Analysis of coniferous species to identify and distinguish juvenile and mature wood

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ABSTRACT: We conducted to describe methods used to differentiate the zones of juvenile and mature wood in stems of coniferous species and to present the importance of good identification of the shares of both types of wood to ensure a rational use of the raw material and final quality of wood products. This study describes in more detail a novel method to separate the juvenile and mature wood tissue in stems of European larch using cluster analysis in the form of the *k*-means algorithm. Moreover, guidelines were also shortly described for forest management which could result in a reduction of the share of juvenile wood in stems of forest trees.

Keywords: differentiation methods; k-means algorithm; forest management

Wood is an anisotropic material, its properties are strictly related with the analysed anatomical direction, determining the uniqueness of wood in comparison with amorphous materials, the properties of which are not dependent on the section direction. Thus the technological processability of wood is determined, among other things, by variation in its structure. This pertains both to interspecies and intraspecies variability, determined by the location of the wood tissue within a single tree and within different trees in the stand (Fabisiak 2005).

Juvenile wood is formed under conditions of the apical meristem action on the cambium in stems of both coniferous and deciduous trees and assuming a cylindrical form, composed of several to several dozens of annual increments in diameter, surrounded by annual rings of mature wood at further development stages (Zobel, van Buijtenen 1989). This action is exerted through phytohormones, first of all auxins as growth stimulants in plants (Hejnowicz 2002). With age the lower sections of stems are no longer found in the live crown zone and are no longer affected by phytohormones or the apical meristem. In this way, away from the active assimilatory and transpiration organs, wood cells with characteristics of mature wood (also referred to as adult wood) are formed from the stem base upwards. With the progression of mature wood towards the apex of the tree as a result of self-pruning and the simultaneous production of juvenile (crown) wood within the live crown zone, the zone of juvenile wood is surrounded towards the apex by rings of mature wood. Trees produce juvenile wood at any age (Saranpää 2003).

Rational utilisation of the renewable raw material base should be based on its optimal use in relation to the capacity to evaluate timber first of all in terms of its quality. In contrast to mature wood, juvenile wood is an undesirable element of the stem structure due to several disadvantageous properties limiting its potential applicability, first of all for construction purposes. Observed differences and heterogeneity of properties in mature and juvenile wood have an evident effect on timber properties, in which these two different forms of the wood tissue coexist. Thus in relation to coniferous trees, which are the subject of most research studies, it is true that juvenile wood is an undesirable element in many wood products and it is considered to be a defect.

Scientists worldwide for years have distinguished juvenile and mature wood zones taking into consideration different macrostructure, microstructure and submicroscopic wood properties as well as its selected physical and mechanical properties. However, it needs to be stressed here that the boundary between these wood zones is not distinct and different values are assumed within a given species, depending on the applied methods to identify it (Cown 1992; Tasissa, Burkhart 1998; Fabisiak 2005; Alteyrac et al. 2006). Also Yang et al. (1986) were of an opinion that the boundary between tested wood types may assume different values within a single tree as a result of individual differentiation and changing external factors.

The presence of juvenile and mature wood zones at the stem cross-section is one of the causes of heterogeneous wood structure, resulting in problems with its rational processing (Geimer et al. 1997; Spława-Neyman, Szczepaniak 1999). For this reason it is very important to identify the boundary between discussed wood types and determination of their share in stems of forest trees is crucial not only from the aspect of pure science, but also for practice connected with optimisation of timber processing and utilisation.

Concepts for the formation of juvenile and mature wood

Growth and development of trees are functions of time and are influenced by many external and internal factors manifested in species-specific and individual traits, site conditions, climate (microclimate), the social class position in the stand, tending interventions and several others, which also have an impact on the structure and properties of the formed wood tissue.

In the opinion of Hejnowicz (2002), in plant development a particular role in the formation of wood tissue is played by the developmental pathways starting from the apex and the cambium. The apical meristem develops in cycles, which is connected with the annual cycle triggering the basipetal (downward) formation of early wood. Apart from cyclical development, progressive developmental changes also occur in plants (visible first of all in trees). They are connected with transition through the juvenile phase to the phase of wood maturity and the transformation from vegetative development to generative development, which obviously influences the wood tissue being formed. Development from the vascular meristem (cambium) facilitates growth in diameter in perennial plants throughout their lives, depositing inside the new layers of secondary wood and outside the phloem. During its development cambium cells are differentiated and thus also wood and phloem cells.

Based on analyses of density, static bending and compression along the grain, Bendtsen and Senft (1986) determined the juvenile period in *Pinus taeda* to be 12 years, on the basis of tracheid length it was identified at 18 years, while in the case of the cellulose fibril angle it was established at 30 years. According to Abdel-Gadir and Krahmer (1993), the determination of the boundary between juvenile and mature wood is complex and difficult, since anatomical changes take place gradually over a period of several years. The demarcation line between juvenile and mature wood varies in particular species (Bendtsen, Senft 1986), different genotypes (Abdel-Gadir, Krahmer 1993) and it is dependent on the geographical location (Clark, Saucier 1989). Fabisiak (2005) reported that the identification of juvenile wood at the stem cross-section is difficult, particularly in coniferous trees. That author was of an opinion that it is easier to identify the juvenile wood zone in deciduous trees, in which vessels of juvenile wood at the cross-section of stems are smaller and arranged differently from mature wood. Moreover, juvenile wood formed in the apical part of trees shows differences in macro- and microstructure in relation to the same type of wood found in the butt end (Larson et al. 2001; Burdon et al. 2004a,b; Tomczak et al. 2008). Many researchers (Clark, Saucier 1989; Pazdrowski, Spława-Nayman 2003; Pazdrowski 2004; Giefing et al. 2005; Pazdrowski et al. 2005; Alteryac et al. 2006; Tomczak et al. 2007a,b, 2008) also specify transition wood exhibiting intermediate (transition) traits between juvenile and mature wood. In the opinion of Larson et al. (2001), the term transition wood refers to annual rings produced after the period of juvenile wood formation, but before the deposition of rings having the structure and properties of mature wood. Juvenile wood took its name from the physiological age of cambium forming it within the assimilatory and transpiration organs (Zobel et al. 1959; Shivnaraine, Smith 1989). Synonyms frequently used by many authors to replace the term "juvenile" include such phrases as crown wood and core wood, pith wood, and less frequently pith-associated wood. Each of the above-mentioned terms is justified due to their formation and position in the stem. The adjective "juvenile" results from the early ontogenetic and physiological stage of tree development, although the juvenile period characterising changes in the wood tissue during individual development of trees does not refer to maturation in the biological sense (Poethig et al. 1990a, cit. Tomczak et al. 2009a).

After Duff and Nolan (1957), Schweingruber (2007) presented the ontogenetic and physiological approach to ageing of wood. In the presented model at the stem base in the pith-associated section ontogenetically and physiologically young wood is found, at the butt end circumference and at the apex it is ontogenetically old and at the same time physiologically young. Similar wood, but not identical in terms of its traits, is produced in the central section of the stem surrounding the pith at all height levels. In this case the term pith refers to the indicated location of this type of wood at the cross-section and the longitudinal section of the stem. In the opinion of many authors juvenile wood most typically covers from several to several dozen annual increments in diameter (Zobel 1984; Ohtani 1986; Saranpää 1994; Yang, Hazenberg 1994; Kennedy 1995; Lindström 2002; Myers 2002; Cooper et al. 2005; Fabisiak 2005; Nawrot et al. 2007, 2009; Kretschmann 2008; Tomczak et al. 2009a, etc.). In turn, crown wood took its name from the zone of the live, physiologically active crown, within which the cambium and newly-formed wood are subjected to a strong influence of phytohormones, first of all auxins, and the apical meristem (Fukazawa 1984; Di Lucca 1989; Gartner et al. 2002; Hejnowicz 2002). According to Burdon et al. (2004a, b), the problem of juvenile wood needs to be considered from two aspects: we distinguish pith wood (core wood) and outer wood at the stem ray, while juvenile wood and mature wood are distinguished at the axial direction, which in the opinion of the authors corresponds to the classical botanical concept of maturity. Paul (1960) questioned the concept of juvenile wood. In his opinion juvenile wood is not necessarily connected with tree growth dynamics, since wood located centrally, at the pith, is subjected to strong effects of forest management. He supported his thesis of narrow annual increments, which were formed under the influence of considerable competition and stocking density. Wood formed in this way was characterised by reduced width of early wood and increase in the share of late wood in the annual ring, i.e. it reminded the macrostructure of mature wood, formed at later stages of development. Theses contradicting that proposed by Paul were presented by many authors (DiLucca 1989; Larson et al. 2001; MacDonald, Hubert 2002; Koubaa et al. 2005), arguing that slow growth in youth does not eliminate the presence of juvenile wood, but limits the width of its zone. Both narrow and wide rings of the juvenile zone retain their character in comparison with narrow or wide rings of mature wood. Despite several names and differences in opinions, the scientific community worldwide has adopted the term juvenile wood as a universal, commonly used name to denote unambiguously the discussed problem. The width of the juvenile wood zone and the duration of its formation are influenced by many exo- and endogenous factors.

Obviously, inferior physical and mechanical properties of juvenile wood (in coniferous species) result in it being a defect causing increased heterogeneity of timber. Juvenile wood is characterised by less attractive gloss as a result of poor light reflecting ability, due to which it is not suitable for the production of veneers or the application in furniture making. Kellogg and Kennedy (1986) [cit. Fabisiak (2005)] reported that veneer produced from juvenile wood is characterised by bigger cracks and their higher frequency. On the other hand, juvenile wood may be used to produce paper, which when obtained from such raw material is of good quality, determined on the basis of such parameters as bursting strength, breaking strength, creasing strength and tensile strength (Barefoot et al. 1964; Hatton, Cook 1992; Hatton 1993; Hatton, Gee 1994 cit. Fabisiak 2005). Thinner cellular walls in juvenile wood facilitate the manufacture of products with greater compaction of components, thus with greater density, lesser porosity, roughness and smoothness as well as good optical properties. A potential defect of paper produced from juvenile wood is connected with its lesser breaking strength resulting from shorter tracheids (Semen et al. 2001 cit. Fabisiak 2005).

Aim

The aim of this paper was to describe and characterize methods to identify juvenile and mature wood zones in stems of coniferous species. Experiments conducted by the authors in this respect facilitate an analysis of various methods and identification of those which in the authors' opinion should be focused on and applied to indicate in tree stems the economically important zones of juvenile and mature wood.

MATERIAL AND METHODS

The description of methods used in the determination and separation of juvenile wood from mature wood in coniferous species was based on previously conducted analyses of literature on the subject and studies carried out by the authors, including experiments (Nawrot 2010; Pazdrowski et al. 2010; Szymański 2011).

RESULTS

Among studies consisting in the differentiation of juvenile and mature wood zones in tree stems and the identification of the effect of various factors on the incidence of juvenile wood we may find numerous papers concerning first of all coniferous species. These studies are characterised by varying research approaches to the problem of juvenile wood occurrence. Thus, depending on the specialisation of researchers the occurrence of juvenile and mature wood was investigated using chemical, physical (including X-ray crystallography), mechanical methods, with the macrostructural approach to properties of wood as a derivative of the stem internal structure and submicroscopic traits in wood-depositing tissues.

Based on macrostructural characteristics the juvenile wood zone in coniferous species was distinguished by Jakubowski (2000, 2004a,b), Pazdrowski (2004), Pazdrowski et al. (2005), Tomczak (2006), Tomczak et al. (2009c) and Nawrot et al. (2007). This method consisted in the identification of the trend line for changes in the degree of wood homogeneity, i.e. the ratio of late wood width to early wood width within annual rings (according to Spława-Neyman 1976). Alteryac et al. (2006) identified the boundary between the discussed wood zones based e.g. on the area of annual increments in diameter. Another widely applied method using traits of wood microstructure to separate the two wood zones is based on the length of anatomical elements, mainly fibres and tracheids. This method was used in relation to various species by many researchers (Yang, Hazenberg 1994; Fabisiak 2005; Yeh et al. 2006, etc.). On the submicroscopic level the most typically applied characteristic of wood structure for the determination of a boundary between juvenile wood and mature wood is the angle of cellulose fibrils in relation to the longitudinal axis of cells (Sahlberg et al. 1997; Bhat et al. 2001; Deresse et al. 2003; Kojima, Yamamoto 2004; Fabisiak, Moliński 2007; Krauss 2010), while less frequently it is the degree of cellulose crystallinity (Marton et al. 1972; Kocoń 1991; Andersson et al. 2004; Nawrot 2010; Pazdrowski et al. 2010; Szymański 2011). The parameter used most often in the determination of a boundary between the two wood zones in the case of physical properties is connected with specific density of annual rings and zones of early and late wood zones separately (Tassisa, Burkhardt 1998; Bao et al. 2001; DeBell et al. 2004; Clark III et al. 2006; Mora et al. 2007). Gadir and Krahmer (1993) determined the boundary between juvenile and mature wood zones in stems of 360 Douglas firs based on density of annual increments. Analysis of wood density indicated the demarcation line between the two wood types between the 15th and 38th annual rings, assuming a mean value of 26 years. A shorter juvenile period was found on the basis of density of late wood (14 years), while it was longer in the case of changes in density of early wood (37 years). Different methods of distinguishing juvenile and mature wood zones were also applied by Koubaa with his team (2005). The transition age in 934 stems of 50-years-old black spruce (*Picea mariana* [Mill.] B.S.P) was determined on the basis of the share of late wood in annual rings to be 9 years, in the case of ring density it was 8 years, and for density of late wood zones – at 12 years. In the opinion of the authors, density of late wood leads to an overestimation of transition age in relation to ring density and the share of late wood in annual increments in diameter. Based on studies of density of late wood zones conducted on discs collected from 99 stems of Scots pine (*Pinus sylvestris* L.) coming from the height of 4 m, Mutz et al. (2004) identified the boundary between juvenile and mature wood between the 18th and 27th annual rings. After several statistical analyses were conducted and a square linear model was specified, the transition boundary was established at cambial age of 21 years. A less frequently applied method used to isolate the discussed wood zones in stems of forest trees is to determine changes in mechanical properties of wood, as it was performed by Dumail et al. (1998), Zhu et al. (2005) and Chiu et al. (2006). However, the boundary between juvenile and mature wood is the most typically identified using the above-mentioned methods so that their mechanical properties may be further compared (Passialis, Kiriazakos 2004; Pazdrowski 2004; Tomczak 2006; Kretschmann 2008; Shupe et al. 2008; Nawrot 2010; Szymański 2011). Using advanced mathematical models (regression) based on several selected traits (properties) of the wood tissue, the range of the juvenile wood zone was determined by Abdel-Gadir and Krahmer (1993), Tassisa and Burkhardt (1998), Zhu et al. (2000), Csoka et al. (2005) and Mansfield et al. (2007). Evidence showing that an unambiguous indication of the boundary between juvenile and mature wood zones is difficult may be provided by a study of Bendtsen and Senft (1986), who on the basis of analyses of wood density, static bending strength and compression strength along the grain determined the juvenile period in *Pinus taeda* to be 12 years, on the basis of tracheid length it was 18 years, while in the case of the angle of cellulose fibrils it was 30 years. As it was reported by Abdel-Gadir and Krahmer (1993), the determination of the boundary separating juvenile wood from mature wood is complicated and difficult, since anatomical changes occur gradually over a period of several years.

DISCUSSION

Modification of the shares of juvenile and mature wood in stems of European larch (*Larix decidua* Mill.) was a subject of the doctoral dissertation presented by Nawrot (2010). He separated the juvenile wood zone from the mature wood zone using the k-means algorithm. He showed considerable applicability of that method and its advantage due to its objectivity and repeatability of results. The graphic method applied to date [e.g. the doctoral dissertation by Tomczak (2006), numerous articles e.g. by Jakubowski (2004a,b) or Szymański (2009)], despite considerable efforts by the authors, was characterised by unavoidable subjectivity. The algorithm ensures repeatability, as it was shown by Nawrot (2010) by eliminating a total of 20 circumference rings each from the set of data, and applying the algorithm to the separation of the zones, obtaining results consistent with the original, at a difference of max. one or two rings.

Despite the relatively simple wood structure in coniferous species in comparison with hardwood, the separation of the juvenile and mature wood zones is difficult. Methods used to date and based on the analyses of macrostructure and morphological traits, biometric dimensions of anatomical elements, physical and mechanical properties of wood, the angle of cellulose fibrils and the degree of cellulose crystallinity do not always facilitate the separation of both wood zones in tree stems. Greater or lesser differences were found in the evaluation.

In relation with the worldwide increase in the supply of timber coming from the plantations of fast-growing trees it is expected for the wood resources coming from the plantations to be characterised by a high share of juvenile wood. In this way the age of trees at which timber is harvested will significantly influence the quality of the raw material and its processability and further uses. Numerous authors (Bendtsen 1978; Zobel 1984; Thörnqvist 1993; Kennedy 1995; Zobel, Sprague 1998; Lindström 2002; MacDonald, Hubert 2002; Myers 2002; Tomczak 2006; Zhang et al. 2006) indicate the extension of cutting age as a method to reduce the share of juvenile wood, and thus to increase the share of mature wood in tree stems. According to Zobel (1984), in contrast to what is frequently heard and read, juvenile wood in coniferous species is not bad wood; it is simply different. In forestry the problems connected with the presence of juvenile wood in tree stems have to be thoroughly investigated and timber quality has to be adapted to meet requirements concerning the use and satisfaction of consumers' needs. The capacity to assess thickness or share of this type of wood in timber will make it possible to adequately manage processing and optimize its end use. Juvenile wood in some branches of industry (particularly in the pulp and paper industry) reaches performance properties of mature wood or even it exceeds them. Thus juvenile wood may not be treated as ballast of low value in the stem volume, but rather new directions for its rational processing and utilization need to be indicated. The presence of juvenile wood may not be eliminated by any means due to the fact that it is an indispensable, genetically determined element of growth and development processes in trees. However, we may try to identify, within certain boundaries, its range on the radius using appropriate silvicultural measures.

In the opinion of Punches (2004), an insight into tree growth and development processes makes it possible for foresters to modify living conditions for trees so as to predict consequences of forest management resulting in the specific quality of end wood products. Dense stocking rates promoting faster canopy closure, management of trees in strong closure ensuring natural stem pruning and artificial pruning should result in the minimization of diameter in the juvenile wood zone in tree stems as well as enhancing wood homogeneity. Performance of management procedures should be characterised by low intensity and frequently repeated cuttings. Good results in the separation of the juvenile zone should be provided by the application of natural regeneration, although in the case of larch it is not applied in commercial practice. In turn, longer rotation periods bring longer deposition periods for mature wood over a greater stem length, increasing the share of this type of wood throughout the entire stem volume. As it was reported by Krauss (2010), wood structure may be investigated at the macro-, micro- and submicroscopic levels, while properties of the wood tissue are an effect of their structure at all levels of that structure. However, an erroneous assessment of submicroscopic properties based on the knowledge of macrostructural properties is also possible, which was confirmed by the trend observed in a study by Nawrot (2010), being a very similar trend to changes in the share of late wood in the annual ring and the degree of cellulose crystallinity. Such a method to identify wood based on changes in values of wood homogeneity index or the share of late wood in annual rings is justified, apart from considerable subjectivity (Fig. 1).

An original and at the same time – as it was shown by Nawrot (2010) – an objective method to separate juvenile and mature wood tissue zones in stems of European larch (*Larix decidua* Mill.) was supplied by the application of the *k*-means algorithm. Cluster analysis is one of the best known data mining methods. It is frequently called segmentation or data clustering, it is an example of an analysis consisting in search for and isolation of a cluster from data, i.e. groups of similar objects. It is a non-directional method, which means that all relationships and regularities are found only on the basis of input data. Organisation of objects into clusters is based on the search for similar objects. In order to compare observations and to determine to what extent they are similar we have to introduce a measure of similarity of observations. In the case of quantitative variables the Euclidean distance is applied most frequently. The Euclidean distance, similarly like other measures comparable to that distance, has a certain flaw, since it may be strongly influenced by the effect of one of the variables whose range of values is greatest. If values of this variable are much greater than values of other variables, then the difference or similarity between observations will be determined to a considerable extent by this one variable only (Harańczyk 2005). In order to prevent such a situation standardisation was applied. The standardised variable is characterised by a mean of 0 as well as variance and standard deviation of 1 (Lissowski et al. 2008) (Fig. 2).

The *k*-means algorithm is a non-hierarchical method, resulting in scatter, in which no cluster is a sub-cluster of another cluster (Hartigan 1975; Hartigan, Wong 1979). The algorithm transfers objects to different clusters, aiming at the minimization of variability inside the cluster and maximisation of variability between clusters. The assumptions of linearity and normality are not necessary in this analysis (Stanisz 2007). The identification of juvenile and mature wood zones was performed using input data in the form of standardised values for the width of annual rings, the percentage share of late wood in the annual ring and the length of the individual, at the moment estimated ring ray. At the beginning the *k* parameter is determined, i.e. the number of clusters which we want to obtain. For the needs of this study the number of clusters was set at two, i.e. juvenile wood and mature wood. The

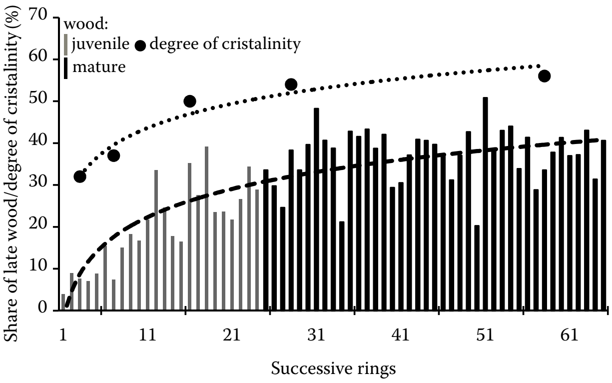

Fig. 1. A relation between the degree of cellulose crystallinity and the share of late wood in tree rings of European larch shown as the logarithmic line of trend

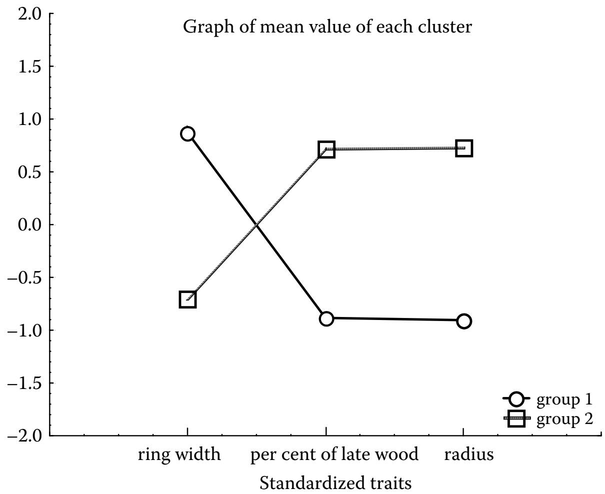

Fig. 2. Graphical interpretation of trends of the mean value for distinguished clusters after standardisation process

algorithm acted to the moment of stabilisation, i.e. the moment when changes no longer occur in the obtained clusters. In the performed calculations a solution was found each time after the first iteration. Cluster centres were selected in such a way so as to maximise the cluster distance. Examples were ascribed to clusters due to their distance from the centres. At such assumptions the algorithm identified the number of observations (annual rings) to the cluster of juvenile wood and mature wood. Calculations with the use of the algorithm were not applied to discs coming from higher sections of stems if the number of rings at those cross-sections was smaller than or equal to the number of rings of juvenile wood, calculated by the algorithm on a disc from a lower section. In such a case it was assumed that a given stem cross-section is composed entirely of juvenile wood. Such a method of identification of the boundary between juvenile and mature wood was used for each tree and each disc except for the situation described above. Additionally, a graph was also used, illustrating changes in the share of late wood on the ray. After a number of rings ascribable to each of the wood zones was obtained, their width was summed up to calculate the width of the cylinder of juvenile wood (mm) and the width of the ring of mature wood (mm). The sum of the above-mentioned widths constitutes the width of a given disc inside bark. Results were used to calculate volumes of juvenile and mature wood in tree stems.

In the opinion of Wodzicki (2001), the structure and properties of wood are a consequence of genetic, environmental and anthropogenic factors acting during the formation of the wood tissue. Individual traits may thus play the most significant role in the modification of quantitative and qualitative traits of wood, while the role of external factors may be limited to serve the functions of inhibitors or stimulators for genetically programmed processes of plant growth and development. A similar opinion was presented by Tomczak et al. (2009b), who speculated that the tree genotype is a significant factor influencing wood quality. According to the authors, problems in the determination how changes at the genotypic level influence plant development arise from variation resulting from the effect of environmental factors manifested in the phenotype.

Previously mentioned traits and properties of juvenile wood indicate that it is advisable to undertake further studies on the effect of external factors on the modification of shares of both types of wood in tree stems and to perfect methods used in the determination of boundaries between them, based to a greater extent on the submicroscopic structure of the wood tissue. In order to popularise this method of separating both zones of the wood tissue in tree stems it would need to be tested on many coniferous species and first of all on forest-forming species.

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