38 mm, the share of late wood - 35.39%, the relative wood density – 0.354g·cm^{-3}. It was established that the wood of grand firs growing on less fertile soils had significantly narrower annual rings and higher wood density than those on more fertile soils.

Keywords: grand fir, wood, macrostructure, density, variability

Introduction

In Polish forests, there are nearly 30 non-indigenous species, more than twenty of which are coniferous. Within this group, six species of the fir genus (*Abies* sp.) are listed: *A. balsamea* – balsam fir, *A. concolor* – white fir, *A. nordmanniana* – Caucasian fir, *A. procera* – noble fir and *A. grandis* – grand fir [Gazda 2012]. The latter is characterised by the greatest dimensions among the other species of the *Abies* genus, since it may reach up to 90 m in height and

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more than 2 m in diameter at breast height, if growing in optimal habitats [Bellon et al. 1977; Albrecht, Hőher 1978]. The grand fir was introduced in Poland in 1856 and, as in Europe, it was primary planted in parks, gardens and arboreta. Later, at the turn of the 19th and 20th centuries, it was included in forest plantations. The studies conducted at the end of the 20th century and the beginning of the 21st century confirmed the suitability of this species for cultivation in Poland. Furthermore, researchers highlighted the faster growth of the grand fir, in relation to other, domestic coniferous species [Bellon 1990; Tumiłowicz, Wodzicki 1990–91; Kulej, Kądziołka 1998; Bellon et al. 2003; Kulej, Socha 2005, 2008; Sosnowski et al. 2005; Kulej 2003].

Apart from assessing the suitability of the grand fir for cultivation, knowledge of the properties of the raw wood, determined by specific plantation conditions, is extremely important. In related Polish literature, there is only one publication where the outcomes of examinations on the wood properties of the grand fir may be found [Moliński, Raczkowski 1993]. However, the cited research was carried out based on one tree only, thus it cannot be considered reliable for evaluating the variability discussed in this paper of the features between particular trees or entire tree populations, growing under varied habitat and stand conditions.

The aim of this paper is to determine the variability of certain macrostructural features and the density of the wood of the grand fir coming from selected stands in southern Poland.

Materials and methods

The research was conducted in 2010 in the Regional Directorate of the State Forests in Cracow, within two forest districts: Myślenice and Nawojowa. In the former, the investigations embraced the forest subdistricts of Tokarnia and Kornatka, while in the latter – the forest subdistricts of Kamianna and Feleczyn were included. At further stages of the studies, the names of the above-mentioned units were encoded as follows: Forest Subdistricts Tokarnia – stand 1, Kornatka – stand 2, Kamianna – stand 3 and Feleczyn – stand 4.

According to the data gathered in table 1, the age of the grand firs under investigation was similar, reaching 30 (stands 1 and 2) or 35 years old (stands 3 and 4). The trees grew in broadleaved forest habitats, in three stands on acid brown soils (stands: 1, 3 and 4), and on rusty podzolic soil in stand 2. The share of grand fir was varied, ranging from 20% (stand 1) to 100% (stand 3).

Table 1. Location, habitat and stand characteristics of the test plots

Code of stand	Forest District, Forest Subdistrict, compartment area	Age	Species composition	Habitat type	Type and subtype of soil	Stocking index
1	Myślenice Tokarnia, 241 f(-01) 1.33 ha	20 20 20 30 20 40	3 fir 1 beech 1 spruce 2 grand fir 1 larch 1 fir	mixed mountain forest	acid brown	0.8
2	Myślenice Kornatka, 99 c 4.16 ha	40 30	6 fir 4 grand fir	mixed upland forest	rusty podzolic	0.7
3	Nawojowa Kamianna, 110 b 1.49 ha	35	10 grand fir	mountain forest	acid brown	2.2
4	Nawojowa Feleczyn, 349 c 0.85 ha	35 60 11	8 grand fir 1 elm 1 Douglas fir	mountain forest	acid brown	1.8

In every stand, in its representative fragment, a rectangular (40 × 50 m) test plot was established, taking up an area of 20 ares. Diameters at breast height of all the living grand firs on this plot were measured. Then, based on Draudt’s method, 30 trial trees were selected; and, from each one, a single increment core was sampled with the use of a Pressler borer. The sample was taken at a height of 1.3 m above ground level, on the northern side of the tree. The increment cores served to determine the selected features of the macrostructure and the wood density. The examination was performed in the laboratory of the Department of Forest and Wood Utilization. Each increment core was placed in a special holder and then, by means of a sharp knife, a ca. 1-mm layer of wood was trimmed from it, perpendicular to the wood grain, revealing the trunk cross-section. The increment cores prepared in this manner were then scanned at a resolution of 1200 dpi. The digital images obtained were used for measuring the widths of the annual rings, with an accuracy of 0.01 mm, using specialised “Przyrost WP” software [Biotronik 2001]. The measurements were taken from the trunk circumference towards the stem pith. For every annual ring, the zones of early and late wood were measured separately, which made it possible to compute the share of both zones within a single ring. The boundary between both incremental zones was established visually (a subjective assessment) by an operator who took the measurements (the same person in all cases). Afterwards, starting from the trunk circumference, the increment cores were divided into sections, each one comprising five annual rings. The latter, the closest to the stem pith, usually contained less than five rings. For the sections obtained, the relative wood density was established, being a quotient of the weight of absolutely dry wood and the volume in its maximum saturation state. In order to obtain the state of maximum saturation, particular sections of the increment cores were placed into test-tubes filled with distilled water and left there until they sank autonomously. Then, their volume was measured using the hydrostatic weighing method [Olesen 1971]. Afterwards, the wood was dried at a temperature of 103 ± 2°C until it became absolutely dry, and then it was weighed. The density of the wood obtained within the particular sections was converted into the wood density for the cross-section at breast height, by computing the mean, weighted by the shares of particular sections within the overall area of this cross-section, according to methodology applied by Ericson [1959]. The outcomes were compared, and then the mean values and coefficients of variation were calculated for the trial trees, test plots and the entire material under analysis.

For performing the statistical analyses, the following procedures were employed [Stanisz 1998, StatSoft, Inc. 2011]. The consistency of the empirical distributions with the normal distribution was estimated with the use of the Shapiro-Wilk test. The homogeneity of variances within the compared groups was assessed using Levene's test. The statistical significance of differences between the means for multiple trials was verified by means of the variance analysis, whereas for identifying one of the compared population as the one responsible for rejecting the null hypothesis of equality of mean values, Scheffe's test was employed. Upon not meeting the assumptions required for applying a parametric test, the significance of the differences was estimated with the use of the Kruskal-Wallis test. The degree of interdependence between two variables was determined based on the coefficient of Pearson's linear correlation. For testing the statistical hypothesis, a significance level of $p \leq 0.05$ was assumed.

Results and discussion

The research covered a total number of 119 increment cores sampled from the trial trees from four test plots (30 trial trees per test plot). The condition of one of the cores made a reliable measurement of the wood properties impossible, therefore it was rejected. Table 2 shows the mean values and the coefficients of variation of the wood properties under investigation. This data indicates that the average annual growth for all the analysed trees accounted for 4.38 mm. With regard to the particular test plots, it ranged between 3.47 mm (stand 2) and 5.27 mm (stand 1). The coefficient of variation for this feature, within a single test plot, varied from 26.1% to 43.7%, whereas in respect of the variation between the particular test plots, it reached a value of 17.1%. The widest individual annual ring was recorded in the wood of one of the increment cores from the test plot in stand 1, with a width of 15.07 mm. This ring was dated to 1994.

Table 2. Mean values and coefficients of variation of the wood properties under investigation

Stand	Type of statistics	S [mm]	U [%]	γ_w [$g \cdot cm^{-3}$]
1	$X_{śr}$	5.27	35.5	0.348
	V [%]	30.5	22.8	9.8
2	$X_{śr}$	3.47	33.3	0.375
	V [%]	43.7	23.0	10.4
3	$X_{śr}$	4.21	35.5	0.355
	V [%]	39.7	18.3	15.9
4	$X_{śr}$	4.57	37.2	0.338
	V [%]	26.1	18.8	9.1
Total	$X_{śr}$	4.8	35.39	0.354
	V [%]	17.1	4.5	4.4

Verification of the consistency of the annual ring width distribution with the normal distribution revealed an inconsistency in reference to the firs from stand 2. The Kruskal-Wallis test, following the verification, proved that the annual rings in the fir wood from stand 2 were significantly narrower than those from stands 1 and 4. Although the variance analysis performed on the data gathered from the three test plots, where the distribution of this variable was consistent with the normal distribution, indicated an occurrence of statistically significant differences between the investigated plots ($p = 0.04699$), Scheffe's test did not enable the identification of the population responsible for rejecting the null hypothesis. The average share of late wood in all the investigated trees accounted for 35.4%; for the particular test plots, the value of this feature oscillated between 33.3% (stand 2) and 37.2% (stand 4). The coefficient of variation between the analysed test plots reached a value of 4.5%, whereas in respect of the variation within the particular test plots, it ranged from 18.3% to 23.0%. Regarding the feature discussed here, no significant differences between the analysed test plots were recorded (Levene's test: $p = 0.81551$, variance analysis: $p = 0.25224$).

The mean value of the relative wood density for all the investigated trees accounted for $0.354 g \cdot cm^{-3}$, whereas the coefficient of variation was 4.4% (table 2). In respect of the mean values and the coefficients of variation within the particular test plots, they spanned the following ranges: from $0.338 g \cdot cm^{-3}$ (stand 4) to $0.375 g \cdot cm^{-3}$ (stand 2), and from 9.1% to 15.9%, respectively.

The statistical analyses performed revealed that the density of the wood in the grand firs from stand 2 was considerably higher when compared with the trees from the test plots in stands 1 and 4, considering that the fir wood from the latter had a significantly lower density than that of stand 3.

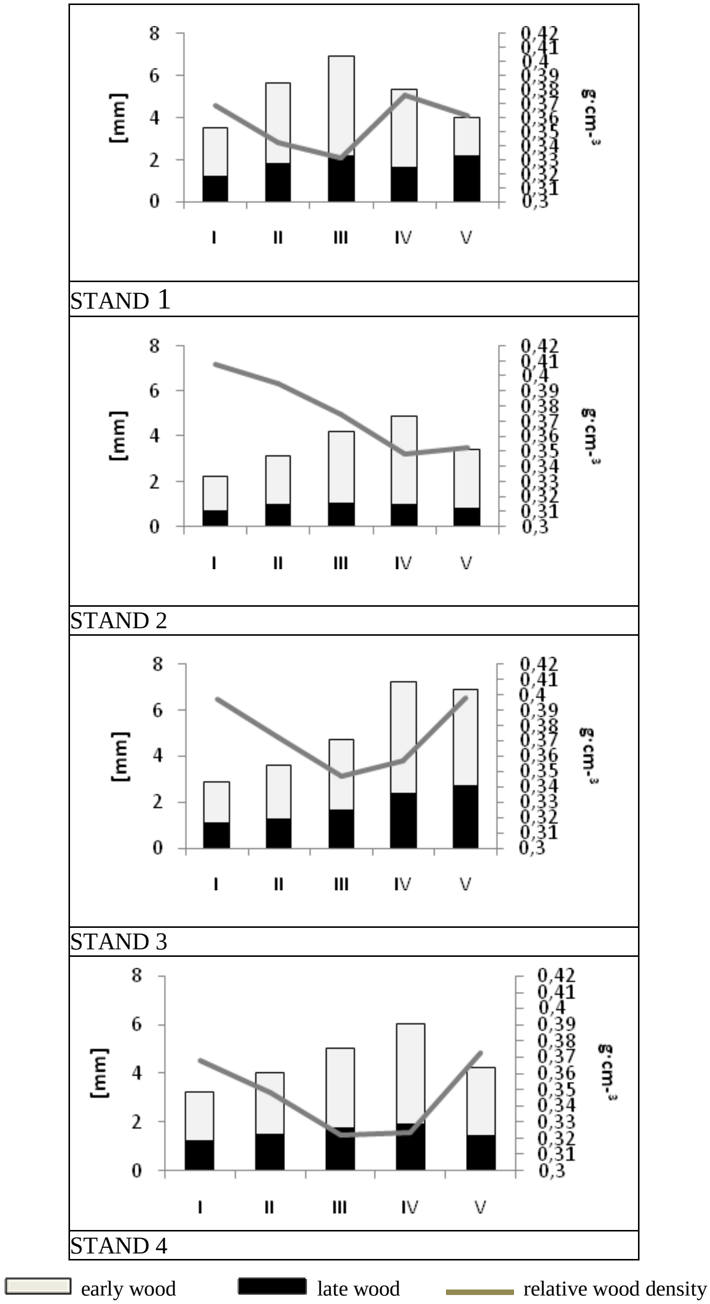

Fig. 1. Variability of the wood properties under investigation along the radius of the trunk cross-section

The diagrams presented in figure 1 indicate that the widest annual rings occurred close to the centre of the trunk cross-section of the trees from all the test plots; however in stands 2, 3 and 4, the widest rings were recorded in section VI, comprising those formed in 1989–1998, whereas in stand 1 the maximum point fell in the years 1994–1998, i.e. section III. Moreover, a gradual decrease in the annual ring widths towards the trunk circumference was observed in the entire analysed material. Similar trends were also recorded in respect of the variability of wood density along the radius of the trunk cross-section. This was true for all the test plots. The lowest values of this feature occurred in the sections situated closely to the stem pith, with wide annual rings, whereas in the circumferential sections a significant increase in wood density was recorded, accompanied by a fall in annual ring width.

The data gathered in table 3 indicates that the coefficients of correlation between the wood properties under investigation were statistically significant. A weak positive correlation was recorded between the share of late wood and the relative density. Whereas, the annual ring width displayed a negative correlation with both the share of late wood and the wood density, although in the first case the strength of dependence was weak, while in the second it was moderate.

Table 3. Values of the correlation coefficients (r) and significance levels (p) for the analysed wood properties

Feature	**S**	**U**
U	R = -0.1270 P = 0.007	–
γ_w	R = -0.5004 P = 0.00	R = 0.2138 P = 0.000

explanation of symbols as for table 2

In North America, the wood of the grand fir is commonly utilised in various branches of the economy. It is widely used in building, wood-based materials (plywood, particle boards, fibreboards, and filling blockboard), packaging, as well as in cellulose and paper manufacture. High-quality wood is occasionally utilised in aircraft engineering. The technological properties of *A. grandis* are similar to those of *A. alba*, which makes it a highly workable material, suitable for mechanical processing (sawing, machining, milling, and planing), gluing, painting, varnishing or even coating with metals [Mućk 1978, Forest Products Laboratory 2010]. Despite the fine technological properties of grand fir wood and the promising results of studies on its suitability for cultivation in Europe, this species has not met with great interest in Poland as yet. This is probably the reason for the low number of research studies dedicated to the wood of the grand fir growing in Polish stands. However, as this species may become more desirable in the future, a recognition of the variability of its macrostructural features and its wood density is crucial, not only for the science advancement but also from a practical point of view. This paper presents the analyses performed on wood of 30–35-year-old grand firs growing in four stands in southern Poland.

The average annual ring width of the grand fir wood under scrutiny accounted for 4.38 mm. The narrowest rings were recorded in the wood of the trees from stand 2. This might have been caused by less fertile soil in this stand. The trophic state index for rusty podzolic soils, like those on which the grand firs from stand 2 grew, ranges from 12.4 to 23.7, whereas for acid brown soils, like those encountered on other test plots, this index is higher, oscillating between 23.4 and 31.9 [Brożek, Zwydak 2003]. The variability in annual ring width along the radius of the trunk cross-section was characterised by a gradual decrease from the stem pith towards the circumferential sections. This is a phenomenon typical of fast-growing coniferous trees [Mućk 1978; Wąsik 2007; Feliksik, Wilczyński 2009]. The relatively high variability in the annual ring width should be associated with the young age of the trees under investigation and the high share of juvenile wood along the radius of the trunk cross-section. The juvenile wood zone is characterised by wider rings when compared with those formed in mature wood at an older age. With regard to a pine tree, the number of annual rings in juvenile wood ranges from 14 to 23, according to various authors [Jakubowski 2004, Mutz et al. 2004, Fabisiak 2005], whereas Hapla et al. [2014] reported that the quantity of annual rings in the juvenile wood of a grand fir varied between 10 and 20. In the present paper, the issues related to juvenile wood were not analysed in detail. However, based on the outcomes obtained for the three test plots (stands: 2, 3 and 4), it may be assumed that the juvenile wood comprised annual rings of the two innermost sections (IV and V), while in stand 1 it embraced 3 sections (III, IV and V). The gathered data is, therefore, similar to that given by Hapla et al. [2014], and it explains the great differentiation in annual ring width along the radius of the trunk cross-section.

On average, the share of late wood in the grand firs under scrutiny accounted for 35.39%. No statistically significant differences between the test plots were detected. The mean value was slightly lower in relation to the averaged results obtained by Niedzielska [1995] for the wood of a silver fir (36.7%), growing within the boundaries of its natural extent in Poland. Moliński and Raczkowski [1993] also reported a slightly higher share of late wood at breast height of a 80-year-old grand fir under investigation – 40%. With regard to another North American species growing in Poland, i.e. the Douglas fir, the share of late wood in these trees occurring in mountain habitats was considerably higher, amounting to 51.2% [Wąsik 2007]. The reasons for the relatively low share of late wood in the annual rings of the investigated fir trees must be sought in their young age and their high share of juvenile wood, as mentioned above. The value of this particular feature will probably grow in the following years, due to an increasing number of annual rings formed by mature wood.

The mean relative density of the wood in all the analysed grand firs totalled 0.354 $g \cdot cm^{-3}$. This made it possible to classify the fir trees under investigation into the group of species with extremely light wood, i.e. with a density below 0.400 $g \cdot cm^{-3}$ [Krzysik 1974]. The value in question was 14% lower than the outcomes obtained by the above-quoted authors, Moliński and Raczkowski [1993] (412 $kg \cdot m^{-3}$ at breast height). American sources report that the density of the absolutely dry wood of a grand fir growing in North America reaches 0.370 $g \cdot cm^{-3}$ [Miles, Smith 2009]. Therefore, if the relative wood density obtained in this research was converted into an absolute density (for absolutely dry wood), assuming that the coefficient of volumetric shrinkage for a grand fir ranges from 10.5% to 11.0% [Forest Products Laboratory 2010; Lukášek et al. 2012], the recalculated value would increase and vary, respectively, between 0.395 and 0.398 $g \cdot cm^{-3}$. This would confirm the hypotheses expressed by Moliński and Raczkowski [1993], that the grand fir growing in Poland is able to form wood with a density higher than that recorded for the US specimens. This is also supported by data from Germany, which indicates a slightly higher (when compared with North American data) wood density of grand firs (0.380 $g \cdot cm^{-3}$ at a height of 1.5 m above ground level) growing under conditions encountered in Central Europe [Hapla et al. 2013]. Nevertheless, the wood density presented here was lower than the relative density of wood in the indigenous silver fir (0.388 $g \cdot cm^{-3}$) investigated by Niedzielska [1995], although this may result from a considerable difference in age between the trees, since the above-mentioned author analysed firs over 100 years old. Comparing the relative wood density of the two North American species occurring in Poland, i.e. the grand fir and Douglas fir, the wood density of the latter was higher. The relative wood density of Douglas fir at an age similar to that of the grand firs (24–28 years) under analysis ranged, depending on the location (mountains, uplands or lowlands), between 0.446 and 0.489 $g \cdot cm^{-3}$ [Wąsik 2007].

The analysis of variability in wood density along the radius of the trunk cross-section of the investigated firs proved that for every test plot, the lowest value of this feature was recorded in the central part of the cross-section, however not directly in the stem pith zone, where it was slightly higher in relation to the adjoining sections. A gradual increase in wood density towards the trunk circumference was observed. Similar regularities in grand firs from Germany were reported by Hapla et al. [2014]. These authors stated that the wood density in annual rings directly adjacent to the stem pith was a little higher than that in the later, surrounding rings. This value then gradually grew towards the bark layer.

The wood density of the grand firs from stand 2 was significantly higher when compared with those from stands 1and 4, which should be linked with the significantly narrower annual rings encountered on the first of the above-mentioned test plots in relation to the other two. The analyses of mutual dependences, in terms of wood density and annual ring width, performed on coniferous species, revealed a negative correlation between both these features [Niedzielska 1995, Wąsik 2007]. The wood of spruce of native provenance (of a similar age) was characterised by a higher density, in relation to the results of this study. The average values of spruce wood ranged from 0.376 to 0.417 $g{\cdot}cm^{-3}$ [Szaban et al. 2014].

The above-mentioned correlation was also confirmed by the grand firs under investigation, in the case of which a negative coefficient of correlation of moderate strength was recorded. This led to the conclusion that cultivating grand firs aimed exclusively at achieving the largest possible volume in the shortest period of time may ultimately result in raw wood of a lower density and, consequently, worse technical quality, as such wood is characterised by less favourable mechanical properties [Tomczak et al. 2010, Lachowicz 2011].

The technical quality of merchantable timber is strictly connected with the raw wood quality, which is mostly affected by the sizes of trunks and wood defects. Although the research scope presented here did not comprise the quality of the trunks of the grand firs under analysis, the field observations which were conducted indicated, without any detailed analyses, that this quality was relatively low. The major reason for such an evaluation was a frequent occurrence of thick snags and branches, at a height of 4 m above ground level, with diameters considerably exceeding 2 cm [Warunki techniczne 2002]. This defect is also considered the main reason for the depreciation of the value of spruce wood, which, like fir wood, contains unstained heartwood [Michalec et al. 2013].

As mentioned above, this is the first paper to present the outcomes of studies on the variability of macrostructural features and the wood density of grand firs growing in selected stands in Poland. For more comprehensive characteristics of the wood of this species, it would be advisable to widen the research area to cover more stands of this sort, and extend the scope of the investigation, including analyses of the variability of the features of the wood's anatomical structure and mechanical properties, as well as an evaluation of the raw wood quality in respect of an occurrence of wood defects. This knowledge would be valuable from the perspective of forest practitioners (cultivating trees of the desired raw wood parameters) and the wood-based industry (processing harvested raw wood).

Conclusions

Based on the studies conducted on certain features of the macrostructure and wood density of grand fir coming from selected stands in southern Poland, the following statements and conclusions have been formulated:

1. The average width of an annual ring for all the analysed trees accounted for 4.38 mm, with the mean values for the particular test plots ranging from 3.47 mm (stand 2) to 5.27 mm (stand 1). This feature showed a relatively high variability, especially if considered within the individual test plots, which may be explained by the young age of the trees and the high share of juvenile wood along the radius of the trunk cross-section.
2. The mean share of late wood in the trunks of the investigated trees was 35.39%. This feature revealed a slight differentiation between the particular test plots.
3. The relative wood density on average reached 0.354 $g \cdot cm^{-3}$. The highest mean value was recorded on the test plot in stand 2 (0.375 $g \cdot cm^{-3}$), while the lowest in stand 4 (0.338 $g \cdot cm^{-3}$). Converting the relative density into an absolute density made it possible to confirm that the values presented in this paper may be higher than those reported for grand firs in North America.
4. The annual rings of the grand firs from stand 2 were significantly narrower and the wood density higher, when compared with the trees from stands 1 and 4. The reasons for this should be sought in the less fertile soil on which the firs from stand 2 grew, characterised by the lower trophic state index.
5. The analysis of variability in the wood features under investigation along the radius of the trunk cross-section proved that annual rings of low wood density occurred in the central part of the cross-section, and this was true for every test plot. Ring width decreased towards the trunk circumference, whereas wood density increased.
6. The coefficients of correlation between the annual ring width and the wood density were negative, and of a moderate strength of dependence. This indicated that cultivating a grand fir aimed exclusively at achieving the largest possible volume in the shortest period of time may lead to raw wood of low density, thus of worse technical quality in the future.
7. Due to a low number of published papers concerning grand fir wood in Poland, it would be advisable to widen the research area to cover more stands of this sort, and extend the scope of the investigation, including, in particular, analyses of the variability of the features of the wood's anatomical structure and mechanical properties, as well as an evaluation of raw wood quality.

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