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The effect of tree senescence on selected properties of wood tissue in Scots pine (*Pinus sylvestris* L.)

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Abstract: *The effect of tree senescence on selected properties of wood tissue in Scots pine (Pinus sylvestris L.).* It was investigated how the process of tree ageing affects the quality of the wood tissue, defined in terms of two properties: the basic density (Q_u)and the modulus of elasticity in static bending (MOE). Three stands were chosen for the study, aged between 155 to 166years, from which a total of nine trees were selected for analysis of wood properties. It was found that Scots pine (*Pinus sylvestris* L.) growing in conditions typical of the region attains technical maturity on reaching an age of approximately 80 years. The marked decline in the tested parameters after the tree age exceeds approximately 75–80years indicates a dynamic ageing process expressed in the gradual deterioration of wood tissue properties.

Keywords: Scots pine, basic density, modulus of elasticity, ageing of trees

INTRODUCTION

Scots pine (*Pinus sylvestris* L.) is a species which occurs widely across Europe. According to Boratyński (1993) its range extends between latitudes of 72°20′ N in Norway, and 37° N in the Sierra Nevada mountains of Spain. In an east-west direction it extends across almost 14 000 km, from a longitude of 8° W in Spain to approximately 141° E in eastern Russia. In Poland, pine covers a larger area than any other tree species, and is therefore of significant economic importance.

Wood is an inhomogeneous material – not only do its properties differ in different parts of the microstructure, but there is also considerable variation within a stem and among stems.

Differences in properties within a stem constitute the most important variation factor of wood, often being greater than variation among trees (Larson 1967; Tajima 1974). Within-tree variation is made up of three main components: intra-ring variations, variations in the radial direction through different annual rings, and variations in the longitudinal direction.

Kotwica (2007) describes pine wood as relatively soft and easily processed, offering high strength and elasticity. The best technical properties are found in wood from trees felled at age 80–120 years with well covered knots.

The properties of pine wood exhibit variation in the axial and radial directions (Machado and Cruz 2005, Pearson and Gilmore 1980). An improvement in mechanical properties can be observed in the radial direction from the core to the perimeter (Machado and Cruz 2005):

- compression strength increases by 44%;
- bending strength increases by 55%;
- the modulus of elasticity improves by 99%, in the range from 1/10 to 9/10 of the radius.

Similar observations were made by Pearson and Gilmore (1980), who reported a 42% improvement in mechanical properties in a radial direction in the wood tissue of 41-year-old trees, and an 82% improvement in the case of 15-year-old trees. The axial and radial variation in the tested properties are explained primarily by the occurrence and proportional contribution of zones of young and mature wood.

The possibility of obtaining specific types of wood is dependent on the age of the trees designated for felling. It can be expected that the older the trees and the larger their breast-height diameters, the greater will be the quantity of more valuable timber (classes A and B)

(Stępień et al. 2013). It should also be borne in mind, however, that in better and stronger habitats the period of production is generally shorter(Szymkiewicz 1985, Szymkiewicz et al. 1996). This is chiefly related to the trees' attaining what is called technical maturity. This is determined by many factors affecting the tree ageing process, which is regulated chemically. When a tree's age exceeds approximately 120years there is a noticeable drop in the cellulose content, and decomposition of lignin occurs. Ageing is also accompanied by changes in the colour of the wood tissue: the heartwood becomes redder and the sapwood more yellow. According to Kránitz (2014), ageing does not cause any other changes in the wood structure apart from those mentioned above, but changes occur in the hygroscopic properties of the wood, as well as slight differences in its physical and mechanical properties.

The aim of the present study was to determine how processes of tree ageing affect the properties of wood tissue as described by the basic density and the modulus of elasticity.

METHODS

The experimental material was taken from mature pine stands aged between 155 and 166years in three different areas (Fig. 1). On each site the heights and breast-height diameters of all trees were measured, and then using statistical characteristics each population was divided into three groups based on diameter and height. From each group one representative tree was selected. These trees were felled, and material was collected from them for further analysis of the wood properties, as illustrated in Fig. 2.

Figure 1. Study sites: 1)Warcinosect. 68i (N16° 51′ 26″ E54° 13′ 22″); 2)Bolewice sect. 250c (N 16° 06′ 46″ E52° 23′ 52″); 3)LZD Murowana Goślina sect. 65d (N17° 06′ 40″ E52° 33′ 17″)

The basic density of the wood (Q_u) was measured in accordance with the PN-77/ D-4101standard, and the modulus of elasticity (MOE)was determined for maximally saturated and for absolutely dry wood.The modulus of elasticity on static bending in a tangential direction under a single concentrated force was determined in accordance with the PN-63/D-04117 standard.

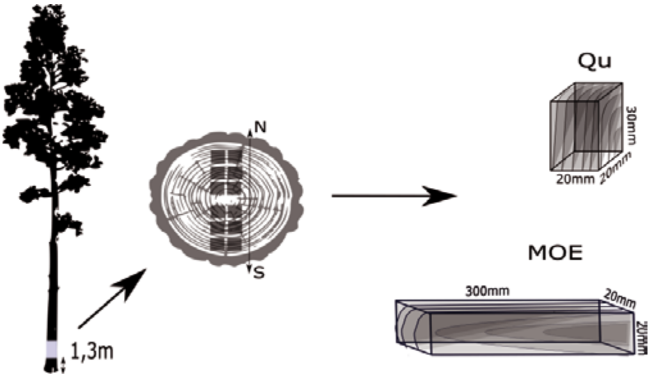

Figure 2. Schema for the collection of material for analysis of wood properties.

The collected empirical data were analysed by means of statistical methods using the *STATISTICA 12* software package.

RESULTS

An analysis was made of the radial variation in the basic density (Q_u)and modulus of elasticity (MOE) of the wood. Maximally saturated wood and absolutely dry wood were studied, with analysis of variation in a north-south direction. Before the analysis a determination was made of the incremental growth rates of the trees in question, which made it possible to determine the average age of each of the samples (Fig. 3).

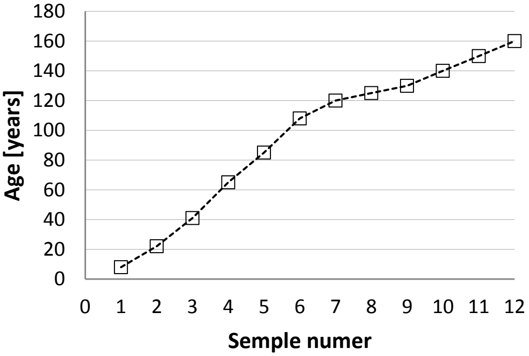

Figure 3. Average age of the samples used for testing wood properties.

Basic density

The average value of the basic density of the wood of the studied pines was 474 kg/m^3,and the coefficient of variation was 15%.The graph showing the variation of density in a radial direction has an irregular shape, with two maxima and two minima (Fig. 3). The wood density increases quite rapidly at first (samples 1–4,from near the core), and then fairly quickly falls off (samples 4–9). Near the perimeter, however, there is again an upward tendency (samples 9–11). It was noted that the densities of the tissue close to the core (samples 1–2) and close to the perimeter (samples 8–10, representing an age of c. 120–130 years) have similar values, in the range 350–400 kg/m^3(Fig 4.).

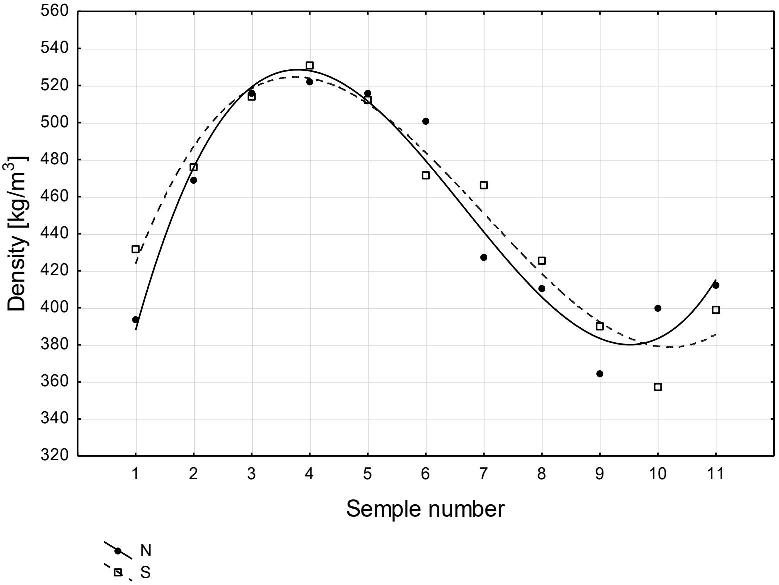

Figure 4. Radial variation in the density (Q_u)of the wood of representative trees.

Statistically significant differences in the density were recorded between samples 3–6 and samples 1 and 7–10. Similar densities were identified between samples 1–2 and 7–10 (Table 1).

Table 1. Tukey's HSD (honestly significant difference) test for radial variation in the basic density of wood from representative trees (significance level $p < 0.05$).

Q_u values in a radial direction	Q_u values in a radial direction										
	1	2	3	4	5	6	7	8	9	10	1
	0.087924										
	0.000192	0.558753									
	0.000170	0.238759	0.999976								
	0.000189	0.568720	1.000000	0.999946							
	0.015296	0.999957	0.906814	0.612397	0.914657						
	0.813269	0.985904	0.065883	**0.016122**	0.066241	0.824560					
	1.000000	0.644776	**0.020418**	**0.005965**	**0.020769**	0.349061	0.992063				
	0.991108	0.107207	**0.001532**	**0.000544**	**0.001552**	**0.038895**	0.526137	0.989743			
0	0.999493	0.507875	0.062832	**0.030956**	0.064678	0.326435	0.876402	0.998892	1.000000		
1	1.000000	0.892374	0.279211	0.165768	0.285951	0.749691	0.996132	1.000000	0.999965	0.999994	

Statistically significant differences are bolded.

Modulus of elasticity

The modulus of elasticity (MOE) of the wood, measured by applied static bending, was analysed in an analogous way to compression strength along the grain. The average value of the MOE for absolutely dry wood was 9337 MPa, with a coefficient of variation of 26%. For maximally saturated wood a value of 5701 MPa was obtained, with a coefficient of variation of 22%.

Analysis of radial variation in MOE revealed a similar pattern as in the case of density (Fig. 4). Initially, up to samples 4–5 (to an age of about 80 years) the MOE value increased, but after that age it began to decrease. Differences in MOE values were also found between the northern (N) and southern (S) directions. On the southern side of the trunk, after the tree age exceeded approximately 80 years, the MOE continued to decrease all the way to the perimeter. On the northern side, however, the decrease continued as far as sample 9 (about 130 years), but then in the part of the trunk close to the perimeter there was a noticeable increase in the MOE (Fig. 5).

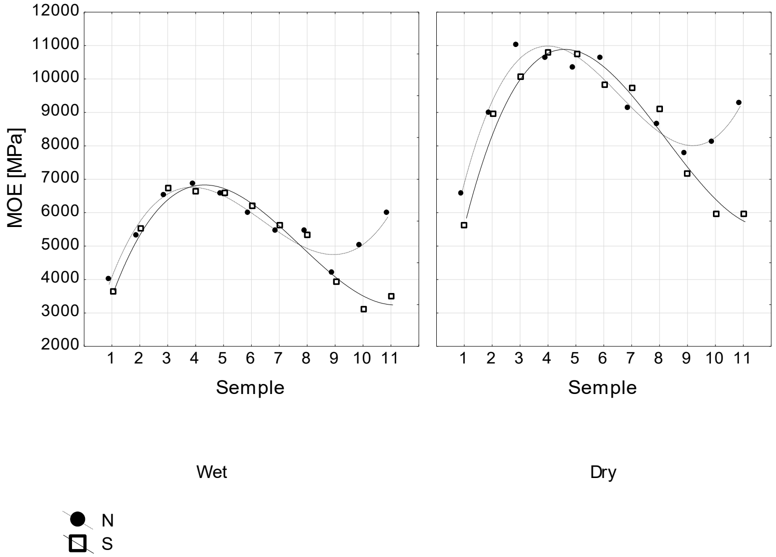

Figure 5. Radial variation in the modulus of elasticity of wood at humidity W = 0% and W > 30%.

Statistical analysis of means demonstrated significant differences in MOE for both maximally saturated and dry wood. These differences occurred between sample 1 and samples 2–7, and between samples 4–5 andsamples 9–11 (Table 2).

However, when variation in MOE was considered separately along northern and southern radii, no statistically significant differences were found between samples 4–5 and the samples from close to the perimeter of the trunk (10–11).

Table 2. Tukey's HSD (honestly significant difference) test for radial variation in modulus of elasticity (MOE) (significance level $p < 0.05$).

MOE [MPa] Dry

	MOE [MPa]										
	1	2	3	4	5	6	7	8	9	10	11
		0.00641	**0.00001**	**0.00001**	**0.00001**	**0.00003**	**0.01587**	0.68435	1.00000	1.00000	0.99976
	0.00020		0.13239	0.05785	0.18574	0.92285	1.00000	1.00000	0.91673	0.99178	0.99998
	0.00001	0.21565		1.00000	1.00000	0.98107	0.41430	0.89334	0.13467	0.61682	0.91731
	0.00001	0.11257	1.00000		1.00000	0.92134	0.25246	0.81907	**0.00081**	**0.00049**	**0.00104**
	0.00001	0.22687	1.00000	1.00000		0.99209	0.50086	0.92001	**0.00047**	**0.00088**	**0.00098**
	0.00001	0.71381	0.99995	0.99882	0.99996		0.98348	0.99834	0.46408	0.87599	0.99228
	0.00007	0.99979	0.89991	0.78936	0.90722	0.99548		1.00000	0.87442	0.98609	0.99993
	0.11173	1.00000	0.78657	0.67917	0.79495	0.95160	0.99991		0.93393	0.99383	0.99999
	0.98877	0.98441	0.34111	**0.00019**	**0.00038**	0.55123	0.89279	0.99188		1.00000	0.99999
0	0.99998	0.99248	0.67386	**0.00035**	**0.00078**	0.80946	0.95912	0.99555	1.00000		0.99998
1	0.99855	0.99962	0.86303	**0.00021**	**0.00032**	0.94114	0.99453	0.99984	1.00000	1.00000	

MOE [MPa] Wet

Statistically significant differences are bolded.

CONCLUDING REMARKS AND DISCUSSION

Cambial growth involves numerous biophysical and biochemical phenomena occurring at cellular level. In view of the complexity of the processes involved in the formation of wood, and the number of its natural modifications, not all of these phenomena have been fully understood and described in detail (Savidge et al. 2000). They depend to some degree on differences in the rate of growth of trees, which slows with age, and this in turn means that the productivity of the tree stand significantly decreases (Zaehle 2005).Hence also the changes related to the physiological functioning of a tree can be presented as a function of age. One of the determinants of these changes is the process of ageing, which can be described in terms of a fall in the hydraulic conductivity of trees or a decline in the quality of the wood tissue produced (Jelonek et al. 2012, Jelonek 2013).Consequences of these changes will undoubtedly include quantitative and qualitative changes in the xylem structure,and related changes in its properties.

An interesting overview of theories relating to tree ageing is given by Brutovská et al. (2013), who state that the ageing process is internally controlled, and applies both to individual trees and whole populations, which may lead to various effects. The effect of wood tissue ageing processes on the properties of pine wood have been described, among others, by Kollmann (1968), who concentrated chiefly on selected properties of wood. In the present work an analysis was made of how the tree ageing process affects the wood density (Q_u) and the modulus of elasticity in static bending (MOE).

The average basic density of wood at breast height was found to be 474 kg/m^3. Similar values (470 kg/m^3) were reported by Witkowska (1999).

Slightly differing values were recorded by Giefing and Jabłoński (1989) (460–490 kg/m^3) and by Tomczak et al. (2006) (430–470 kg/m^3).Studies of wood density in trees in Poland have also been made by Kobyliński (1967) and Paschalis (1980). The basic density of pine wood was precisely described by Trendelenburg (1939), who reported in detail the variation in density along a longitudinal section.

The average basic density of pine wood (*Pinus sylvestris* L.) at post-felling age at breast height was found in the present work to be 474 kg/m^3.Large variation in the density was recorded in a radial direction. The values initially increase, reaching a maximum at an age of around 55–70 years, and then they decrease rapidly until an age of approximately 140 years is reached. After 140 years there is large variation in density between the analysed trees and between the northern and southern radii.

The basic density (Q_u) and the modulus of elasticity (MOE) show similar patterns of radial variation. Initially, up to a tree age of approximately 70years, the values increase, after which they fall off rapidly until an age of around 120–130years. It is interesting to note that as regards the properties of the wood close to the perimeter, the differencesbetween the northern and southern sides are not so significant in the case of wood density as in the case of modulus of elasticity, where the differences in the extreme samples are close to 50%. It can be assumed that this significant growth in modulus of elasticity in the region close to the perimeter on the northern side is related to naturalbiomodification of the wood tissue, occurring as a response to wind pressure.

Determination of the modulus of elasticity in static bending gave average values of E = 9.3 GPa for dry wood and E = 5.7 GPa for maximally saturated wood. The radial variation in modulus of elasticity for dry and for maximally saturated wood showed similar patterns. However, the measured values of modulus of elasticity showed marked differentiation between tests performed on maximally saturated and dry wood.This can be explained by the fact that the humidity of wood is of great significance in strength testing, particularly in a hygroscopic range from 0% to 30%. This effect is not uniform over the whole hygroscopic range. According to Küch (1943) the greatest changes occur within a range of humidities from approximately 15% to 0%.

This is a result of the occurrence of desorption strengthening and the appearance in the wood of dry secondary bonds (Jelonek 2013).

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Streszczenie: *Wpływ procesów starzenia się drzew na wybrane właściwości tkanki drzewnej u sosny zwyczajnej (Pinussylvestris L.).* W pracy przeprowadzono analizę wpływu procesu starzenia się drzew na właściwości tkanki drzewnej sosny zwyczajnej (Pinussylvestris L.) opisane gęstością umowną (Qu) oraz modułem elastyczności przy zginaniu statycznym (MOE). Badania przeprowadzono w trzech drzewostach sosnowych wieku od 155 do 166 lat.Uzyskane wyniki wskazują, iż sosna zwyczajna osiąga swoje maksimum wartości technicznych tkanki drzewnej w wieku około 70 lat. Po przekroczeniu tego wieku następuję gwałtowny spadek zarówno gęstości jak i modułu elastyczności tkanki drzewnej.

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