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Sapwood area and selected quantitative crown traits in the European larch (*Larix decidua* Mill.)

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SUMMARY

The study was an attempt to determine sapwood ring area and to identify relationships between selected quantitative characteristics of the crown and sapwood area. The sapwood ring area measured at breast height is correlated most strongly with crown projection area, followed by crown volume, with the correlation with outer crown area being weakest. Sapwood area measured at crown base is correlated more strongly with biometric crown characteristics. Also the coefficient P_w, being the ratio of outer crown area to sapwood ring area, was calculated for two measurement heights: 1.3 m and crown base. This coefficient assumes higher values for measurements taken at crown base than at 1.3 m. Among trees of the main stand according to Kraft's classification, the coefficient P_w took higher values for trees occupying inferior social classes of tree position in the stand.

Key words: sapwood ring area, social class of tree position, crown projection area, crown volume, outer crown area

1. Introduction

There is a strong interdependence between crown size and the area of the sapwood, which conducts water and minerals from a tree's roots to its leaves. This involves the maintenance of an equilibrium between volume of transpiration, needle (leaf) area, sapwood area and hydraulic capacity of the stem to supply leaves with water (Sellin and Kupper 2004). According to many authors, this phenomenon is described by the pipe model theory (Shinozaki et al. 1964, Chiba 1998, Berthier et al. 2002, McDowell et al. 2002, Jelonek et al. 2008), assuming a balance between the size of the assimilatory organ and conducting area (sapwood), which also affects the process of heartwood formation. Heartwood and sapwood have different properties and their proportions within the stem have a significant effect on rational utilization of timber (Duda, Pazdrowski 1975, Nawrot et al. 2008).

The dependence between sapwood area and the area of the assimilatory and transpiring organ or crown size is determined by several external factors, such as social class of tree position, tree density or site conditions (Thompson 1989, Shelburne et al. 1993, Ojansuu, Maltamo 1995, Jelonek et al. 2006). According to Longuetaud et al. (2006), sapwood area may be a good bioindicator of the state of health of trees as a function of crown condition with regard to adverse external factors.

The aim of the study was to determine sapwood ring area and dependencies between selected biometric parameters of tree crown and sapwood area in the stems of European larches, growing in fresh mixed coniferous forest sites and representing four age classes (II–V) and a main stand according to Kraft's biological classification. Reliable knowledge on the relationships between sapwood area and its distribution along tree height (coefficient Pw) and selected biometric crown traits may be used to assess the size and proportions of macroscopic characteristics of standing timber, and thus to optimize its utilization with regard to the different chemical, physical and mechanical properties of sapwood and heartwood (Krzysik 1978, Kokociński 2002, 2004).

2. Methods

Analyses were conducted on stands of age classes II, III, IV and V growing in the Choszczno Forest Division (the Regional Directorate of State Forests in Szczecin), where larch was found as an admixture (at least in the group mixture) in fresh mixed coniferous forest sites. In selected compartments, mean sample plots of 0.5 ha were established, where breast height diameters were measured on all trees of the investigated species and listed in 2 cm diameter subclasses. Next, height was measured in proportion to the frequency of trees in these diameter subclasses. The height curve was plotted, on the basis of which – after the calculation of breast height diameters for model trees – their corresponding heights were read off. Based on the obtained height and diameter characteristics of the trees, 12 model trees were selected (with 3 for each mean sample plot) using the Hartig method (Grochowski 1973) as well as Kraft's biological classification (1884). The small number of model trees per plot (3) resulted both from a conscious decision to ensure minimum intervention in the stands and from the costs connected with harvesting material for analysis in the administrative units of the State Forests. Only the first three social classes of tree position in the canopy, i.e. the main stand, were considered. This classification, based on quality appraisal of the tree crown and height in relation to the immediate environment, described relatively well the tree crown and social class of tree position in the community. For each model tree, crown projection radii were measured in the four main geographical directions, and then the trees were felled. After felling, the length of live crown and of the entire tree were measured, and then the stems were divided into 2 m sections, from which central disks were cut in order to analyze selected wood macrostructure characteristics. Disks from a distance of 1 m from the lower butt end corresponded to a height of approximately 1.3 m, i.e. breast height. The disks were used to measure wood radii inside the bark as well as heartwood radii in the four main geographical directions. Tree crown volume was calculated as the volume of a cone, considering the Burger form factor (after Jaworski 2004):

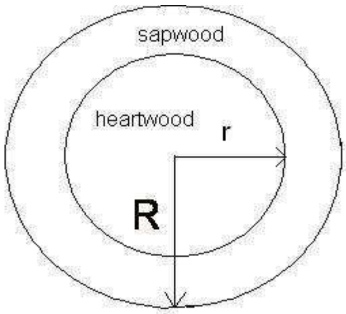
$$V = 0{,}4 * \frac{\pi}{4} * b^2 * l$$

The outer crown area was calculated from the formulation derived from the equilateral cone:

$$P = \frac{\pi}{4} * b\sqrt{4l^2 + b^2}$$

where:
b = crown width,
l = crown length.

The sapwood ring area was calculated as the difference of areas of circles with radii R and r (Fig. 1):



$$P = \pi(R^2 - r^2)$$

where:
R = radius of wood inside bark,
r = radius of heartwood.

Figure 1. Diagram showing the measurement of sapwood ring area. Based on a handbook by Bronsztejn and Siemiendiajew (1968).

Crown projection area was calculated from the formula for the area of a circle, *r* being the average crown radius. Statistical analysis was performed on measured elements of the wood and calculated quantitative characteristics of the crown, using the STATISTICA 6.0 PL computer software package (Kala 2002, Stanisz 2007). Due to the absence of normal distribution of the analyzed elements of wood macrostructure as well as the quantitative characteristics of the crown, non-parametric statistics were applied. In order to verify the significance of differences in the values of sapwood area in age classes and Kraft's classes, the Kruskal-Wallis ANOVA test was used, which is equivalent to a univariate analysis of variance and is used to compare a large number of groups. Spearman's rank correlation coefficient was applied to describe the power of correlation between two measurable traits, as it is used to describe dependencies of quantitative traits of small numbers. The results were presented in the form of tables and diagrams.

3. Results

The mean sapwood ring areas in age classes and in social classes of tree position are presented in Figs. 2A and 2B. Sapwood area decreases from age class II to age class IV, with the maximum value found in trees representing age class V (Fig. 2A). In turn, when social classes of tree position in the canopy are considered, sapwood area increases as social class improves (Fig. 2B).

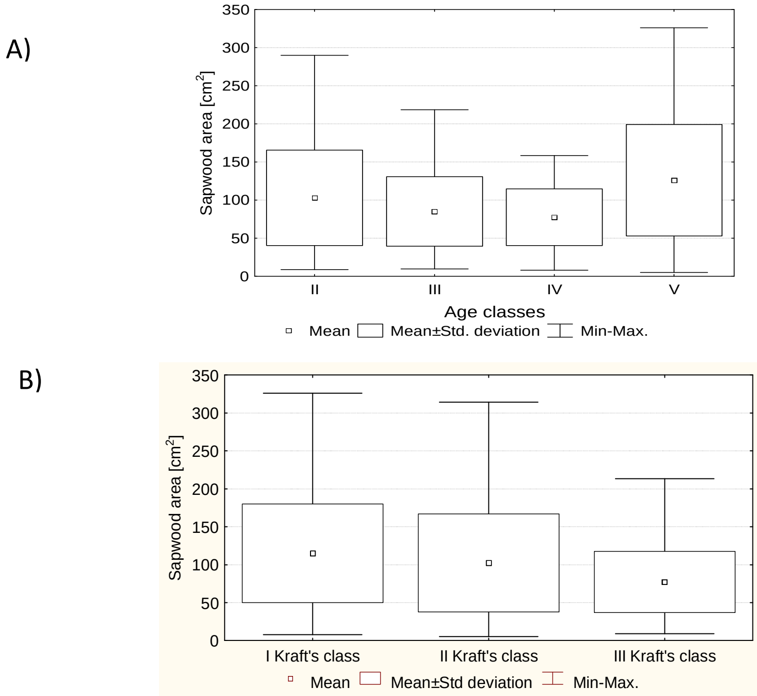


Figure 2. Mean values of sapwood ring area in age classes (A) and social classes of tree position (B)

In view of the fact that, apart from height, diameter at breast height is the measurement most frequently applied to trees in forestry, Fig. 3 presents sapwood at the height of this diameter, i.e. 1.3 m. Values of sapwood area at breast height are similar to its mean value at different heights (Figs. 3, 2A). Values of sapwood area in Kraft's social classes of tree position show a trend which differs from that of the mean. In age classes III and IV sapwood area increases with improving social tree position in the community. In age classes II and V sapwood area increases from trees representing Kraft's class III to dominant trees, while in predominant trees (Kraft's class I) it decreases slightly (Fig. 3).

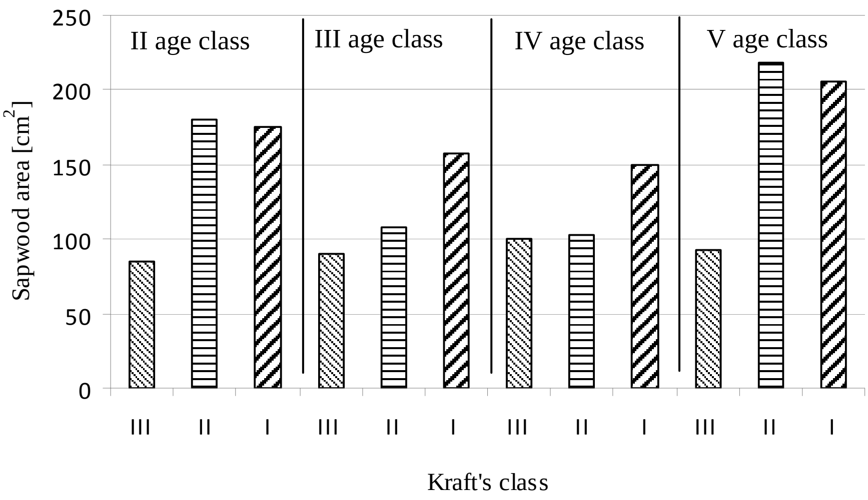


Figure 3. A comparison of sapwood area at breast height in age classes and Kraft's social classes of tree position

Powers of the correlations between sapwood ring area and elements describing the structure of the crown were calculated using Spearman's correlation coefficients (Table 1). Sapwood ring area at breast height is correlated most strongly with crown projection area (r = 0.68), followed by crown volume (r = 0.42), while the analyzed crown characteristic with the weakest correlation is outer crown area (r = 0.38). The same trait measured at the height of crown base correlates more strongly with values describing crown structure, while all correlation coefficients are statistically significant at significance level $\alpha = 0.05$. Stronger correlations with biometric traits of the crown in relation to breast height sapwood area are also observed for mean sapwood area (Table 1). Moreover, biometric traits of the crown in larches were also correlated, among which relationships between crown projection area and its volume, and between outer crown area and volume, turned out to be statistically significant. Statistically significant correlations were found between mean sapwood area and sapwood area at crown base, as well between sapwood area at crown base and sapwood area at breast height (Table 1).

Table 1. Spearman's correlation coefficients

	(1)	(2)	(3)	(4)	(5)	(6)
Mean sapwood area [cm^2] (1)	1.00	0.66*	0.96*	0.49	0.68*	0.43
Sapwood area at crown base [cm^2] (2)	0.66*	1.00	0.63*	0.62*	0.68*	0.58*
Sapwood area dbh [cm^2] (3)	0.96*	0.63*	1.00	0.42	0.64*	0.38
Crown volume [m^3] (4)	0.49	0.62*	0.42	1.00	0.73*	0.95*
Crown proj. area [m^2] (5)	0.68*	0.68*	0.64*	0.73*	1.00	0.55
Crown external area [m^2] (6)	0.43	0.58*	0.38	0.95*	0.55	1.00

* differences statistically significant at $p < 0.05$

Selected quantitative traits of the crown of analyzed European larches (*Larix decidua* Mill.) are presented in Table 2. Values of the described characteristics of the crown in larches increased with the age of trees and with improving social class of tree position in the community. Exceptions were trees representing age class IV, whose crowns were markedly smaller than those of the others. This resulted most probably from genetic traits of the trees and from tending interventions performed.

Table 2. Quantitative characteristics of the crown in European larches (*Larix decidua* Mill.) in age classes by social class of tree position in the stand

Age class	Kraft's class	Crown volume [m^3]	Projection crown area [m^2]	External crown area [m^2]
II	I	24.55	9.90	35.96
	II	31.66	11.64	42.74
	III	16.59	8.30	26.84
Mean		24.27	9.95	35.18
III	I	70.37	12.57	88.86
	II	40.45	7.55	65.68
	III	34.61	6.61	60.04
Mean		48.48	8.91	71.53
IV	I	19.14	6.38	34.18
	II	16.26	6.16	29.67
	III	14.43	5.73	27.33
Mean		16.61	6.09	30.39
V	I	90.88	26.42	82.68
	II	43.39	14.86	52.05
	III	27.01	11.64	36.96
Mean		53.76	17.64	57.23

Next, statistical analysis was performed on the values of sapwood area taken at breast height in order to verify the significance of differences between the analyzed age classes and social classes of tree position in the community. Due to the absence of normal distribution of the analyzed traits, the non-parametric Kruskal-Wallis test was applied to test the differences. Based on the test, statistically significant differences in values of sapwood area measured at breast height were observed between age class V and all the other age classes (Table 3).

Table 3. Results of Kruskal-Wallis test for values of sapwood area at breast height in the analyzed age classes.

Kruskal-Wallis test: H (3, N= 160) =13.36342 p =0.0039				
Dependent – sapwood area	II age class	III age class	IV age class	V age class
II age class		1.000000	1.000000	0.000003*
III age class	1.000000		1.000000	0.000013*
IV age class	1.000000	1.000000		0.000152*
V age class	0.000003*	0.000013*	0.000152*	

* differences statistically significant at $p < 0.05$

Moreover, the Kruskal-Wallis test was performed in order to verify the significance of differences in sapwood area at breast height in Kraft's social classes of tree position in each of the investigated age classes. Based on the tests, similar relationships were found in age classes II and V, in which codominant trees (Kraft's class III) differed statistically significantly in terms of sapwood area from the other two social classes of tree position, i.e. dominant trees (Kraft's class II) as well as trees in Kraft's class I, i.e. predominant trees (Table 4; 5).

Table 4. Results of Kruskal-Wallis test for sapwood area at breast height in Kraft's social classes of tree position in age classes II and III.

	Kruskal-Wallis test: H (2, N= 30) =7.933607 p =0.0189 (II age class) Kruskal-Wallis test: H (2, N= 37) =9.034905 p =0.0109 (III age class)					
	II age class			III age class		
Dependent – sapwood area	{1} R: 19.30	{2} R: 17.64	{3} R:8.67	{1} R: 25.62	{2} R: 18.17	{3} R:12.67
I Kraft’s class{1}		1.0000	0.0062*		0.0903	0.0019*
II Kraft’s class {2}	1.0000		0.0057*	0.0903		0.6398
III Kraft’s class {3}	0.0062*	0.0057*		0.0019*	0.6398	

* differences statistically significant at $p < 0.05$

In age class III, predominant trees (Kraft's class I) differed statistically significantly in sapwood area from codominant trees (Kraft's class III). Thus differences were observed between extreme positions within the main stand according to Kraft (Table 3). No statistically significant differences at α =0.05 were found in sapwood area between trees differing in social class of tree position in age class IV (Table 5).

Moreover, the coefficient P_w, being a ratio of the outer crown area (P_k) to sapwood ring area (P_b), was calculated for measurement heights of 1.3m (Table 6) and live crown base (Table 7), being expressed in m^2/cm^2. The purpose of calculating values for this coefficient was to determine how the value of sapwood area changes depending on the distance of the tested sample from the physiologically active crown.

Table 5. Results of Kruskal-Wallis test for sapwood area at breast height in Kraft's social classes of tree position in age classes IV and V.

	Kruskal-Wallis test: H (2, N= 43) = 8.008 p =0.0182 (IV age class) Kruskal-Wallis test: H (2, N= 49) =11.996 p =0.0025 (V age class)					
	IV age class			V age class		
Dependent – sapwood area	{1} R: 18.53	{2} R: 18.33	{3} R:30.23	{1} R: 31.53	{2} R: 28.00	{3} R:15.06
I Kraft's class {1}		1.0000	0.2174		0.8288	0.0008*
II Kraft's class{2}	1.0000		0.1960	0.8288		0.0313*
III Kraft's class {3}	0.2174	0.1960		0.0008*	0.0313*	

* differences statistically significant at $p < 0.05$

Table 6. Values of coefficient P_w in age classes by Kraft's social class of tree position, at a measurement height of 1.3 m

Kraft's class	Age class				
	II	III	IV	V	Mean
I	0.21	0.57	0.23	0.40	0.35
II	0.24	0.61	0.29	0.24	0.34
III	0.32	0.66	0.27	0.40	0.41
Mean in age classes	0.25	0.61	0.26	0.35	
Std deviation	0.05	0.04	0.03	0.08	
Coefficient of variation	18%	7%	10%	22%	

The coefficient P_w reached the highest value in trees of age class III, while the lowest in trees representing age class II. This coefficient in age classes IV and V took intermediate values. The parameter showed a similar trend for the two analyzed measurement heights (Tables 6 and 7). In view of Kraft's classes the highest value of coefficient P_w was recorded for Kraft's class III, while the lowest for Kraft's class I, which was connected with a smaller sapwood area in trees occupying inferior social classes of tree position in the community. Coefficient P_w took higher values for measurements at crown base than at breast height, which indicates a decrease in sapwood area with tree height.

Table 7. Values of P_w in age classes by Kraft's social class of tree position, for measurements at crown base

Kraft's class	Age class				
	II	III	IV	V	Mean
I	0.38	0.76	0.83	0.87	0.71
II	0.48	0.90	0.85	0.87	0.77
III	1.12	1.08	0.36	0.80	0.84
Mean in age classes	0.66	0.91	0.68	0.84	
Std deviation	0.33	0.13	0.23	0.03	
Coefficient of variation	60%	15%	34%	11%	

4. Discussion

The shape of the crown and its size are determined by genetic factors, as well as being modified by environmental conditions during the lifetime of the tree. Genotypic and phenotypic variation of the tree crown may be interdependent with wood quality, i.e. they may be indicators of such quality attributes as the proportion of sapwood and heartwood in the stem (Pazdrowski 1994). Growth and increment of trees are to a considerable degree dependent on the size of their crown, which indirectly indicates the size of their assimilatory organ. Productivity of the assimilatory organ depends on individual characteristics of trees, on social class of tree position, crown size and climatic factors (Lemke 1966). According to Shinozaki et al. (1964), sapwood area is closely related to the size of the assimilatory organ (the so-called pipe–model theory). The sapwood zone, which conducts water and minerals from the roots towards the crown, has to remain in a state of equilibrium with the physiologically active, transpiring crown. The largest sapwood ring area was found in trees representing age class V, and the smallest in trees in age class IV (Fig. 2A). The higher values of sapwood ring area for trees in age classes II and III are probably connected with the immaturity of parenchymal cells initiating the formation of heartwood. A lower proportion of heartwood is equivalent to a higher area of sapwood. The highest sapwood area was observed in trees belonging to social class I (predominant trees), and the lowest for codominant trees (Fig. 2B). Predominant trees are characterized by higher values of quantitative crown traits, and hence probably a higher sapwood area used to provide homeostasis of the water balance. According to Lemke (1966), mean measured elements of the crown are highest in social class I, decrease in class II (approximating the mean for the stand) and are lowest in class III. Among the calculated quantitative characteristics of the crown, the strongest, statistically significant correlation was found between sapwood ring area measured at breast height and crown projection area (r = 0.64). Similar results were reported by Stancioiu and O’Hara (2005), who identified a strong linear relationship between crown projection area and sapwood area measured at breast height in *Sequoia sempervirens* (D.Don) Endl. A strong positive relationship between sapwood area and the size of the assimilating and transpiring organ has been reported by numerous researchers (Whitehead et al. 1984, Yang et al. 1994, Mörling and Valinger 1999, Sellin and Kupper 2003, Jelonek et al. 2008). Differences in sapwood ring area at breast height were statistically significant (at a significance level of 95%) between trees in age class V and those in the other three younger age classes. This probably results from the larger crowns of larches representing age class V (Table 2), and thus the maintenance by the tree a larger conducting area, remaining in a close relationship with the transpiring and assimilating crown throughout the lifetime of the tree (Maguire and Kanaskie 2001). In the investigated Kraft's classes, statistically significant differences in sapwood ring area were recorded in age classes II and V between trees representing Kraft's class I (predominant trees) and the other two Kraft's classes. This is probably the effect of considerable differences in the values of quantitative characteristics of the crown between trees occupying different social classes of tree position within the main stand. In age class III statistically significant differences were observed between trees occupying extreme social classes of tree position. Trees with wide, spreading crowns belong generally to the upper storey. As a result of the more limited access to light and the pressure of adjacent crowns, trees belonging to social class III are found to exist under inferior living conditions and produce lower leaf mass (Lemke 1966). The lack of significant differences in the size of sapwood area by social class of tree position in age class IV probably results from the very similar crown sizes, in spite of the different social classes of tree position. It should also be stressed here that the European larch is an extremely light-demanding forest-forming species, in older age classes forming stands composed of only the first three Kraft's social classes, which frequently exchange places in the stand during their lifetime. In the opinion of Borowski (1974), the course of basal area increment does not display a trend identical to that found for increment in height. The course of increment in basal area of a tree, in contrast to that of height increment, reflects changing environmental conditions more than species-specific traits.

The calculated coefficient P_w was characterized by higher values at crown base than at a height of 1.3 m. This is connected with the decrease in sapwood ring area with tree height. Similar conclusions were reported by Yang et al. (1994), who in a study of *Cryptomeria japonica* identified a reduction in sapwood area with tree height. The ratio of leaf area to sapwood area was calculated by Stancioiu and O'Hara (2005), who studied *Sequoia sempervirens* (D.Don) Endl. The mean value of this ratio was 0.40 m^2/cm^2 at breast height and 0.57 m^2/cm^2 at crown base. Similar results were recorded in this study on the European larch, in which the mean value of the coefficient P_w was on average 0.37 m^2/cm^2 for measurement height 1.30 m, while at crown base it averaged 0.77 m^2/cm^2. According to Margolis et al. (1995), more shade-tolerant species are characterized by higher values of the ratio of leaf area to sapwood area. The problem discussed in this study is of importance not only for pure science, but also for forestry and wood industry practice. Insight into factors affecting the formation of sapwood, and thus also heartwood, as well as relationships between crown structure and the proportion of sapwood in tree stems, may be used to modify the production of good quality timber and to optimize its utilization. However, due to the complexity of the problem, further research is required.

5. Conclusions

Due to the modest quantity of samples used for this analysis the results ought to be treated with caution, rather as indicating a trend and contributing to further studies to be conducted in the future.

The mean sapwood ring area increases with improvement in social class of tree position in the stand. Among age classes, statistically significant differences in sapwood area at breast height were found between age class V and the other three, younger age classes.

Positive correlations were found between sapwood ring area measured at breast height and crown projection area (r = 0.64), crown volume (r = 0.42) and outer crown area (r = 0.38). Stronger correlations (statistically significant) with biometric characteristics of the crown were observed for sapwood area measured at crown base.

Higher values of the coefficient P_w were observed at crown base than at breast height. Among trees of the main stand according to Kraft, the coefficient P_w took higher values for trees occupying inferior social classes of tree position.

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