WOOD RESEARCH
57 (1): 2012
31-44

BIOMECHANICAL STABILITY OF PINES GROWING ON FORMER FARMLAND IN NORTHERN POLAND

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(Received March 2010)

ABSTRACT

It was attempted in this study to determine the effect of former farmland soils on biomechanics and stability of trees by analyzing axial variation in basic density of wood, bending strength of absolutely dry wood and that of wood with moisture content over fiber saturation point.

The analyses were conducted on wood of Scots pines grown on four positions in northern Poland coming from mature stands aged from 97 to 102 years, growing on former farmland and on forest soils. Results showed significant differences in terms of wood properties analyzed in this study between compared groups of trees and at the same time indicated different stability of stands growing on former farmland soils in relation to trees growing on forest soils.

KEYWORDS: Scots pine, biomechanical stability, wood quality, basic density, former farmland, desorption strengthening.

INTRODUCTION

Relatively small ecological requirements, high adaptability of Scots pine and its timber of multifaceted uses make Scots pine the dominant species in our climatic zone. According to Plomion et al. (2001) wood tissue formation is highly complex and studies conducted to date still have not provided comprehensive insight into this process. Apart from the genetic background an essential role in the modification of timber quality is played by traits resulting to a bigger or lesser extent from growth and development conditions or human activity (Prescher and Ståhl 1986, Wodzicki 2001, Jelonek et al. 2009a, Tomczak et al. 2009).

Biomechanics of trees and the effect of different external factors on physical and mechanical properties of wood tissue have been investigated by many researchers (Mencuccini et al. 1997, Peltola et al. 1999, Pazdrowski and Spława-Neyman 1997, Peltola et al. 2007, Jelonek et al. 2008, 2009a, 2009b). In the initial stage studies on biomechanics of trees focused mainly on hydraulic functions modifying the mechanical stem skeleton (Zimmermann 1983, Tyree and Ewers 1991), while knowledge describing mechanical limitations of trees has been developing fast (King 1981, Niklas 1992, Mencuccini et al. 1997).

Biomechanics of trees is directly connected with mechanical and hydraulic properties of anatomical elements. During growth and development of trees, and thus the cyclical formation of wood tissue, the structure of anatomical elements is optimized. Numerous modifications aim at achieving a compromise between mechanical and hydraulic properties of trees (Mencuccini et al. 1997).

A simple biomechanical model of trees as a narrowing pole was presented at the end of the 19th century. Slightly later the tree model was modified, presenting it as a sum of two weights, i.e. the weight of the crown and the weight of the trunk being a homogenous column found in the state of weightlessness (Baker 1995, Saunderson et al. 1999).

In Finland studies on biomechanics of Scots pine were conducted by Hassinen et al. (1998). Due to the complexity of integration and the dynamics of the phenomenon, biomechanics of trees is presented in a highly simplified form. This is a consequence first of all of a considerable variation of trees within a single species, as well as a relatively little known dynamic reaction of trees to the action of a stress factor in the form of wind (Kenneth et al. 2006).

A growing tree attempts to optimize its structure so that stresses are relatively uniformly distributed and there are no redundant (unstressed) areas.

In terms of mechanics there are many force systems in a growing tree. Bending forces acting on the trunk (stem) are caused e.g. by wind and growth stresses, or static pressure resulting from the weight of the trunk and the crown (Hejnowicz 2002).

From the point of view of mechanics the most effective anatomical structure of the organ has to be a compromise of the counteraction to individual deformations (stresses) separately. For a woody plant on which a symmetrical crown is embedded, the radially symmetrical section seems to be optimal.

Allocation of biomass during tree growth is subjected to biophysical limitations. For example the size of the assimilating organ, which directly affects photosynthetic productivity, has to be mechanically supported and provided with access to water and nutrients. Thus, the environment has a significant effect on biomechanics of trees. For instance, in the forest community trees reach considerable dimensions because they have mechanical support, access to water and nutrients (Mencuccini et al. 1997).

The crown, responsible for the production of xylem, may be related with a relatively large stem cross section of the trunk with wood of small density or a considerably smaller trunk, but characterized by wood of high density. Such a system will always be a compromise between the diameter of tracheid elements and the thickness of cell walls. Thus, the hydraulic system of plants will be closely related with biomechanical requirements, consisting in an appropriate distribution of weight at an adequate scale of anatomical elements (Schniewind 1962).

Moreover, axial transport in the plant is limited by its height and cross section, while mechanical functions are performed by both sapwood and heartwood. Thus both the hydraulic and mechanical functions most probably affect the maintenance of the optimal surface of sapwood.

As it was reported by Hejnowicz (2002), depending on the occurrence of growth stresses in wood considerable differences and modifications may be found in the strength of the trunk. A condition for the occurrence of growth stresses is constant, sufficiently fast deposition of wood counteracting relaxation of stresses. As a consequence, differences may occur in the strength of a stem with the same diameter, but different wood deposition rates in the outer ring including several (around a dozen) latest annual increments.

The slenderness factor, being a ratio of plant height to its diameter (in case of trees being determined at breast height), is a good indicator describing optimization of biomechanical systems in plants.

The effect of former farmland soils on modifications of wood properties in Scots pine (*Pinus sylvestris* L.) and their effect on the biomechanical system of trees are relatively little known. In this study analyses were conducted on two basic properties, facilitating an evaluation of a relationship between axial variation of wood density and bending strength on the one hand and characteristics describing the distribution of biomass affecting stability of trees.

MATERIAL AND METHODS

Analyses were conducted in mature pine stands of age classes V and VI, growing under conditions optimal for this forest-forming species at this latitude on former farmland and forest soils in northern Poland.

The area of the analyses is highly varied, with the difference in altitudes ranging from 40 to 161 m a.s.l. Mean annual temperature in the investigated area is over 7°C, mean annual precipitation is approx. 725 mm, the length of the vegetative period is approx. 220 days and mean annual wind velocity is slightly over 4 $m.s^{-1}$.

Experimental plots were located in two neighbouring forest divisions, two in the Warcino Forest Division and two in the Trzebielino Forest Division .

On each of the four experimental plots a 1-ha mean sample plot was established, on which breast height diameters of all trees were measured and heights were measured in proportion to their numbers in adopted (2 cm) diameter sub-classes. Based on the obtained diameter and height characteristics of trees twelve mean sample trees (three at each plot) were determined using the Urich II method (Grochowski 1973), representing the first three classes according to the classification presented by Kraft (1884) (Tab. 1).

Tab. 1: Characteristics of trees.

Growth conditions	Kraft class	Age (years)	DBH (cm)	Height (m)	Stand quality
1: Forest	I	97	49.0	26.9	I
	II		42.0	26.2	
N: 54° 11' 00" E: 17° 14' 86"	III		37.0	25.4	
2: Former farmland:	I	99	49.0	25.0	
	II		42.0	24.5	
N: 54° 11' 40" E: 17° 14' 52"	III		37.0	23.0	
3: Forest	I	97	46.0	25.0	
	II		38.0	23.0	
N: 54° 9' 50" E: 16° 52' 57"	III		32.0	21.5	
4: Former farmland	I	102	36.0	24.0	
	II		30.0	23.0	
N: 54° 11' 36" E: 16° 55' 24"	III		25.0	21.5	

Crown projections were plotted for selected model trees in two geographical directions, i.e. N-S and E-W. Based on obtained projections crown diameter was determined accurate to 10 cm.

Next model trees were felled and first selected biometrical characteristics of trees were measured, i.e. tree length and the length of live crown.

On the basis of obtained biometrical parameters the slenderness factor was determined for trees, being a ratio of their height to breast height diameter. As it is reported by Jaworski (2004), this coefficient reflects stability of trees, which is manifested in their wind firmness.

The following parameters were next calculated:

- proportionality of crown (P.k.), being a ratio of crown diameter in the N-S direction to its diameter in the E-W direction,
- crown inclination (W.k.), being a negative value of the ratio of mean crown diameter to tree height – the closer this value is to zero, the less inclined the crown is,
- the centre of gravity (S.c.), being a ratio of crown length to tree height,
- crown flattening degree (S.s.), being a ratio of mean crown diameter to its length.

Next from felled trees material was collected for analyses of selected physical and mechanical properties of wood, i.e. basic density (q_u) and bending strength (R_g). Material for laboratory analyses came from 50-cm blocks collected from a distance of 1.30 m - 1.80 m from the kerf plane, next from the middle of the stem (calculated from stem base to the base of the live crown) and the base of the live crown. The diagram of experimental material sampling is presented in Fig. 1.

Fig. 1: Location of experimental plots.

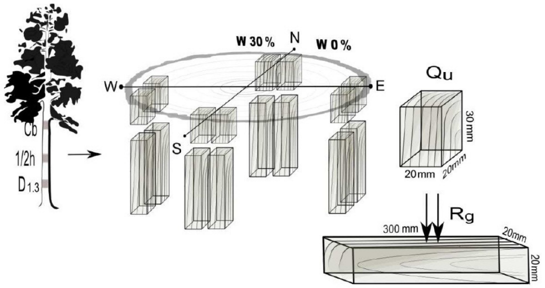


Fig. 2: A diagram of collection of material for tests of physical and mechanical wood properties.
D 1.3= DBH
1/2h= middle of the stem
Cb= base of the live crown

Wood density was determined using the stereometric method and it was referred to as basic density.

$$Q_u = \frac{m_o}{V_{max}} \quad (kg.m^{-3}) \tag{1}$$

where: m_o – weight of absolutely dry sample (kg),
V_{max} – volume of sample in the state of maximum swelling (m^3).

Bending strength (R_g) was determined on a Tira Test 2300 testing machine equipped with computer software by Matest Service and it was calculated from the following formula:

$$R_g = \frac{3 \times P_{max} \times l}{2 \times b \times h^2} \quad (MPa) \tag{2}$$

where : P_{max} – maximum (destructive) compressive force (N)
l - spacing of supports (mm)
b - width of sample (mm)
b - height of sample (mm).

All determinations were made accurate to 0.01 MPa.

Bending strength was tested on absolutely dry samples ($W_{0\%}$) and on wet samples ($W_{>30\%}$), which moisture content exceeded fibre saturation point (30 %).

Wood strength tested at moisture content over fibre saturation point, also called strength of wet wood or basic strength, shows the current quality of wood as construction material and it is determined only by primary bonds (Grzeczyński 1975, 1985).

Wood moisture content was determined by the oven-dry method (PN-77/D-04100). Mechanical properties were tested in accordance with the requirements of the respective standards (PN-79/D-04102). Collected empirical material was analyzed using methods of mathematical statistics with the application of the Statistica 8.0 PL statistical package.

RESULTS

The study was an attempt to analyze the effect of external factors, in this case the type of soils on the stability of trees described by stem biomechanics. On average pines growing on former farmland soils were characterized by lower basic density of wood tissue, lower strength parameters both in absolutely dry wood and wood with the maximum saturation of cell membranes with water and with a lower desorption strengthening than it was observed in pines, which grew under conditions typical of forest sites (Tab. 2).

Tab. 2: Statistical characteristics of analyzed wood properties.

		Mean	No.	Standard deviation	Minimum	Maximum	Coefficient of variation
Qu (kg.m^{-3})	Forest Former farmland	**430.26** * **398.46** *	119 124	53.00 52.34	334.04 267.93	564.72 509.03	12.32 13.14
Rg $w_{30\%}$ (MPa)	Forest Former farmland	24.45 22.39	146 166	6.26 4.47	10.57 8.73	42.21 33.16	25.61 19.95
Rg $w_{0\%}$ (MPa)	Forest Former farmland	**56.61** * **46.69** *	145 161	13.47 15.71	27.20 26.31	87.87 112.88	23.79 33.65
DS (MPa)	Forest Former farmland	**32.19** * **24.44** *	145 158	11.12 14.17	8.92 4.20	60.85 89.06	34.54 57.99

* differences statistically significant ($p>0.05$)

R_g $w_{0\%}$= bending strength was tested on absolutely dry samples ($W_{0\%}$)

R_g $w_{30\%}$= bending strength was moisture content exceeded fiber saturation point (30 %)

DS= desorption strengthening

It was observed that variation in strength of dry wood and variation in desorption strengthening were much bigger in trees representing former farmland soils, amounting to 34 % and 58 %, respectively, whereas in trees coming from forest soils the recorded values were 24 % and 35 %, respectively.

Analyses of basic density of wood conducted in this study showed that it is characterized by normal distribution (Fig. 2) and it is statistically significantly lower in wood coming from trees grown on former farmland soils than (398 kg.m^{-3})comparised to wood density of pines growing under forest site conditions (430 kg.m^{-3}) (Tab. 2).

Wood density in all analyzed trees decreased gradually with an increase in height, reaching its minimum at the base of the crown. Wood of trees coming from forest soils had on average higher density at all analyzed levels in comparison to the density recorded when analyzing wood of pines coming from former farmland (Fig. 3).

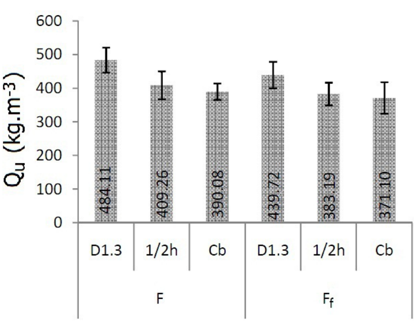


Fig. 3: Basic density of wood.

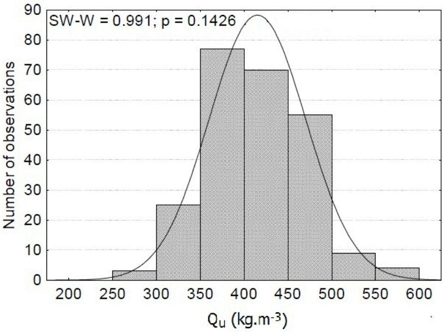


Fig. 4: The distribution of basic density.

Next wood density was divided into 10 decyls and it was compared at individual levels (Fig. 4). Both at breast height and at mid-stem length wood of pines coming from forest soils was of a higher density at each of the 10 adopted decyls. The course of the curve illustrating individual decyls was irregular. At the same time at all levels a dynamic increase in density was observed in the range from the 8th to the 10th decyl in pines coming from forest soils. This increase was also found in trees coming from former farmland, but it was only at the height of the base of the live crown.

Next analyses of bending strength were conducted at wood moisture content of over 30 % (over fibre saturation point) and on absolutely dry wood.

Pines coming from former farmland were characterized by a statistically significantly lower bending strength of dry wood (46.7 MPa) and lower desorption strengthening (24.4 MPa) in relation to trees coming from forest soils, in which these values were 56.6 MPa and 32.2 MPa, respectively.

In stems of pines coming from former farmland a gradual decrease was observed for values of the analyzed mechanical properties with an increase in tree height. The smallest differences, statistically non-significant, were found in those trees between the breast height diameter plane and mid-height of the tree. In turn, in stems of trees growing on forest soils the highest values of bending strength were found at breast height (1.3 m), while at a ½ tree height and at the base of the live crown these values were similar (Fig. 5).

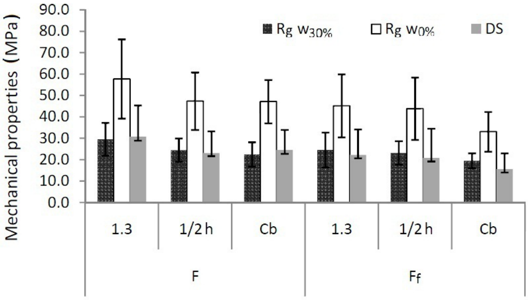


Fig. 5: Axial variation in mechanical properties of wood in Scots pine.
F = forest soil
Ff = formxtrength was moisture content exceeded fiber saturation point (30 %)
DS= desorption strengthening

Analyzed wood strength was divided into 10 decyls and it was compared at individual levels (Fig. 6).

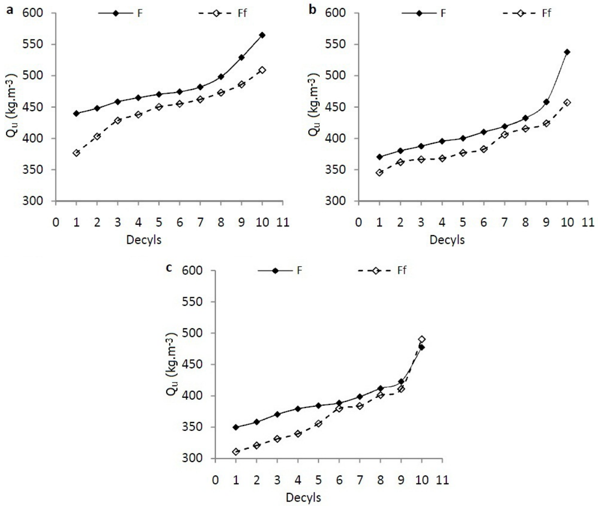


Fig. 6: Decyls of basic density of wood in Scots pine: a) – at breast height, b) – at height equivalent to mid-length of a tree, c) – at the base of live crown.
F = forest soil
F_f = former farmland soil

Much bigger differences were found between the compared groups of trees in case of strength of absolutely dry wood than that of maximally saturated wood. These differences are particularly evident at breast height (Fig. 6a) and to a slightly lesser extent at the base of tree crown (Fig. 6c). At the above mentioned planes wood of pines coming from forest soils was characterized by a much higher strength in each of the 10 decyls than it was the case for wood of pines coming from former farmland. In turn, at mid-length of the stem the strength of wood tissue in the compared pines was similar (Fig. 6b).

Trends in the discussed property of absolutely dry wood from pines originating from former farmland and forest soils became closer in the 9th and 10th decyls, i.e. in the strongest samples. However, this was the case only at breast height and at the base of the crown. Moreover, the curve illustrating the course of the analyzed strength at mid-height of trees was characterized by the smallest slope among the analyzed levels, which would indicate considerable mechanical homogeneity of wood at this level.

The distribution of strength in wood with moisture content exceeding fibre saturation point in pines coming from forest soils was similar to the distribution observed in wood of pines coming from former farmland. The trend of the line illustrating values of wood strength in individual decyls for maximally saturated wood was similar at all compared heights and it was similar to that observed in absolutely dry wood at mid-tree height (Fig. 6b). The relatively small angle, which is formed by the trend line with the axis of ordinates, indicates that absolutely dry wood is characterized by a relatively small variation in strength in relation to wood with moisture content exceeding fibre saturation point. At the same time, we need to stress here the differences in strength of dry wood and maximally saturated wood. In pines coming from former farmland it was considerably lower than in pines coming from forest soils. This is a consequence of a bigger desorption strengthening of wood in pines from forest soils, amounting to 32.2 MPa in relation to the value (24.4 MPa), which was observed for wood of pines coming from former farmland (Tab. 2).

In the subsequent analysis biometric traits affecting the statics of compared trees were investigated.

Crowns of trees growing on forest soils were similar in size to crowns of pines coming from former farmland (approx. 121 m^3 in the former and 124 m^3 in the latter). At the same time crowns of pines from forest soils were slightly less proportional (P_k), slightly less inclined (W_k) and similarly flattened (asymmetrical) (S_s) (Fig. 8). Moreover, those trees had a slightly higher centre of gravity (S_c) in comparison to pines coming from former farmland.

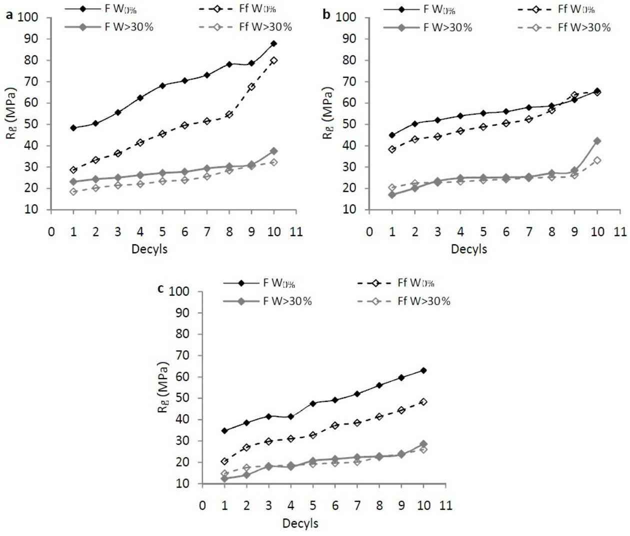


Fig. 7: Decyls of wood strength in Scots pine: a) - at breast height, b) – at mid-tree height, c) – at the base of live crown.

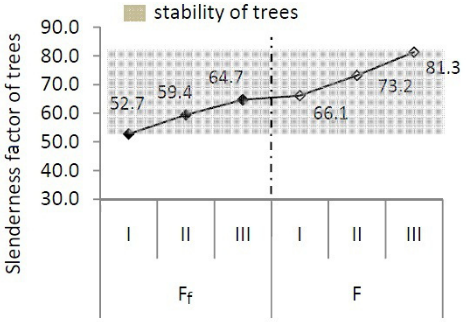


Fig. 8: Slenderness factor of trees–stability of trees.

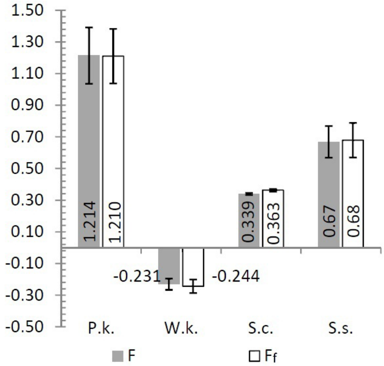


Fig. 9: Selected crown parameters.

Trees growing on former farmland were characterized by stems with a lower slenderness factor (from 53 to 64) than pines coming from forest soils, in which this factor was higher and ranged from 66 to 81 (Fig. 7). Slenderness factor in all analyzed trees was found in the range, in which trees may be classified as stable (Burschel and Huss 1997). At the same time, trees growing on former farmland fell within the lower range limit, which would indicate their slightly higher stability in comparison to trees coming from stands growing on forest soils (Fig. 7).

DISCUSSION

Studies on biomechanical models of trees generally focus on problems of stem stiffness, resistance to breakdown and elastic stability.

The biomechanical theory of tree growth claims that the radial growth of trees is a response to mechanical stress caused by the action of wind force onto trees (Baker 1995, Peltola 2006). Other theories describe stem biomechanics (tree statics) as a response to tree growth and the translocation of the centre of gravity subjected to gravity forces (Alméras and Fournier 2008).

We need to particularly stress the fact that mechanical and hydraulic properties in the stem are positively correlated and they are connected with changes in anatomical elements (Mencuccini et al. 1997). Thus studies concerning tree biomechanics most frequently pertain to the outer, hydraulically conductive part of the stem (Mencuccini et al. 1997, Berthier et al. 2001). In this study the analysis was conducted on the outer "coat" of wood, which primarily participates in the dynamic response of the tree to stress factors. It was attempted to determine biomechanical stability of trees not on the basis of Young's modulus, as it was the case in the study cited above, but it was rather focused on destructive tests investigating bending strength and thus maximum strength of wood tissue and its density. In order to follow axial variation the measurements were taken at three levels in the stems.

The primary aim of the study was to make an attempt at a comparison of the effect of former farmland soils and individual biometric traits of trees on stem mechanics in Scots pine. Stability is defined by the slenderness factor, which at the young age is relatively high and with age decreases to approx. 50 (Erteld and Hengst 1966, Jaworski 2004). It is considered an appropriate measure for the determination of stability of trees and their wind firmness (Jaworski 2004, Peltola 2006). Pines coming from forest soils in relation to pines coming from former farmland were characterized by a markedly higher slenderness factor (close to 80) and a similar strength of the outer "coat" of wood in the state of maximum swelling. Moreover, curves illustrating strength of wood with moisture content over fibre saturation point (Fig. 6) are relatively little inclined, which would indicate high mechanical homogeneity of this zone in the living tree. However, this thesis is not fully confirmed by wood density and the strength of absolutely dry wood, which seem to be much more varied than strength of wood with maximally saturated membranes.

It was observed that all analyzed properties decrease with an increase in height; moreover, desorption strengthening was markedly higher in wood of pines coming from forest soils than those from former farmland. Similar results concerning the analysis of desorption strengthening were recorded in studies on wood properties of pines coming from other regions of Poland (Jelonek et al. 2009a, b).

Desorption strengthening, being a result of wood hygroscopicity, is - presented as an oversimplification - a consequence of its ultrastructure (Grzeczyński 1975). In case of such polysaccharides as e.g. cellulose, hydrogen (secondary) bonds between hydroxyl groups stabilize their structure, considerably affecting their properties. Bonds of this type are formed in wood in the course of its drying and have an effect on its properties. It may be assumed that in the wood of pines grown on forest soils a considerable number of secondary bonds were formed in cellulose, which significantly improved strength of absolutely dry wood in comparison to maximally swollen wood. In the opinion of the authors this type of regularity, due to wood moisture content in stems of living trees (50-75 %), does not have a significant effect on its strength in terms of tree biomechanics, although it shows the multifaceted and complex nature of the discussed problem.

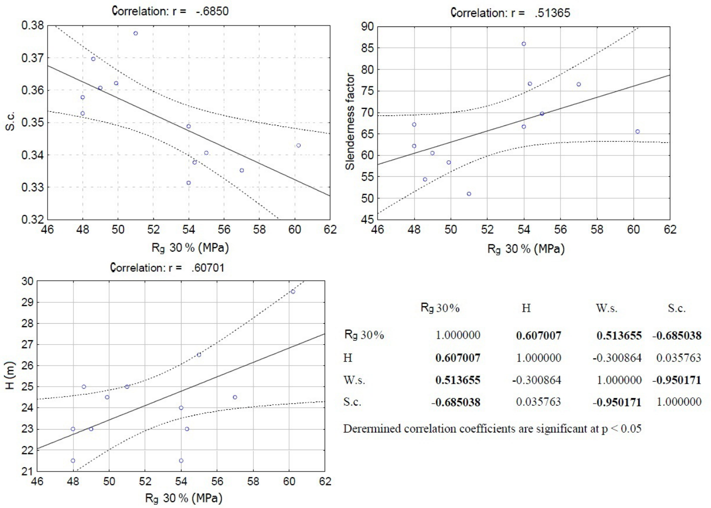
The gradual decrease in properties analyzed in this study, occurring with an increase in height, seems justified. This is confirmed by the frequently stressed (Niklas 1992, Coutts and Grace 1995, Mencuccini et al. 1997) multifunctional role of the stem, which - rising the crown upwards - has to provide it with an adequate mechanical support. At the same time it has to serve a hydraulic function, as thus its structure is optimized in terms of served functions.

The above seems to be supported by the fact that strength analyzed in this study is closely dependent on statics of trees (Fig. 9). Among all the biometric traits analyzed in this study only tree height, slenderness factor (W.s.) and the centre of gravity (S.c.) significantly affect bending strength. (Fig. 10).

It increases with the translocation of the tree centre of gravity upwards (a decreasing S.c. factor) and with a reduction of tree stability and thus a disproportional increase in its height in relation to the diameter. Moreover, no significant dependencies were found between traits describing tree statics and strength of absolutely dry wood.

The other traits, such as breast height diameter or proportionality of the crown as well as its inclination, did not have a significant effect on wood strength. Most probably this was determined by the fact that the crowns of analyzed trees were symmetrical, proportionally developed, i.e. they did not determine the translocation of the centre of gravity outside its geometrical axis. In turn, breast height diameter of trees is directly connected with the stability coefficient and it is most probably a variable, which a trees adopts in order to maintain stability in relation to its height.

Pines grown on forest soils in comparison to those from former farmland were characterised by a higher slenderness factor and the highest strength of the wood tissue at breast height. Such a mechanism seems justified when we consider a tree from the point of view of mechanics, i.e. as a supported log. In this case wood strength will be a mechanism forming a safe cross section, providing adequate protection of the stem against the action of e.g. wind. We also need to discuss the distribution of axial variation in wood strength, which was obtained in case of pines coming from former farmland. Similar values of wood tissue strength at breast height and at mid-stem height may have been caused by a slightly higher tapering of these trees at the simultaneous translocation of the centre of gravity downwards, as it was manifested by a lower slenderness and a slightly bigger crown length in these trees.



	Rg 30%	H	W.s.	S.c.
Rg 30%	1.000000	**0.607007**	**0.513655**	**-0.685038**
H	**0.607007**	1.000000	-0.300864	0.035763
W.s.	**0.513655**	-0.300864	1.000000	**-0.950171**
S.c.	**-0.685038**	0.035763	**-0.950171**	1.000000

Deremined correlation coefficients are significant at $p < 0.05$

Fig. 10: Dependencies of bending strength (R_g 30 %) on the centre of gravity (S.c.) and slenderness factor and tree height (H).

Moreover, it may be assumed that in wood of compared pines there were differences in the submicroscopic wood structure referring to the proportion of the crystalline form of cellulose in wood tissue. A considerable number of secondary bonds, most probably found in wood with a lower proportion of crystalline cellulose, in this case significantly increased wood of absolutely dry wood in comparison to maximally swollen wood (Grzeczyński 1975).

It was also observed that the slenderness factor (stability) determined in this study has a significant effect on strength first of all in maximally swollen wood. This strength increased with a reduction of tree stability, i.e. with the disproportional increase in its height in relation to breast height diameter.

Recorded results indicate that natural modifications of wood tissue occur most probably in trees providing enhanced resistance and stability of individual trees and whole stands.

Most probably the combination of genotype with the specific growth conditions found on former farmland leads to the formation of phenotypes with a different structure and properties of wood tissue in comparison to phenotypes found on forest phytocenoses. Such a situation may in the future lead to the diversification of prices and methods of timber utilization depending on its origin (former farmland vs. typical forest soils).

CONCLUSIONS

Pines grown on forest soils in comparison to those grown on former farmland are characterized by bigger stem slenderness and higher wood density at a similar bending strength of maximally saturated wood.

The wood zone analyzed in this study, with moisture content close to that of wood tissue in a living tree, is characterized by a slight variation both in pines coming from forest soils and those from former farmland.

Pines grown under conditions found on former farmland are characterized by a considerably higher bending strength of absolutely dry wood, thus showing their markedly higher desorption strengthening than that recorded in pines grown on former farmland.

A close relationship was found between bending strength of maximally saturated wood and tree height, slenderness factor (stability) and the centre of gravity of trees.

ACKNOWLEDGMENT

This work was supported by a grant of the Polish Ministry of Science and Higher Education: N 309 426938.

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